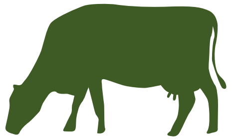

# KEYS TO SUSTAINABLE GRAZING

Cindy Klootwijk

**Economic and environmental consequences of grazing strategies for dairy farms**

KEYS TO SUSTAINABLE GRAZING
Cindy Klootwijk
2019

## Propositions

**1.** Regardless of milk production level, a higher intake of fresh grass contributes to the economic sustainability of dairy farms.
(this thesis)

**2.** Reducing grazing losses from rejected grass patches requires the quantification of fresh grass allowance.
(this thesis)

3. Without a reward system for farmers, the non-provisioning services provided by their land will decline.

**4.** The role of researchers is not limited to delivering facts.

**5.** We should not sell our outdated insights to the developing world.

**6.** Questioning conventions is essential for personal growth.

**Propositions belonging to the thesis, entitled**

*Keys to sustainable grazing: economic and environmental consequences of grazing strategies for dairy farms*

Cindy Klootwijk
Wageningen, 7 June 2019

# Keys to sustainable grazing

*Economic and environmental consequences of grazing strategies for dairy farms*

**Cindy Klootwijk**

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# Keys to sustainable grazing

## *Economic and environmental consequences of grazing strategies for dairy farms*

**Cindy Klootwijk**

**Thesis**

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## Abstract

In order to maintain grazing at highly productive dairy farms (i.e. farms with a high stocking density on the available grazing area), farmers start to change from traditional continuous and rotational grazing systems to compartmented continuous grazing (CCG) and strip grazing (SG). Unlike the traditional grazing systems, CCG and SG are grazing systems in which cows receive a new grazing area each day. A complete overview of the interlinked effects of grazing strategies, grassland utilization and cow productivity on the economic and environmental performance of highly productive farms was missing. The aim of this thesis, therefore, was to quantify the technical performance of improved grazing strategies, such as CCG and SG, in order to determine the economic and environmental consequences for dairy farms. In a grazing experiment we showed that, overall, CCG and SG can support fresh grass intake of high yielding dairy cows at high stocking densities, without compromising on milk production. Results showed furthermore that increasing fresh grass intake of dairy cows can improve the economic performance of dairy farms, at various levels of milk production, and that reducing grazing losses can improve both the economic and the environmental performance of dairy farms. To improve fresh grass intake, the right amount of fresh grass has to be allocated to the herd, which requires a reliable estimate of the fresh grass allowance. To improve such estimates, we first showed that one region-specific calibration equation to estimate fresh grass allowance can be used across grazing systems. Second, we showed the importance of correcting the fresh grass allowance for the formation of rejected patches surrounding dung. Third, we found a more labour-friendly method to quantify fresh grass allowance, which can take into account rejected patches, using drone technology.

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# Chapter 1

*General introduction*

# 1 The role of grazing on dairy farms



### *1.1 Background*

Grasslands are ecological communities dominated by introduced or indigenous grasses or grasslike plants, covering up to 40% of Earth's terrestrial surface (Blair *et al.*, 2014). Climate, fire and grazing are important drivers that shape the species composition and biomass production of grassland ecosystems through time and space (Blair *et al.*, 2014). These grassland ecosystems provide multiple provisional and non-provisional services that people benefit from (Rodríguez-Ortega *et al.*, 2014). Provisional services are the products directly obtained from ecosystems, and include the production of human-edible food, such as meat and milk. Ruminants are able to convert grass biomass which is inedible to humans into these high quality food products, and they therefore contribute to net food security (van Zanten *et al.*, 2016). Besides food, ruminant grazing can bring additional benefits in terms of non-provisional services. These non-provisional services include regulating services, such as climate regulation and flood control, supporting services, such as nutrient cycling and biodiversity, and cultural services, such as recreation and landscape conservation (Rodríguez-Ortega *et al.*, 2014). The net contribution of ruminant grazing to ecosystem services depends among others on the grazing system (Blair *et al.*, 2014).

According to Allen *et al.* (2011), a grazing system is "a defined, integrated combination of soil, plant, animal, social and economic features, stocking (grazing) method(s) and management objectives designed to achieve specific results or goals". This broad definition illustrates the variety of factors that determine a grazing system. Grazing systems are very diverse and differ according to their agro-ecological and socio-economic context (Godde *et al.*, 2018). Generally, a managed grazing system can be characterized by the stocking period (i.e. grazing and rest period per time unit), the stocking density (i.e. animal or forage intake units per land area unit) and the stocking method (i.e. manipulation of where and what the animals graze) (Allen *et al.*, 2011). Depending on these characteristics, grazing systems vary in the amount of feed supplementation. In drylands and mountains, for example, natural grasslands form the primary source of feed for ruminants in extensive systems in which cows are moved in search for feed and water (Tamou, 2017). In countries like Ireland and New Zealand, we also find primarily low-input dairy farming systems that are fully pasture-based. In other countries, for example the Netherlands, milk production is generally based on fertilized sown grasslands with supplementary feeding and corresponding high output, whereas beef cattle in the USA spend the first part of their life on pastures, and are finally fattened in feedlots based on concentrate feed. Globally, livestock production from pasture-based systems has increased during the last decades, mainly due to intensification (i.e. producing more per unit of input) (Godde *et al.*, 2018).

### *1.2 Developments in pasture-based systems*

Changes in pasture-based systems are driven by a combination of interlinked and dynamic factors, including demographical, technical, agro-ecological and socio-economic factors. Since the beginning of the 21st Century, the global grazing area has decreased, whereas productivity has increased (i.e. intensification). These developments are mainly driven by a global increase in the demand for food of animal origin, and an increase in land competition (Godde *et al.*, 2018). In the past 20 years, for example, the global production of meat and milk from cattle has increased by about 37%, from 523 to 719 million ton. Due to large regional and local heterogeneities, however, the exact development of pasture-based systems differs largely across regions.

In temperate regions, we find two opposite trends. On the one hand, we observe grazing land abandonment and de-intensification. Grazing land abandonment especially occurs in lowly populated and remote areas with unprofitable businesses (JRC, 2013), whereas de-intensification is mainly observed in systems that are highly susceptible for environmental damage (Godde *et al.*, 2018). On the other hand, we observe further trends of intensification, although increasingly limited by environmental legislation and biological and technical ceilings (e.g. agronomic yield gaps are relatively small). The intensification of pasture-based systems has resulted in changes in farm characteristics towards an increase in herd size, stocking rate, milk yield per cow and use of automatic milking systems (Parsons *et al.*, 2004). Increases in herd size have reduced the fresh grass availability per cow, which resulted in the need for supplementary feeding on dairy farms. Combining grazing with supplementary feeding can be challenging, since an incorrect balance between fresh grass allowance and feed supplementation results in inefficient grassland use and reduced milk yields. This challenge is one of the drivers for a decreasing trend in on-farm grazing and an increasing trend in indoor-housing, as can be observed in several countries in North-West Europe. In this thesis, I focus on farms with a high stocking density on the available grazing area (further referred to as highly productive dairy farms) in temperate regions, using Dutch dairy farming as a case study.

The abovementioned intensification dynamics can have consequences for farm profitability, the environment, the health and welfare of cows, the natural landscape and other sustainability issues. This raises the question whether this trend is sustainable and what the role of grazing will be on future dairy farms. To find answers to these questions we will first describe diverse sustainability issues of pasture-based systems.

## 2 Sustainability of pasture-based systems



Nowadays, sustainability is seen as a concept including three pillars, i.e. economic, environmental and social sustainability. Economic sustainability on dairy farms implies balancing assets and liabilities and expenses and revenues related to milk production (Kay *et al.*, 2012), and includes issues such as farm profitability, price volatility and employability. Environmental sustainability on dairy farms implies minimizing emissions to the air, water and soil, and using natural resources at a rate not exceeding their regenerative capacity, and includes issues such as global warming, eutrophication, acidification, and depletion of fossil energy, phosphorus and water stocks, or loss of biodiversity or land quality. Social sustainability on dairy farms implies that the milk production system should be embedded into its social cultural context, should be respectful towards animals and should contribute to equitable management of resources. Social sustainability includes issues such as health and welfare of cows, farmers (labour intensity) and consumers; consumer demand and landscape quality (De Boer, 2012).

### *2.1 Economic sustainability*

Several studies have shown positive effects of grazing on the economic performance of dairy farms. Generally, zero-grazing dairy farms feed higher amounts of supplements to increase milk production, which results in higher revenues from milk but also in higher feed costs (Meul *et al.*, 2012). Comparing data across countries, Dillon *et al.* (2008) concluded that the costs of milk production decreased as the share of fresh grass in the diet increased. An increase in fresh grass intake results in a decrease in feed supplementation, leading to lower costs related to feeding and contract labour (Sanderson *et al.*, 2001). The actual economic benefit of an increase in the share of fresh grass in the diet, however, depends on milk price, and costs for, for example, feed, buildings, machinery and labour and subsidies, which vary across countries. In addition, it highly depends on the efficiency of converting fresh grass into milk (Evers *et al.*, 2008; Van den Pol-van Dasselaar *et al.*, 2014a).

This key performance parameter, however, inherently differs across pasture-based systems. Van Vuuren (1993), for example, argued that in theory even the best quality roughage can only support production levels of about 27 litre of milk per cow per day. Milk production levels on full roughage diets often peak at 20 to 22 litre of milk per cow per day in practice (Van Vuuren, 1993), because roughage is not optimally used in terms of quantity or quality, implying that there is room for improvement of farm profitability. To further increase the milk production, concentrates are needed to fulfil the required extra energy demand (Kristensen *et al.*, 2005). An incorrect balance between fresh grass allowance and feed supplementation can reduce grassland utilization, and increase variations in dry matter intake and milk production per individual cow (Hennessy *et al.*, 2015). Achieving a high grass utilization in order to improve the economic benefit of grazing is especially challenging when grazing is combined with supplementary feeding, since cows are less motivated to graze when alternative feed is offered.

### *2.2 Environmental sustainability*

From an environmental perspective, grazing can have both positive as well as negative effects. In general, pasture-based systems show higher nitrogen (N) losses in the form of nitrate leaching than zero-grazing systems (Di and Cameron, 2002). The risk of nitrate leaching while grazing results from the high local concentrations of N in urine and manure patches, which exceeds the plant requirements (Vellinga *et al*., 2011). In addition, N is deposited throughout the whole grazing season, not accounting for optimal timing of fertilization. Nitrate leaching potentially leads to an increased nutrient loading in surface and ground water, which may cause eutrophication, resulting in algae bloom and consequently decreased water quality (Howarth *et al*., 1988). This can have detrimental effects on aquatic life in ground and surface waters. Ammonia volatilization, on the other hand, is higher in zero-grazing than in pasture-based systems (Bussink and Oenema, 1998). More ammonia is emitted during indoor manure storage and associated field application of this manure than during manure deposition by grazing cows. Ammonia volatilization during grazing is reduced because urea in urine is separated from the enzyme urease in the faeces, which lowers the formation of ammonia, and hence, its volatilization. Grazing, however, does results in high local phosphorus (P) concentrations in manure patches. Phosphorus can run-off in the form of phosphate but this occurs less frequently than nitrate leaching, because P can bind to soil particles to a certain extent (Misselbrook *et al*., 2013).

A recent review of Lorenz *et al.* (2019) provides the state-of-the-art knowledge on GHG emissions in pasture-based systems, based on a meta-analysis of standardized carbon footprints from 30 published papers. They defined three grazing systems, i.e. a pasture-based (low input) system with a minimum of 50% fresh grass and a maximum of 25% concentrates in the ration; a mixed system with less than 50% fresh grass and/or more than 25% concentrates in the ration and a confinement system with 0% fresh grass. Results showed that these production systems can produce with similar GHG emissions per unit of milk when excluding carbon sequestration. In line with Thoma *et al.* (2013), they found a large variability in GHG emissions within these three categories of grazing systems, possibly due to individual differences in farm management. They showed that an increase in milk yield, fresh grass intake and feed efficiency decreased the carbon footprint, independent of the production system. Lorenz *et al.* (2019), however, did not include carbon sequestration of grasslands in their analysis of carbon footprints, which means that the total benefits of the grass based systems can be higher than presented in their paper. Garnett *et al.* (2017), however, argue that the benefits of carbon sequestration are time limited due to a ceiling in carbon storage per land unit and cannot outweigh the long-term GHG emissions of the numerous ruminants in our current food production systems.

The intensification of pasture-based systems has resulted in a focus on the provisional services rather than the non-provisional services of grasslands, which among others resulted in biodiversity losses (Blair *et al.*, 2014). Quantifying the effects of grazing management on biodiversity, however, can be challenging since it is sometimes difficult to separate short-term management effects from long-term population responses (Scheper, 2015). In addition, it implies the qualitative rating of species and functional groups within an ecosystem (Del Prado *et al.*, 2011). Van Klink *et al.* (2015) distinguished four main types of impact of grazing; (1) disturbance and unintentional predation, (2) reduction of plant resource availability by defoliation or trampling, (3) increase in resource availability for dung-dependent insects and (4) changes in habitat quality through alterations of plant diversity, vegetation structure and abiotic conditions, with the first two being detrimental, the third beneficial and the fourth either detrimental or beneficial (Wallis de Vries, 2016). The intensification of pasture-based systems, with an increase in stocking density, clearly affects the incidence of disturbances, unintentional predation, defoliation, trampling and alters the vegetation types and structure. In general, species richness exponentially decreases with an increase in land use intensity (Kleijn *et al.*, 2009; Allan *et al.*, 2014). Kleijn *et al.* (2009) also mention that relative costs for conservation of biodiversity increases with an increase in land use intensity.

### *2.3 Social sustainability*

Grazing can contribute to improved health and welfare of dairy cows, because the dairy cows can express a wider range of their natural behaviour in the pasture (Burow *et al.*, 2013). Von Keyserlingk *et al.* (2017) showed that cows are highly motivated to enter an outdoor access. In addition, Smid *et al.* (2018) showed that cows express a preference for a large pasture over a small sand pack when given the choice. A review by Arnott *et al.* (2017) revealed that there are considerable welfare benefits from incorporating pasture access into dairy production systems. On the other hand, when not well managed, there are also negative effects of an outdoor access. The negative effects are exposure to rain and sun when no shelter is provided. In combination with high temperatures cows can easily be forced outside their thermo-neutral zone and experience heat-stress, especially when milk production is high. Literature shows the effect of heat-stress on biological functioning in terms of reduced milk production and reproductive performance, but has yet to show the potential effects on the affective state of cows (Polsky and Von Keyserlingk, 2017). Outdoor access generally also increases the risk of being infected by specific pathogens such as intestinal worms, lungworms and liver fluke. One can argue, however, that it might be easier to prevent the disadvantages of outdoor grazing than to tackle the welfare disadvantages related to indoor housing.

When it comes to the decision whether or not to provide outdoor access to cows, an often heard social argument is the labour that relates to grazing. Grazing requires time to set-up and maintain the infrastructure of pastures, i.e. fencing, providing fresh drinking water and cleaning of the cow path. Depending on the quality of this infrastructure and the distance from the barn to the pasture it takes time to fetch the cows for milking. In addition, grazing management requires time and craftsmanship. Due to weather changes during the grazing season, the variability and unpredictability of the grass production is high. This requires advanced management skills of the farmer to adequately respond to changes in grass availability. The perceived labour intensity of grazing might also depend on the farmers' personality traits and skills to manage this variability related to grazing. On the other hand, time needed for mowing, silage making and feeding is less in a grazing system compared to an indoor housing system. In addition, since the working activities of a grazing system compared to an indoor-housing system are different, personal preferences herein might also influence the perceived labour intensity.

## 3 Towards sustainable grazing

### *3.1 Knowledge gap*

The above described overview shows that grazing can have positive and negative effects on sustainability issues. In this thesis, I will explore the economic and environmental consequences of two potentially beneficial grazing strategies, whereas their effects on social sustainability issues will be discussed in chapter 7.

In order to maintain grazing at highly productive dairy farms, famers start to change from traditional continuous and rotational grazing systems to compartmented continuous grazing (CCG) and strip grazing (SG). Unlike the traditional grazing systems, CCG and SG are grazing systems in which cows receive a new grazing area each day. Daily rotational systems are hypothesized to increase grass yield, reduce grazing losses from trampling or rejected patches (RP), and reduce clustering of excreta by forcing a more even distribution of manure.

CCG and SG, however, largely differ in key grazing characteristics, such as pre- and post-grazing heights and period of regrowth. In CCG, cows rotate across a fixed number of fields of a fixed size. A CCG therefore uses fixed fencing, and requires an adjustment of supplementary feeding to the realized grass growth in the fixed period of regrowth. In SG, however, cows rotate across fields of variable size, which is determined by the feed requirements and grass availability. SG therefore requires more labour for moving fences, but is hypothesized to result in a higher grass utilization than CCG for two reasons. First, period of regrowth and hence grass yield is expected to be higher in SG than in CCG. Second, because of the smaller area per cow in SG grazing losses from selective grazing are expected to be lower.

Van den Pol-van Dasselaar *et al.* (2014a) indicated the importance of technical parameters such as grass yield, grazing losses and grass utilization for the sustainability performance of grazing systems. Creighton *et al.* (2011) also highlighted the potential of improved grass utilization to improve the economic and environmental performance of grazing systems. A complete overview of the interlinked effects of grazing strategies, grassland utilization and cow productivity on the economic and environmental performance of highly productive farms is missing. This lack of knowledge hinders decision-making regarding optimal grazing management. In order to quantify economic and environmental consequences of improved grazing strategies, such as CCG and SG, we need detailed insights in the technical performance of these systems. Therefore, the aim of this thesis was to quantify the technical performance of improved grazing strategies, such as CCG and SG, in order to determine the economic and environmental consequences for dairy farms. We used the Netherlands as a case study.

### *3.2 Approach and outline of the thesis*

The outline of the thesis is visualized in Figure 1. To determine the economic and environmental consequences of improved grazing strategies for Dutch dairy farms, two building blocks are required: modelling and data collection. First, I need insight into the effect of recent policy changes, such as the abolishment of milk quota and new manure policy, on farm structure, management, income and environmental impact of an average Dutch farm. To do so, we use an optimization model that combines bio-economic optimization modelling and a life cycle assessment approach (chapter 2). Optimization models include a guiding principle (e.g., maximizing farm income that guarantees an optimal solution before and after implementing a strategy. By using a whole-farm optimization model to analyse the economic and environmental consequences of different strategies, differences in results can be fully attributed to the modelled strategies. Economic optimization was used as economic incentives are one of the important drivers in management decisions of farmers.

Second, I need insight in the technical performance of grazing strategies. These technical data are collected in a large grazing experiment as part of the project 'Amazing Grazing'. The Amazing Grazing project aims to find grazing strategies for dairy farms with feed supplementation and high stocking rates on the available grazing area (Schils *et al.*, 2018b). The grazing experiment aims at quantifying technical performance of compartmented continuous grazing (CCG) and strip grazing (SG) for farms with a high stocking density (7.5 cows $ha^{-1}$) on the grazing area. A long-list of measurements that will be done during this experiment include measurements related to soil quality, grass production, grass intake and milk production. For this thesis, we focus on measurements related to grass yield, grazing losses and grass utilization since we hypothesize that these technical parameter influence both the economic and environmental performance of grazing systems. Results of measurements related to grassland utilization are discussed in chapters 3, 4, 5. Chapter 3 describes the effect of grazing system on the rising plate meter calibration for herbage mass estimation. Chapter 4 describes the quantification of the formation of RP in intensive grazing systems to improve fresh grass allowance estimation. Chapter 5 describes the potential of drone technology to correct fresh grass allowance for selective grazing. Additional results on measurements related to grass production, grass intake and milk production are further discussed in chapter 7. The technical data as collected during the grazing experiment, together with already existing literature, feeds into the model as used for chapter 2. Results on the economic and environmental consequences of grazing strategies are discussed in chapter 6.

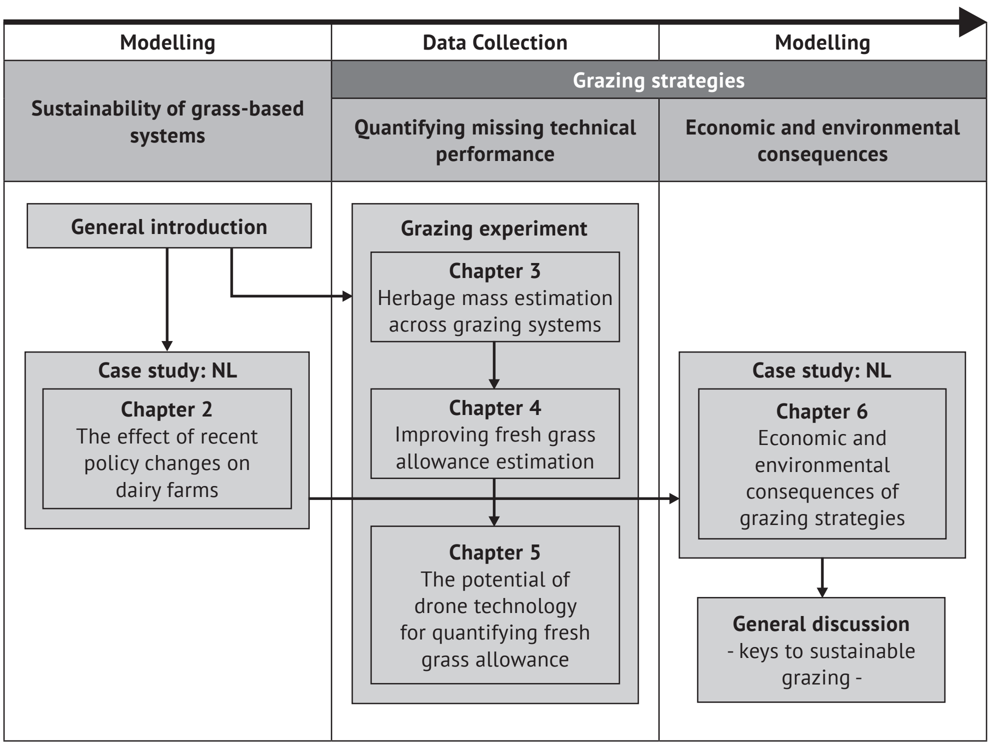
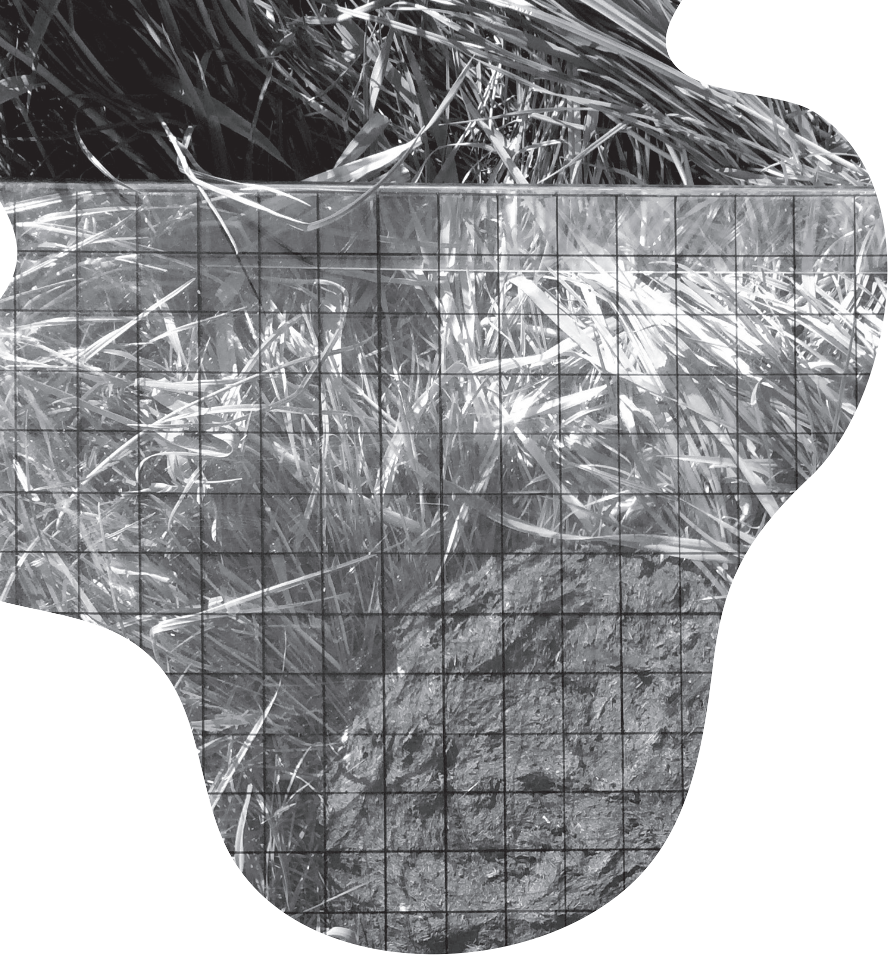



**Figure 1.** *Outline of the thesis.*



# Chapter 2

## *Dutch dairy farms after milk quota abolition: economic and environmental consequences of a new manure policy*

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## ABSTRACT

The abolition of the Dutch milk quota system has been accompanied by the introduction of a new manure policy to limit phosphate production (i.e., excretion via manure) on expanding dairy farms. The objective of this study was to evaluate the effect of these recent policy changes on the farm structure, management, labour income, nitrogen and phosphate surpluses, and greenhouse gas emissions of an average Dutch dairy farm. The new manure policy requires that any increase in phosphate production be partly processed and partly applied to additional farmland. In addition, phosphate quotas have been introduced. Herein, we used a whole-farm optimization model to simulate an average farm before and after quota abolition and introduction of the new manure policy. The objective function of the model maximized labour income. We combined the model with a farm nutrient balance and life-cycle assessment to determine environmental impact. Based on current prices, increasing the number of cows after quota abolition was profitable until manure processing or additional land was required to comply with the new manure policy. Manure processing involved treatment so that phosphate was removed from the national manure market. Farm intensity in terms of milk per hectare increased by about 4%, from 13,578 kg before quota abolition to 14,130 kg after quota abolition. Labour income increased by €505 $yr^{-1}$. When costs of manure processing decreased from €13 to €8 $t^{-1}$ of manure or land costs decreased from €1,187 to €573 $ha^{-1}$, farm intensity could increase up to 20% until the phosphate quota became limiting. Farms that had already increased their barn capacity to prepare for expansion after milk quota abolition could benefit from purchasing extra phosphate quota to use their full barn capacity. If milk prices increased from €355 to €420 $t^{-1}$, farms could grow unlimited, provided that the availability of external inputs such as labour, land, barn capacity, feed, and phosphate quota at current prices were also unlimited. The milk quota abolition, accompanied by a new manure policy, will slightly increase nutrient losses per hectare, due to an increase in farm intensity. Greenhouse gas emissions per unit of milk will hardly change, so at a given milk production per cow, total greenhouse gas emissions will increase linearly with an increase in the number of cows.


**Key words:** Dairy Act, farm expansion, phosphate quota, manure processing

## 1 Introduction



In 1984, milk quotas were introduced in Europe to address oversupply in the market. The quota policy restricted the amount of milk to be produced by each member state and, consequently, by individual farmers. In April 2015, the European Union (EU) milk quota system was abolished in response to the increasing global demand for milk and to agreements on trade liberalization in global dairy markets (EU, 2015). The abolition of the quota system allows farmers to increase their milk production and is expected, therefore, to increase milk production in most EU countries (Lips and Rieder, 2005).

Livestock density in the Netherlands is the highest in Europe. This is due to the central location of the Netherlands in western Europe, where the demand for livestock products is high, combined with easy import of feed due to close proximity to the harbour of Rotterdam. This high livestock density, however, also results in high production (i.e., excretion via manure) of nitrogen and phosphate per hectare, which causes environmental problems such as eutrophication of ground and surface water (Oenema *et al.*, 2005). Moreover, the livestock sector, including dairy production, is one of the main contributors to greenhouse gas (GHG) emissions (Gerber *et al.*, 2013). The expected increase in milk production per farm due to quota abolition might increase the environmental impact of dairy production.

To limit nitrate leaching from agricultural production to ground and surface water, the European Nitrates Directive was introduced (EU, 1991), imposing a maximum application of 170 kg of N from animal manure per hectare. Within this directive, 7 member states, including the Netherlands, obtained a derogation to go beyond the 170-kg limit, under certain country-specific conditions. One such condition for the Netherlands is a phosphate production ceiling of 172.9 million kg $yr^{-1}$ for the entire Dutch livestock sector, including a phosphate production ceiling of 84.9 million kg $yr^{-1}$ for the dairy sector. To accommodate this phosphate ceiling, the Dutch government introduced a new manure policy. This "Dairy Act" of 2015 is aimed at supporting the growth of the Dutch dairy sector while limiting increases in phosphate production.

Abolition of the milk quota and introduction of the Dairy Act might change the Dutch dairy sector. Changes in farm structure and management can affect a farmer's income and the environmental impact of dairy production. Several studies have analysed the effect of quota abolition on the economic and environmental performance of the dairy sector, most using macroeconomic models and analysed effects at region or country level (Lips and Rieder, 2005; Kempen *et al.*, 2011). Kempen *et al.*, (2011), for example, predicted a loss in overall agricultural income, and an increase in environmental effects (e.g., nitrate leaching and methane emission) related to an expanding dairy herd in large parts of Europe, especially the Netherlands. To our knowledge, however, the effect of the quota abolition in combination with the introduction of the Dairy Act is unknown. Moreover, we found no studies that took a farm-level perspective and considered changes in farm management in response to changes in policy.

The objective of this study, therefore, was to evaluate the effect of quota abolition and introduction of the Dairy Act on the structure, management, and labour income of a Dutch dairy farm. In addition to these effects, we also considered changes in environmental impact (i.e., nitrogen and phosphorus losses, and GHG emissions). To determine the economic and environmental impact, we combined a whole-farm linear programming model with a farm nutrient balance and life-cycle assessment. We have illustrated strategies for an average Dutch dairy farm on sandy soil. To understand the current political context, we first describe milestones in Dutch environmental policy.

## 2 Materials and methods

### *2.1 Milestones in dutch environmental policies before quota abolition*

Since about 1980, policies have been aimed at regulating the environmental impact of Dutch agricultural production, including dairy production (Oenema and Berentsen, 2005). A first milestone in environmental policy was the introduction of phosphate application standards in 1987. These standards were based on fixed phosphate excretions per type of animal and set limits on the application of phosphate from animal manure per hectare of grassland or crop land (Berentsen and Tiessink, 2003). Farmers exceeding these standards had to pay a levy. Introduction of phosphate application standards, however, barely reduced nutrient losses from agriculture, because application standards and levies were so generous that dairy farms were essentially unaffected (Berentsen *et al.*, 1992).

A second milestone occurred with the introduction of the European Nitrates Directive (EU, 1991), aimed at reducing the negative effects of nitrogen surpluses on water quality. This directive shifted the focus from phosphate to nitrogen. To ensure compliance with the nitrates directive, the Netherlands introduced the mineral accounting system (MINAS) in 1998; MINAS was based on a farm-gate balance approach, using farm-level inputs and outputs to determine a farm-specific surplus of nitrogen and phosphate (Oenema and Berentsen, 2005). Nutrient surpluses at the farm level that exceeded levy-free surpluses were charged. The MINAS system was considered a step forward in environmental policy, because nutrient surpluses are better indicators of nutrient leaching than manure application standards, and because MINAS gave farmers the autonomy to determine how to reduce their surplus.

A judgment of the European court (EU, 2003) about MINAS's lack of compliance with the nitrates directive, in combination with other practical reasons such as increasing administrative burdens and possibilities of fraud, led to the abolition of MINAS in 2006 and the introduction of 3 fertilizer application standards—the third milestone. The first standard comprises a maximum application of 170 kg of N from animal manure per hectare of land. Several member states, including the Netherlands, obtained a derogation to go beyond the 170-kg limit, under certain country-specific conditions. Derogation is specific for these member states because they have a high proportion of grassland and a relatively long growing season, justifying a higher nutrient uptake (EU, 2010). Current derogation regulation in the Netherlands prescribes that farms with at least 80% grassland are allowed to apply, depending on soil type and region, 250 kg of N from animal manure per hectare on all of their land. Farmers who receive this derogation are not allowed to use synthetic phosphate fertilizer. To receive derogation for 2014–2017, the Netherlands must comply with a phosphate production ceiling of 172.9 million kg $yr^{-1}$ and a nitrogen production ceiling of 504.4 million kg $yr^{-1}$ for the entire Dutch livestock sector. The second standard comprises a maximum application of nitrogen fertilizer per hectare of land, including mineral nitrogen from manure, and accounts for nitrogen fixation, deposition, and mineralization. The third standard comprises a maximum application of phosphate fertilizer per hectare of land, including phosphate from manure. Although the first and second standards overlap to a degree, all 3 apply to every Dutch dairy farm. The application standards for nitrogen and phosphate fertilization have been decreased several times over the past decade.Farmers exceeding these standards can be brought to court.

### *2.2 Additional policy after quota abolition*

To comply with the phosphate production ceiling set by the EU as a condition for derogation, the Dutch government prescribed the dairy sector a phosphate production ceiling of 84.9 million kg $yr^{-1}$ based on production levels in 2002. In 2014, however, this limit was exceeded by 0.7 million kg of phosphate (CBS, 2015). To limit further growth as a result of the quota abolition, a new manure policy, referred to as the "Dairy Act," was adopted in December 2014 as a framework law. The Dairy Act prescribes routes for handling the phosphate surplus at the farm level and limits an increase in phosphate production at the sector level. The concrete content of this law consists of 3 parts that have been developed over time based on progressive insight. Figure 1 shows the implications of these 3 parts for a farm, of which the area remains constant but the number of animals increases.

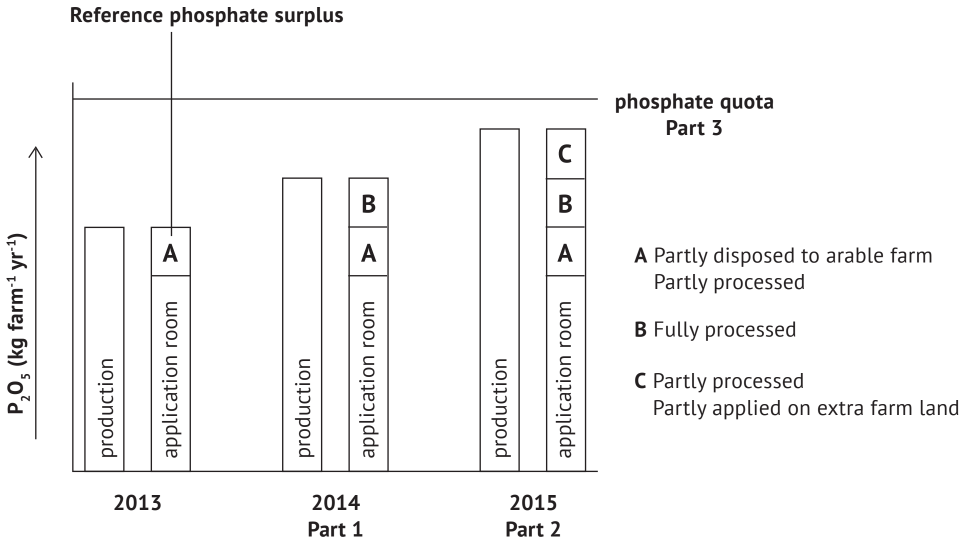



**Figure 1.** *New Dutch manure policy after quota abolition (the "Dairy Act"). The total surplus of 2015 is based on farm-specific excretion factors, whereas calculation of surpluses A, B and the phosphate quota are based on standard excretion factors per type of animal.*

The starting situation is given by the reference phosphate surplus of a farm in 2013, defined as the production minus the application room (surplus A in Figure 1). Phosphate production is defined here as the number of livestock × fixed phosphate excretions per type of livestock (Appendix Table A1), and phosphate application room as the number of hectares × the phosphate application standards. Previous legislation stipulated that part of the reference surplus should be processed based on region-specific rules (i.e., 30% in the south, 15% in the east, and 5% in other regions of the Netherlands; Nitraatrichtlijn, 2014); the remaining part can be disposed to other Dutch farms with application room.

The first part of the Dairy Act, developed in 2014 and introduced in 2015, indicated that any increase in phosphate surplus on top of the reference surplus needed to be fully processed. Manure processing involves treating the manure so that phosphate is removed from the national manure market, which can be done by destruction (incineration or gasification to ash), treatment, or export. When the second part of the Dairy Act was developed in 2015, a maximum was set to the volume of the extra phosphate surplus that may be fully processed (surplus B in Figure 1). This maximum was determined by the phosphate production of a farm in 2014.

The second part of the Dairy Act will be introduced in 2016. In an attempt to tie dairy production more closely to the use of land on the same farm, any phosphate surplus on top of surpluses A and B (surplus C in Figure 1) should be partly processed and partly applied to additional land that should be purchased or hired by the farm. Requirements related to the percentage of this surplus C for which extra land should be acquired depend on the level of the total phosphate surplus in the year of analysis (0% if the surplus is <20 kg $ha^{-1}$, 25% if the surplus is 20 to 50 kg $ha^{-1}$, and 50% if the surplus is >50 kg $ha^{-1}$; Rijksoverheid, 2015).



Because signals indicated that phosphate production in the dairy sector would grow considerably in spite of the new manure policy, the Dutch government announced a third part of the Dairy Act in July 2015. This part consists of a phosphate quota at the farm level to restrict total Dutch phosphate production to comply with the national production ceiling of 172.9 million kg $yr^{-1}$ set by the EU. Each farm is assigned a farm-specific phosphate production quota based on the average number of cows on the farm in July 2015 and standard excretion factors (RVO, 2014). The date that this new quota system was announced and the counting date with regard to the number of animals on the farm were aligned to avoid farmers anticipating this new legislation. Quotas can be transferred between dairy farms.

Whereas calculation of surpluses A, B, and the phosphate quota are based on standard excretion factors per type of animal, the actual phosphate surplus in the year of analysis can be based on farm-specific excretion factors.

This overview of milestones in Dutch environmental policies shows that dairy farmers continuously have to anticipate uncertainties and changes in regulations. This study aims to evaluate the effect of the most recent policy changes, including the abolition of the milk quota and introduction of the Dairy Act, on the structure, management, and labour income of a Dutch dairy farm. Changes in environmental impact, including losses of nitrogen and phosphate and emission of GHG emissions are considered as well.

## *2.3 Dairy farm model*

We used a dairy farm optimization model to simulate a Dutch dairy farm before and after quota abolition and the inclusion of the Dairy Act. The model was originally developed by Berentsen and Giesen (1995), but was recently updated by Van Middelaar *et al.*, (2014). We also updated the prices and included the stipulations of the Dairy Act in the model. The objective function of the model maximized labour income, (i.e., gross returns minus variable and fixed costs). Important activities were on-farm feed production, purchase of feed, animal production, manure application, purchase and application of synthetic fertilizers, and field operations.

We assumed that the average cow in the model belonged to the Holstein Friesian breed and calved on February 1. Female young stock were kept for yearly replacement of the dairy herd, whereas male calves and surplus female calves were sold at an age of 2 wk. The model distinguished between summer and winter for feeding. Based on feed restrictions, the model matched the feed requirements of the cow with on-farm feed production and purchased feed. Feed requirements concerned energy, RDP balance, true protein digested in the small intestine, and phosphorus. In addition, DMI capacity was limited, based on Jarrige (1988). On-farm feed production included production of maize silage and production of grass for grazing and silage making. One hectare of silage maize yields 15.5 t of DM $yr^{-1}$, which equals 102 GJ of $NE_L$ (CBS, 2013). Grassland yield depends on the level of nitrogen fertilization, which can vary from 100 to 500 kg $ha^{-1}$ $yr^{-1}$. Based on 225 kg of N $ha^{-1}$ $yr^{-1}$, 1 ha of grassland yields 66 GJ of $NE_L$ $yr^{-1}$. Purchased feeds included maize silage (to be ensiled by the farmer; KWIN-V, 2014) and 3 types of concentrates that differed in protein levels (i.e., standard, medium, and high). We updated the costs of farm inputs according to long-term expected market prices (KWIN-V, 2014). All dietary options were available in winter and summer, except for fresh grass (only available in summer). Table 1 shows the feed characteristics and prices of the available feed products. We determined farm-specific excretion based on inputs and outputs at herd level, represented by the average cow with young stock.

**Table 1.** *Feed characteristics and prices of available feed products.*

| Feedstuff | $NE_L$ (MJ/kg of DM) | DVE[1] (g/kg of DM) | OEB[2] (g/kg of DM) | Fill value[3] (kg/kg of DM) | Nitrogen (g/kg of DM) | Phosphorus (g/kg of DM) | Market price[4] (€/t of DM) |
|---|---|---|---|---|---|---|---|
| **Concentrate** | | | | | | | |
| Standard protein | 7.21 | 100 | 6 | 0.29-0.72 | 24.1 | 4.5 | 215 |
| Medium protein | 7.21 | 133 | 28 | 0.29-0.72 | 32.2 | 5.0 | 250 |
| High protein | 7.21 | 200 | 83 | 0.29-0.72 | 48.3 | 8.0 | 315 |
| **Grazed grass** | | | | | | | |
| 125 kg of N | 6.62 | 94 | 9 | 0.90 | 28.0 | 4.1 | - |
| 175 kg of N | 6.68 | 96 | 16 | 0.90 | 29.4 | 4.1 | - |
| 225 kg of N | 6.73 | 98 | 23 | 0.90 | 30.9 | 4.1 | - |
| 275 kg of N | 6.77 | 99 | 31 | 0.90 | 32.4 | 4.1 | - |
| **Grass silage** | | | | | | | |
| 125 kg of N | 5.89 | 70 | 22 | 1.10 | 25.6 | 4.1 | - |
| 175 kg of N | 5.93 | 71 | 31 | 1.10 | 27.4 | 4.1 | - |
| 225 kg of N | 5.97 | 73 | 39 | 1.10 | 29.0 | 4.1 | - |
| 275 kg of N | 6.00 | 74 | 47 | 1.10 | 30.6 | 4.1 | - |
| **Maize silage** | 6.56 | 58 | -36 | 0.91 | 10.9 | 1.9 | 60 |

[1]True protein digested in the small intestine according to Dutch standards (Tamminga *et al.*, 1994).
[2]Rumen-degradable protein balance according to Dutch standards (Tamminga *et al.*, 1994).
[3]Fill value per kilogram of DM feed expressed in kilogram of a standard reference feed (see Jarrige, 1988). The fill value of concentrates increases with an increase in concentrate intake.
[4]Applies only to purchased feed products (KWIN-V, 2014).

Constraints of the model included links between activities (e.g., between feeding requirements and produced and purchased feed, and between manure production/application and environmental policies). Environmental policies, for example, include limits to the application of nitrogen and phosphate on the farm as explained before. According to the application standards for 2015–2017 (Nitraatrichtlijn, 2014), the maximum annual amount for mineral nitrogen on sandy soil is 250 kg ha$^{-1}$ for grassland and 140 kg ha$^{-1}$ for maize land, and the maximum annual amount for nitrogen from animal manure is 230 kg ha$^{-1}$ with derogation and 170 kg ha$^{-1}$ without derogation. For phosphate, the maximum annual amount is 90 kg ha$^{-1}$ for grasslands and 60 kg ha$^{-1}$ for maize land. The environmental impact calculations formed an integral part of the model and are explained in the next section.

### *2.4 Environmental impact*

A common method of quantifying losses of nutrients is the nutrient balance approach (Oenema e*t al*., 2003). A nutrient balance computes the difference in nutrients entering and leaving a system, and can be used to quantify environmental indicators such as the nutrient surplus expressed per hectare of land or per unit of valuable output. This study used a farm-level nutrient balance to quantify nitrogen and phosphate surpluses per hectare of on-farm agricultural area, as an indicator for the local environmental pressure related to nitrogen and phosphate losses. Inputs of nitrogen and phosphorus are in the form of concentrates, maize silage, fertilizer, and atmospheric deposition, whereas outputs are in the form of milk, culled animals, and, potentially, manure. A positive nitrogen balance implies that nitrogen is potentially lost to the environment through, volatilization of ammonia or nitrous oxide, or through runoff and leaching of dissolved nitrate, for example. A positive phosphate balance implies that phosphate can accumulate in the soil and is potentially lost to the environment through leaching and runoff, contributing to eutrophication of ground and surface waters (Sharpley, 1995).

In contrast to site-specific effects such as eutrophication, climate change is a global problem. To analyse the effect on climate change, therefore, changes in GHG emissions should be evaluated at the chain level, taking into account not only on-farm processes, but also other stages along the production chain (Van Middelaar *et al*., 2013). We used life-cycle assessment to evaluate emissions of the 3 major GHG related to agricultural production: carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$), from cradle to farm gate. Processes included were the extraction of raw materials to produce farm inputs, the manufacturing and distribution of these inputs, and all processes on the dairy farm.

Emission calculations have been described in detail by Van Middelaar *et al*., (2014). Emissions from the production and combustion of energy sources, and from production of synthetic fertilizer, pesticides, and tap water were based on Weidema *et al.*, (2013). Emissions from the production of concentrates were updated (Appendix Table A2). We calculated enteric methane from dairy cows based on empirical relations between DMI of feed ingredients and methane emission factors per ingredient (FeedPrint, 2015). For young stock, we based enteric methane emission on Intergovernmental Panel on Climate Change (IPCC) tier 2 methods and default values (IPCC, 2006). Methods to calculate emissions from manure management, and from fertilizer application to the field, were derived from national reports (e.g., De Mol and Hilhorst, 2003).

Greenhouse gases were summed up based on their equivalence factor in terms of $CO_2$: 1 for $CO_2$, 28 for biogenic $CH_4$, 30 for fossil $CH_4$, and 265 for $N_2O$ (IPCC, 2013). Emission of GHG were expressed per tonne of fat- and protein-corrected milk (FPCM). To express emissions per tonne of FPCM, we used economic allocation to allocate emissions between milk and meat.

### *2.5 Setup of the analysis*

The starting point for model was an average dairy farm in 2014 (i.e., before quota abolition), applying day grazing. Input data, including milk quota, farmland, barn capacity, labour availability, and dairy cow production traits, were based on national statistics (CBS, 2015; LEI, 2015) and are included in Table 2. Milk price was based on expectations for 2014–2024 according to KWIN-V (2014) and is included in Table 2. Maximum grass intake during grazing was assumed 10 kg of DM $cow^{-1}$ $day^{-1}$ (Taweel *et al.*, 2004; Abrahamse *et al.*, 2009; Kennedy *et al.*, 2009). We used the linear programming model for economic optimization of this farm before quota abolition (i.e., situation 2014).

**Table 2.** *Model input data to simulate an average Dutch dairy farm before quota abolition (situation 2014) and after quota abolition and introduction of the Dairy Act (situation 2016).*

| Item | Unit | Situation 2014 | Situation 2016 |
|---|---|---|---|
| **Milk quota**[1] | t $yr^{-1}$ | 679 | No |
| **Farmland**[1] | ha | 50 | 50 |
| **Barn capacity**[1] | No. of cow | 83 | 83 |
| **Labour availability**[1] | h | 4,000 | 4,000 |
| **Milk production**[2] | kg $cow^{-1}$ $yr^{-1}$ | 8,160 | 8,160 |
| **Fat content**[1] | % | 4.40 | 4.40 |
| **Protein content**[1] | % | 3.50 | 3.50 |
| **Milk price**[3] | € $t^{-1}$ | 355 | 355 |
| **Replacement rate**[1] | % | 26.4 | 26.4 |
| **Dairy Act**[1] | | No | Yes |
| Reference surplus 2013 | kg of phosphate $yr^{-1}$ | - | 800 |
| Reference surplus 2014 | kg of phosphate $yr^{-1}$ | - | 1,142 |
| Phosphate quota | kg of phosphate $yr^{-1}$ | - | 4,841 |
| **Manure disposal**[3] | € $t^{-1}$ $yr^{-1}$ | 9 | 9 |
| **Manure processing**[3] | € $t^{-1}$ $yr^{-1}$ | 13 | 13 |
| **Extra labour**[3] | € $h^{-1}$ | 17 | 17 |
| **Extra barn capacity**[3] | € $cow^{-1}$ $yr^{-1}$ | - | 558 |
| **Extra farmland**[3] | € $ha^{-1}$ $yr^{-1}$ | - | 1,187 |
| **Extra phosphate quota**[3] | € kg of $phosphate^{-1}$ $yr^{-1}$ | - | 2.10 |

[1]CBS (2015), [2]LEI (2015), [3]KWIN-V (2014).

Then, we removed the milk quota from the model and included the Dairy Act. We used economic optimization again to determine the new optimal farm plan (i.e., situation 2016) and evaluate changes in farm structure, management, labour income, nitrogen and phosphate surpluses, and GHG emissions resulting from the policy changes. Input data to optimize the situation after quota abolition (situation 2016) are included in Table 2. The reference phosphate surplus in 2013 and the phosphate surplus in 2014 were based on the average number of cows on a Dutch dairy farm in the corresponding years according to national statistics (CBS, 2015). The phosphate quota was based on the average number of cows on a Dutch dairy farm in 2014, as the average number of cows in 2015 was not available yet (CBS, 2015). We allowed 70% of the reference phosphate surplus in 2013 to be disposed to another farm without processing. The price of liquid manure (slurry) disposal without processing was assumed to be €9 $t^{-1}$, and the additional price of processing was assumed to be €4 $t^{-1}$ (KWIN-V, 2014). Purchase of farmland, barn capacity, and phosphate quota was optional (Table 2). Costs of additional land that can be either used for grass or maize were assumed to be €1,187 $ha^{-1}$ $yr^{-1}$, based on the current average Dutch land price of €46,000 $ha^{-1}$ (KWIN-V, 2014), an interest rate of 4.5% (KWIN-V, 2014), and an inflation rate of 1.92% over the past 5 yr (CBS, 2015). The price of additional labour was assumed to be €17 $h^{-1}$, and the price of additional barn capacity was assumed to be €558 cow $place^{-1}$, including young stock. Costs of phosphate quota were assumed to be €2.10 $kg^{-1}$ of phosphate, based on current prices for quota in the pig sector (i.e., €70 $pig^{-1}$, producing 7.4 kg of phosphate), a depreciation period of 5 yr, and an interest rate of 4.5% (KWIN-V, 2014).

### *2.6 Sensitivity analyses*

Assumptions on production parameters and market factors can influence results. We performed a sensitivity analysis to explore 5 alternative situations for 2016, based on existing ranges of 2 production parameters and 3 market factors. Situation 2016A simulated a farm with a larger barn capacity before quota abolition. We set barn capacity at 120 dairy cows before optimization, based on an increase in barn capacity on Dutch dairy farms toward quota abolition in practice (PBL, 2013). Situation 2016B simulated a highly productive dairy farm; milk yield per cow and grass and maize yield per hectare were increased by 10% compared with situation 2016. National statistics show a range in average milk production on Dutch dairy farms in 2014 from about 6,697 kg $cow^{-1}$ $yr^{-1}$ (25% lowest) to 9,616 kg $cow^{-1}$ $yr^{-1}$ (25% highest) (CRV, 2014). Situation 2016C simulated the effect of lower prices for manure disposal and processing. The price for manure disposal was set at €5 $t^{-1}$, and the additional price for manure processing at €3 $t^{-1}$, based on price ranges according to KWIN-V (2014). Situation 2016D simulated the effect of a lower land price. The price of additional land was set at €573 $ha^{-1}$ $yr^{-1}$, based on long-term rental contracts (KWIN-V, 2014). Situation 2016E simulated the effect of a higher milk price. The price per tonne of milk was set at €420, based on the maximum milk price during the last 10 yr (KWIN-V, 2014).

## 3 Results and discussion

### *3.1 Farm structure, management, and labour income before quota abolition*

Farm structure and management of the farm before quota abolition (situation 2014) are shown in Table 3. Farm size was restricted by milk quota. Based on an average milk production of 8,160 kg $cow^{-1}$ $yr^{-1}$ and a replacement rate of 26.4%, 83 dairy cows and 49 young stock were kept (Table 3). Farmland was divided in 80% grassland and 20% maize land, which allowed an application of 230 kg of N $ha^{-1}$ $yr^{-1}$ from animal manure. In summer, the diet of the dairy cows consisted of 10.0 kg (DM) of fresh grass, 1.1 kg (DM) of grass silage, 3.1 kg (DM) of maize silage, and 5.7 kg (DM) of concentrates $cow^{-1}$ $day^{-1}$. The maximum amount of fresh grass was fed because this was the cheapest feed resource. The amount of grass silage was based on the amount of grass left for ensiling, minus the amount of grass silage fed in winter. Maize silage and concentrates were added to meet the requirements for energy and RDP balance, because these 2 feed restrictions appeared to be binding. In winter, the diet consisted of 7.3 kg (DM) of grass silage, 3.3 kg (DM) of maize silage, and 6.2 kg (DM) of concentrates cow$^{-1}$ day$^{-1}$.



**Table 3.** *Farm structure and management of an average Dutch dairy farm before quota abolition (situation 2014) and after quota abolition and introduction of the Dairy Act (situation 2016).*

| Item | Unit | Situation 2014 | Situation 2016 |
|---|---|---|---|
| **Farm structure** | | | |
| Dairy cows | No. | 83 | 87 |
| Young stock | No. | 49 | 51 |
| Total milk production | t yr$^{-1}$ | 679 | 707 |
| Total farmland | ha | 50 | 50 |
| Grassland | % | 80 | 80 |
| $N_{min}$ application on grassland[1] | kg of N ha$^{-1}$ yr$^{-1}$ | 225 | 225 |
| Maize land | % | 20 | 20 |
| Farm intensity | Kg of milk ha$^{-1}$ | 13,578 | 14,130 |
| **Diet dairy cows: summer** | kg DM cow$^{-1}$ day$^{-1}$ | | |
| Grass | | 10.0 | 10.0 |
| Grass silage | | 1.1 | 0.3 |
| Maize silage | | 3.1 | 2.7 |
| Concentrates | | 5.7 | 6.7 |
| Diet restricted by[2] | | E,R,G | E,R,G |
| **Diet dairy cows: winter** | kg of DM cow$^{-1}$ day$^{-1}$ | | |
| Grass silage | | 7.3 | 7.3 |
| Maize silage | | 3.3 | 3.3 |
| Concentrates | | 6.2 | 6.2 |
| Diet restricted by[2] | | E,R,T | E,R,T |
| **External inputs** | | | |
| Purchased maize silage | t of DM yr$^{-1}$ | 0 | 0 |
| Purchased concentrates | t of DM yr$^{-1}$ | 193 | 218 |
| Hired labour | h | 42 | 127 |
| **Manure management** | | | |
| Manure application restricted by | | - | Phosphate |
| Total excretion | kg of phosphate yr$^{-1}$ | 3,990 | 4,200 |
| Extra phosphate quota | kg of phosphate yr$^{-1}$ | - | 0 |

[1]$N_{min}$ = N mineral.
[2]E = energy requirements, R = rumen degradable protein balance, G = maximum fresh grass intake, T = true protein digested in the small intestine.

Requirements for energy, RDP balance, and true protein digested in the small intestine were met. Purchased feed consisted of 193 t of DM concentrates, and external labour requirement was 42 h $yr^{-1}$. There was no manure surplus, which meant that all the manure was applied on the farmland. The total phosphate excretion of 3,990 kg was lower than the quota of 4,841 kg. This was explained by the fact that the phosphate quota was based on standard excretion factors, whereas phosphate excretion in the model was based on farm-specific excretion. In addition, the phosphate quota was based on 89 dairy cows (CBS, 2015), whereas only 83 cows were needed to fulfil the milk quota. The difference in the number of cows between an average farm in practice and our model farm is explained by the fact that in 2014, many farmers produced above their milk quota in anticipation of the quota abolition.

Labour income on the farm before quota abolition was €10,343 $yr^{-1}$ (Table 4). Revenues could be attributed primarily to milk sales, and costs to feed purchases and fixed costs for buildings and machinery. The net farm income for this type of farm would generally be €20,000 $yr^{-1}$ higher than the labour income because of owner equity.

**Table 4.** *Labour income (€ $yr^{-1}$) for an average Dutch dairy farm before quota abolition (situation 2014) and after quota abolition and introduction of the Dairy Act (situation 2016).*

| Item | Situation 2014 | Situation 2016 |
|---|---|---|
| **Revenues** | | |
| Milk | 241,037 | 250,843 |
| Livestock sales-purchases | 27,430 | 28,546 |
| Governmental payments | 13,500 | 13,500 |
| **Variable costs** | | |
| Concentrate purchases | 47,877 | 54,210 |
| Roughage purchases | 0 | 0 |
| On-farm roughage production | 52,983 | 52,182 |
| Manure disposal and processing | 0 | 0 |
| Hired labour | 714 | 2,145 |
| Other | 36,378 | 37,858 |
| **Fixed costs** | 133,672 | 135,646 |
| **Labour income** | 10,343 | 10,848 |

### *3.2 Farm structure, management, and labour income after quota abolition*

Farm structure and management of the farm after quota abolition and introduction of the Dairy Act (situation 2016) are shown in Table 3. Farm size was no longer restricted by milk quota but by phosphate application room. On the farm, 87 dairy cows and 51 young stock were kept, and total milk production was 707 t of milk $yr^{-1}$. Due to the limitations of the Dairy Act, increasing the number of cows was only possible when manure was processed or extra land was obtained. However, the revenues of an extra cow did not outweigh the extra costs of manure processing and extra land, in combination with the costs of extra barn capacity, hired labour, and feed. Farm intensity increased from 13,578 kg of milk $ha^{-1}$ before quota abolition to 14,130 kg of milk $ha^{-1}$ after quota abolition. The winter diet was the same as before quota abolition, but the summer diet contained less grass and maize silage per cow per day, as well as more concentrates. With an increase in the number of cows per hectare, less grass silage per cow per day was available in summer. This resulted in a lower RDP balance, compensated for by an increase in concentrates per cow per day. The external labour requirement increased to 127 h $yr^{-1}$. With a total phosphate excretion of 4,200 kg $yr^{-1}$, phosphate quota was still not restricting. The labour income of this farm was €10,848 (Table 4), only slightly higher than before quota abolition.

### *3.3 Sensitivity analyses*

Table 5 shows the results of the sensitivity analyses. Situation 2016A represented a farm that increased its barn capacity before quota abolition to 120 dairy cows plus young stock. Results showed that the available barn capacity was fully used (Table 5). Increasing the number of cows beyond the available barn capacity was not economically attractive under current prices. Six additional hectares of farmland were obtained to increase the phosphate application room compared with situation 2016. The percentage of grassland remained 80%, which allowed for derogation. The number of cows per hectare was restricted by both the nitrogen and phosphate application room, resulting in an intensity of 17,440 kg of milk $ha^{-1}$. To meet the feeding requirements of the dairy herd, 94 t (DM) of maize silage and 316 t (DM) of concentrates were purchased. Total phosphate excretion was 5,884 kg $yr^{-1}$. As a result, 1,043 kg of extra phosphate quota was purchased. The possibility of disposing 70% of the phosphate surplus from 2013 was maximally used. In addition, 608 kg of phosphate was processed. Due to higher fixed costs related to increased barn capacity, labour income was only €2,005 $yr^{-1}$.

Situation 2016B represented a highly productive farm. Results showed a farm size of 107 dairy cows, and no additional land was obtained. Based on the Dairy Act, a further increase in the number of cows would require additional land. Similar to situation 2016A, the number of dairy cows per hectare was restricted by the total nitrogen and phosphate application room.

Due to higher productivity, however, farm intensity was 19,191 kg of milk $ha^{-1}$. Labour income was €32,093 $yr^{-1}$. Results showed that farm productivity could considerably increase labour income.

In situation 2016C, the costs of manure processing were decreased to €8 $t^{-1}$ of manure. Results showed a farm size of 100 dairy cows, and no additional land was obtained. The number of dairy cows was restricted by the phosphate quota. Again, the number of cows was higher than the number of cows used to calculate the phosphate quota, due to lower farm-specific excretion values compared with standard values. Labour income was €11,162 $yr^{-1}$.

In situation 2016D, land costs were decreased to €573 $ha^{-1}$. Results showed a farm size of 100 dairy cows. Similar to situation 2016C, the number of dairy cows was restricted by the phosphate quota. In this situation, however, 8 additional hectares of land were obtained to apply all manure on farmland. The number of cows per hectare was restricted by the phosphate application room.

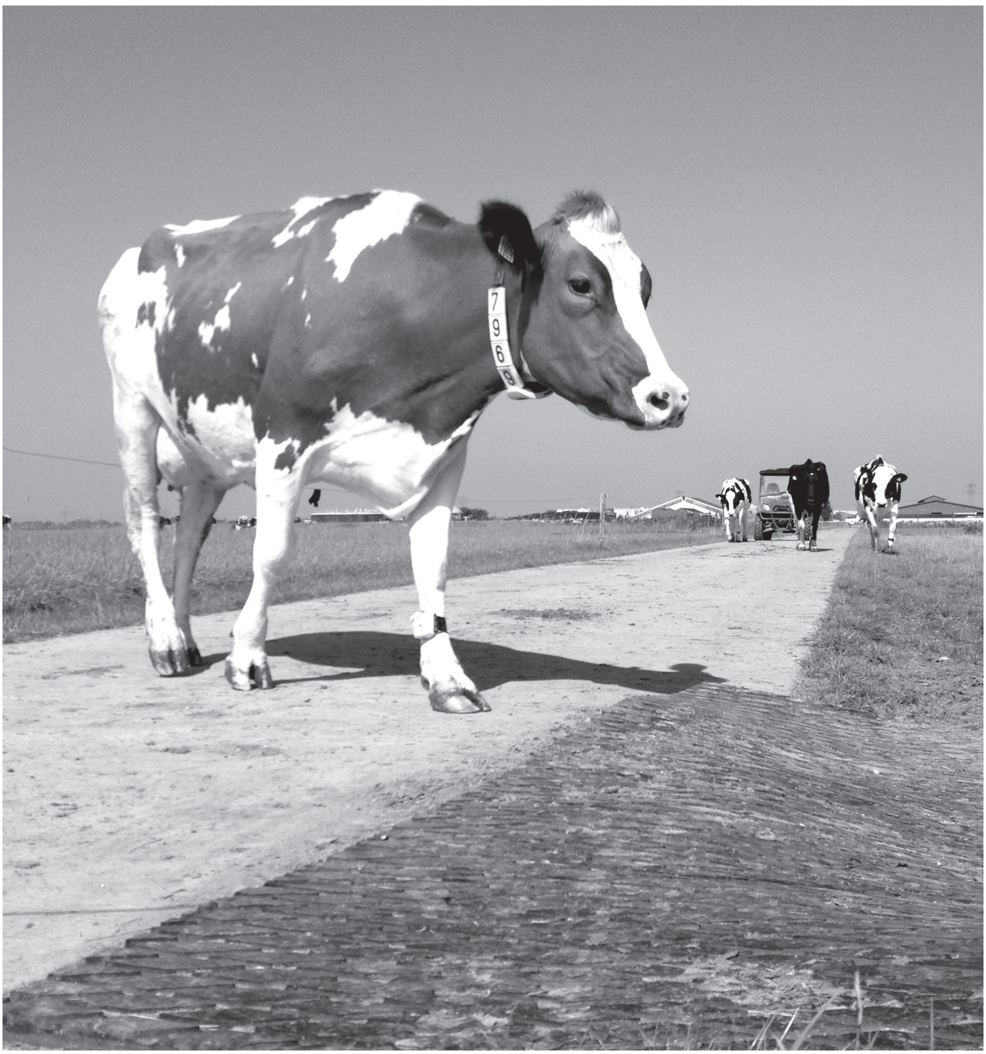


**Table 5.** *Farm structure and management for an average Dutch dairy farm with grazing in sensitivity analyses A to E for situation 2016.*

| Item | Unit | Situation 2016 A: Increased barn capacity | Situation 2016 B: Higher field and cow productivity | Situation 2016 C: Lower manure disposal and processing prices | Situation 2016 D: Lower land price | Situation 2016 E: Higher milk price |
|---|---|---|---|---|---|---|
| **Farm structure** | | | | | | |
| Dairy cows | No. | 120 | 107 | 100 | 100 | 180 |
| Young stock | No. | 71 | 63 | 59 | 59 | 106 |
| Total milk production | t $yr^{-1}$ | 979 | 961 | 817 | 814 | 1,469 |
| Total farmland | Ha | 56 | 50 | 50 | 58 | 84 |
| Grassland | % | 80 | 80 | 80 | 80 | 80 |
| Maize land | % | 20 | 20 | 20 | 20 | 20 |
| Farm intensity | kg of milk $ha^{-1}$ | 17,440 | 19,191 | 16,331 | 14,130 | 17,440 |
| **External inputs** | | | | | | |
| Purchased maize silage | t of DM $yr^{-1}$ | 94 | 80 | 48 | 0 | 141 |
| Purchased concentrates | t of DM $yr^{-1}$ | 316 | 290 | 263 | 251 | 474 |
| Hired labour | h $yr^{-1}$ | 1,064 | 694 | 480 | 556 | 2,937 |
| Nitrogen application on grassland | kg of N $ha^{-1}$ $yr^{-1}$ | 250 | 250 | 250 | 225 | 250 |
| **Manure management** | | | | | | |
| Manure application restricted by[1] | | tN, P | tN, P | tN | P | tN, P |
| Total phosphate excretion | kg of phosphate $yr^{-1}$ | 5,884 | 5,376 | 4,841 | 4,841 | 8,826 |
| Applied on own land | kg of phosphate $yr^{-1}$ | 4,717 | 4,208 | 3,857 | 4,841 | 7,075 |
| Manure disposal | kg of phosphate $yr^{-1}$ | 560 | 560 | 560 | 0 | 560 |
| Manure processing | kg of phosphate $yr^{-1}$ | 608 | 608 | 424 | 0 | 1,191 |
| **Purchased phosphate quota** | kg of phosphate $yr^{-1}$ | 1,043 | 534 | 0 | 0 | 3,985 |
| **Labour income** | € $yr^{-1}$ | 2,005 | 32,093 | 11,162 | 14,240 | 80,489 |

[1]tN = total mineral nitrogen, P = phosphate.

2

In situation 2016E, the milk price was increased to €420 $t^{-1}$. Results showed a farm size of 180 dairy cows and 84 ha of land. The number of cows was restricted by machinery capacity, which could be solved quite easily in practice. Reaching this artificial maximum implied that the farm could experience unlimited growth when external inputs such as labour, land, barn capacity, and feed were available without limits at current prices. The number of cows per hectare was restricted by the nitrogen and phosphate application room, resulting in a farm intensity of 17,440 kg of milk $ha^{-1}$. The external labour requirement was 2,937 h $yr^{-1}$. Total phosphate excretion was 8,826 kg $yr^{-1}$, which means that 3,985 kg of phosphate was purchased. Labour income was €80,489 $yr^{-1}$.

### *3.4 Environmental impact*

Figure 2 shows the nitrogen and phosphate surpluses per hectare of the farm before (situation 2014) and after (situation 2016–2016E) quota abolition. The nitrogen surpluses per hectare after quota abolition (192 to 213 kg $ha^{-1}$) were higher than before quota abolition (186 kg $ha^{-1}$). The level of nitrogen surplus was highly related to farm intensity, except for situation 2016B.

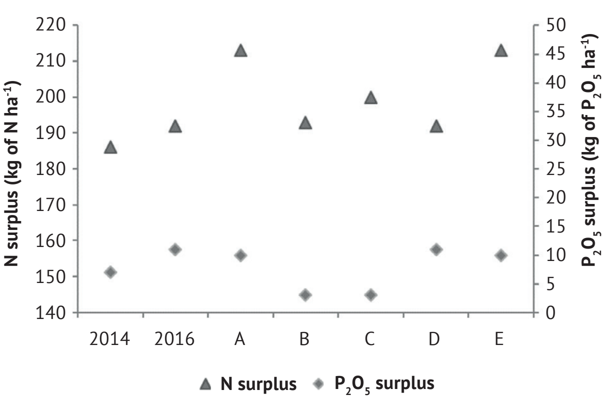



**Figure 2.** *Nitrogen (N) and phosphate ($P_2O_5$) farm surpluses per hectare for an average Dutch dairy farm before quota abolition (2014) and after quota abolition (2016). Results A to E are variants of 2016 scenario, A = increased barn capacity, B = higher field and cow productivity, C = low manure disposal and processing prices, D = low land price, and E = higher milk price.*

Situation 2016B had the highest intensity but a relatively low nitrogen surplus, related to higher farm productivity, meaning more efficient use of inputs. The phosphate surpluses after quota abolition varied from 3 to 11 kg $ha^{-1}$, whereas the phosphate surplus before quota abolition was 7 kg $ha^{-1}$. The lower phosphate surpluses after quota abolition in situation 2016B were explained by higher farm productivity and, in situation 2016C, by the relatively large amount of phosphate disposal and processing.

Figure 3 shows the results for GHG emissions per tonne of FPCM for the farm before (situation 2014) and after (situation 2016–2016E) quota abolition. The GHG emissions per tonne of FPCM after quota abolition (range from 938 to 1,001 kg of $CO_2$eq $t^{-1}$ of FPCM) were in the same range as before quota abolition (985 kg of $CO_2$eq $t^{-1}$ of FPCM). Per tonne of FPCM produced, the increase in off-farm emissions from concentrate production was offset by the decrease in on-farm emissions related to enteric fermentation and roughage production. Situation 2016B resulted in the lowest GHG emissions. This can be explained by an increase in farm productivity, resulting in, for example, dilution of GHG emissions related to maintenance.

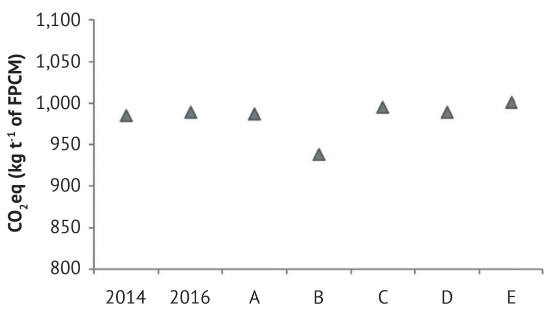



**Figure 3.** *Greenhouse gas emissions [kg of $CO_2$ equivalents ($CO_2$-eq) per tonne of fat- and protein-corrected milk (FPCM)] for an average Dutch dairy farm before quota abolition (2014) and after quota abolition (2016). Results A to E are variants of scenario: A = increased barn capacity, B = higher field and cow productivity, C = low manure disposal and processing prices, D = low land price, and E = higher milk price.*

Taking into account the increase in total milk production, total GHG emissions (i.e., from cradle to farm gate) at the farm level increased from 707,385 kg of $CO_2$eq $yr^{-1}$ before quota abolition to 738,706 kg of $CO_2$eq $yr^{-1}$ after quota abolition. This increase of 4.4% implied an almost linear increase of GHG emission with the number of cows.

### *3.5 General discussion*

Milk production in the Netherlands has increased in recent years because farmers have anticipated the end of the milk quota system, but it is unlikely that the volume of milk production in the Netherlands will undergo further substantial increases under the new manure policy. Due to additional costs related to manure processing, additional farmland, and the phosphate quota, the costs of production will probably increase rather than decrease. In addition, the possibility of obtaining additional land varies across the Netherlands, limiting the expansion of dairy farms in areas where farmland is scarce. Most importantly, the phosphate quota will restrict the growth of the national dairy herd. It is unlikely that the Netherlands will become more competitive or supply more milk to the world milk market.

Our review of developments in manure legislation shows continuous changes and uncertainties in the transitions from old to new regulations. This creates risks for dairy farmers in anticipating developments in the dairy sector. In addition to policy risks, dairy farmers face market risks. The alternative situation, with a high milk price, showed a large effect of milk price on income. In addition, the volatility of the milk price in the EU is increasing due to decreasing governmental intervention (Holmer, 2015).

Increasing phosphate efficiency at the farm level offers the potential to increase milk production within the limits of the phosphate quota. Balancing phosphorus levels in the diet with the phosphorus requirements of the cow, for example, offers the potential to decrease phosphate excretion. Based on the current analysis, cows were found to be fed 37% above phosphorus requirements in winter and 42% in summer, indicating potential for improvement.

So far, the costs for extra phosphate quota are unclear. Based on current prices for quota in the pig sector, we assumed yearly costs of €2.10 $kg^{-1}$ of phosphate. This followed from a total investment of €413 dairy $cow^{-1}$, a depreciation period of 5 yr, and an interest rate of 4.5% (KWIN-V, 2014). Further analysis of the results showed that for the situations with the increased barn capacity and with the high milk price, phosphate quota would be purchased until yearly costs reach a level of about €11 $kg^{-1}$ of phosphate, which equaled an investment in phosphate quota of around €2,000 dairy $cow^{-1}$.

In agreement with Daatselaar *et al.*, (2015), nitrogen surplus per hectare increased with an increase in farm intensity. Nutrient surpluses in this study were at the lower range of nutrient surpluses found on an average Dutch dairy farm in practice (LEI, 2015). Differences can be explained by the use of an optimization model, which may increase farm efficiency, and by the fact that most recent data on nutrient surpluses of actual farms (LEI, 2015) are from 2011. Our results showed higher GHG emissions per tonne of FPCM than Van Middelaar *et al.*, (2014), which can be explained by the update of emission factors for concentrate production (FeedPrint, 2015) and an update of the global warming potentials of $CH_4$ and $N_2O$ (IPCC, 2013).

## 4 Conclusions

Several factors have limited the growth of Dutch dairy farms after quota abolition. Based on current prices, increasing the number of cows is profitable up to the level that requires manure processing or additional land to comply with the new manure policy. This results in an increase in the number of cows and in farm intensity of about 4% compared to before quota abolition. When costs of manure processing or of land decrease, phosphate quota becomes a limiting factor. Within the phosphate quota, however, farm intensity can increase about 20% by increasing the efficiency of phosphate use. If milk prices increased to the high level of 2013-2014, farms could grow unlimited, provided that the availability of external inputs such as labour, land, barn capacity, feed, and phosphate quota at current prices were also unlimited. Results showed that the milk quota abolition, accompanied by the Dairy Act, will slightly increase nutrient losses per hectare, due to an increase in farm intensity. Greenhouse gas emissions per unit of milk will barely change, so at a given milk production per cow, total GHG emissions will increase linearly with an increase in the number of cows.



### *Acknowledgments*

We thank the Province of Fryslân (the Netherlands) and Melkveefonds (LTO Nederland and Wageningen UR Livestock Research; the Netherlands) for financially supporting this research.

### *Appendix*

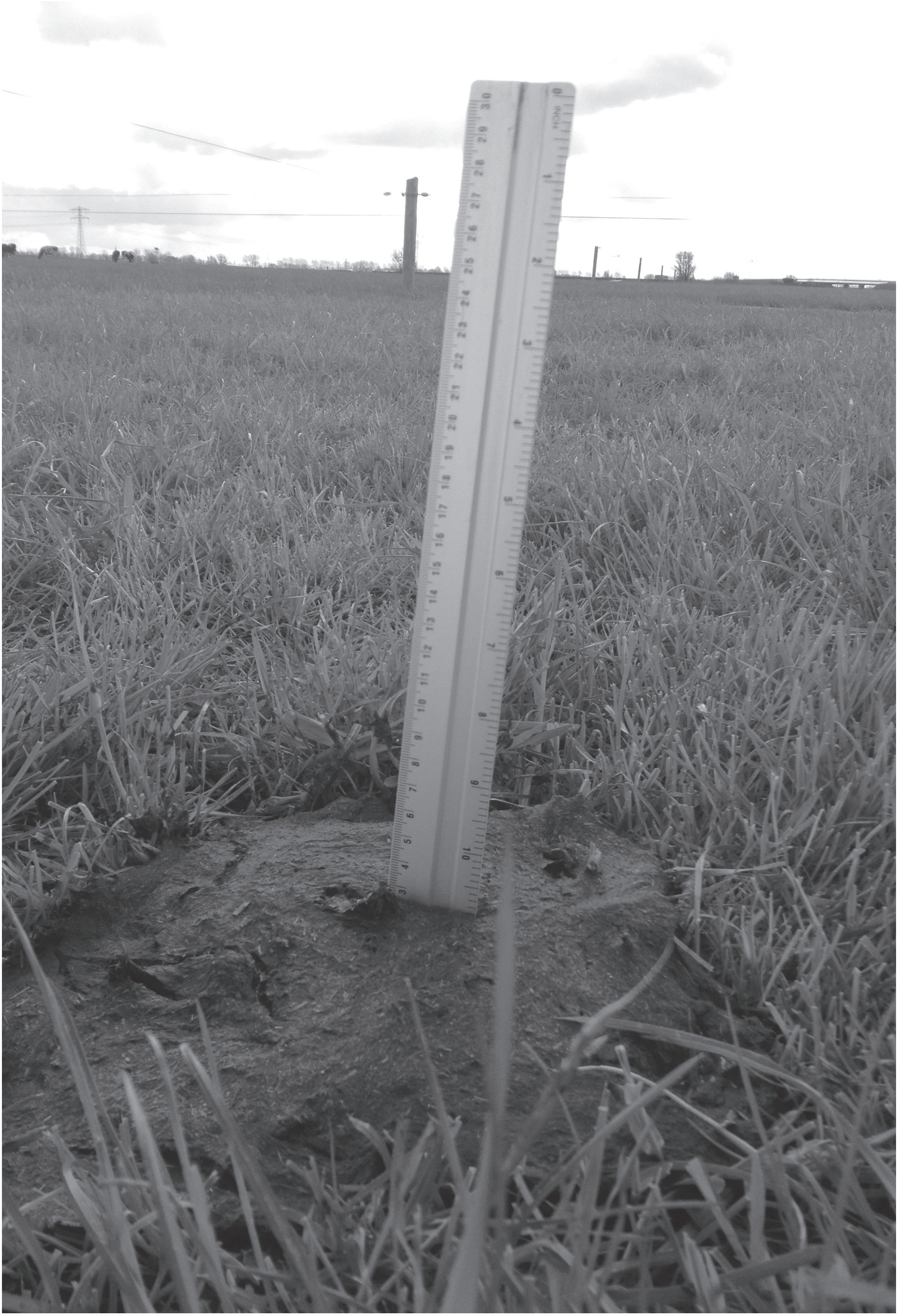
**Table A1.** *Dutch phosphate excretion values for 2015 to 2017 (RVO, 2014).*

| Item | Milk yield (kg of milk $yr^{-1}$) | Phosphate excretion (kg of phosphate $animal^{-1}$ $yr^{-1}$) |
|---|---|---|
| **Dairy cow** | 8,125 - 8,374 | 41.3 |
| | 8,375 - 8,624 | 42.0 |
| | 8,625 - 8,874 | 42.7 |
| **Young stock <1** | | 9.6 |
| **Young stock >1** | | 21.9 |

**Table A2.** *Composition of concentrates with 3 protein levels (standard, medium and high) and corresponding greenhouse gas (GHG) emissions for production of ingredients.*

| | Concentrate composition (%) | | | GHG[1] emissions |
|---|---|---|---|---|
| **Protein level** | **Standard[2]** | **Medium[2]** | **High[3]** | **(total $CO_2$ equivalent in kg $t^{-1}$)** |
| Peas | 0.00 | 1.20 | 0.00 | 752 |
| Barley | 0.35 | 0.15 | 0.95 | 388 |
| Soybean meal CF45-70 CP <450[4] | 0.07 | 1.49 | 0.00 | 615 |
| Soybean meal CF45-70 CP >450[4] | 0.09 | 0.48 | 0.00 | 636 |
| Soybean meal Mervobest | 0.00 | 0.15 | 28.45 | 632 |
| Soybean hulls CF 320-360[4] | 14.52 | 19.47 | 0.00 | 391 |
| Sugarcane molasses SUG <475[4] | 3.01 | 3.17 | 2.10 | 302 |
| Rape seed, expeller | 0.17 | 0.99 | 0.03 | 528 |
| Rye | 5.15 | 1.10 | 1.84 | 449 |
| Wheat | 2.05 | 2.17 | 0.15 | 390 |
| Palm kernel expeller CF <180[4] | 11.80 | 15.95 | 19.33 | 547 |
| Sugarbeet pulp SUG >200[4] | 3.80 | 4.70 | 6.33 | 366 |
| Maize | 15.87 | 6.57 | 1.48 | 595 |
| Wheat middlings | 11.32 | 2.07 | 2.62 | 249 |
| Soy oil (palm kernel oil) | 0.01 | 0.00 | 0.00 | 3,902 |
| Maize glutenfeed CP 200-230[4] | 8.60 | 1.65 | 17.32 | 1,815 |
| Sunflower seed meal CF >240[4] | 0.67 | 1.00 | 0.22 | 487 |
| Salt | 0.46 | 0.56 | 0.00 | 180 |
| Chalk (finely milled) | 0.99 | 1.28 | 0.00 | 19 |
| Triticale | 5.45 | 6.03 | 1.32 | 587 |
| Palm kernel oil | 0.20 | 0.40 | 0.00 | 3,902 |
| Rape seed, extruded CP >380[4] | 0.18 | 0.47 | 0.00 | 481 |
| Rape seed, extruded CP 0-380[4] | 1.78 | 5.38 | 0.00 | 477 |
| Rape seed meal | 0.00 | 0.15 | 0.00 | 484 |
| Premix | 1.00 | 1.00 | 1.00 | 4,999 |
| Vinasses Sugarbeet CP <250[4] | 2.99 | 3.00 | 0.00 | 394 |
| Magnesium oxide | 0.04 | 0.01 | 0.00 | 1,060 |
| Distillers grains and solubles | 9.36 | 17.93 | 7.47 | 296 |
| Citruspulp dehydrated | 0.00 | 0.00 | 7.64 | 747 |
| Fat animal origin | 0.00 | 0.00 | 0.04 | 7,726 |
| Ureum | 0.00 | 0.00 | 1.70 | 1,650 |

[1]Greenhouse gas emissions for production of ingredients were updated based on FeedPrint (2015).
[2]Concentrate composition of standard and medium protein level were updated based on Nevedi (2012, 2013, 2014, 2015).
[3]Concentrate composition of high protein level was based on Van Middelaar *et al.*, (2014).
[4]CF = crude fibre, SUG = sugar (in g $kg^{-1}$).




# Chapter 3

## *The effect of grazing system on the rising plate meter calibration for herbage mass*

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## ABSTRACT

The rising plate meter (RPM) is used to measure grass height, which subsequently is used in a calibration equation to estimate herbage mass (HM), being an important parameter to optimize feed management in grazing systems. The RPM is placed on the sward and measures the resistance of the sward towards the plate, which depends not only on grass length, but also on sward structure. The accuracy of this calibration equation for the RPM to estimate HM across grazing systems, however, has not been evaluated yet. Therefore, our aim was to analyse the effect of grazing system on the rising plate meter calibration for herbage mass. To do so, we studied two grazing systems, i.e. compartmented continuous grazing (CCG) and strip grazing (SG), that differ in key grazing characteristics, such as pre- and post-grazing heights and period of regrowth, that may influence tiller density and vertical flexibility of the sward. The experiment was performed from April until October in 2016 and 2017 with 60 dairy cows at a fixed stocking rate of 7.5 cows $ha^{-1}$. To calibrate the RPM, 256 direct measurements on HM > 4 cm were collected by cutting and weighing plots of grass for CCG and SG. Differences in HM < 4 cm may explain differences in HM > 4 cm between both grazing systems. Therefore, HM < 4 cm was additionally measured on four out of each eight plots per grazing system by cutting out quadrats until 0 cm with an electric grass trimmer. Our results indicate that we can use one region-specific calibration equation across grazing systems, despite relatively large differences in pre- and post-grazing heights and period of regrowth. In contrast, we found that grazing system clearly affected the HM < 4 cm, with 2042 kg DM $ha^{-1}$ for CCG and 1676 kg DM $ha^{-1}$ for SG.

**Key words:** intensive grazing, herbage mass, forage management, rising plate meter

## 1 Introduction

Several studies have shown that the economic benefit of grazing increases with an increase in grass intake (Evers *et al.*, 2008; Van den Pol-van Dasselaar *et al.*, 2014b). An increase in grass intake results in a decrease in feed supplementation, leading to lower feeding costs (Sanderson *et al.*, 2001). Fresh grass intake is to a large extent determined by herbage mass (HM). Insight into HM, therefore, is of utmost importance for a dairy farmer to optimize feed management. Sanderson *et al.* (2001), for example, concluded that measuring HM within 10% error margin can improve forage budgeting by allocating an adequate amount of grass to the herd. They found this breakeven point by varying the percentage of under- or overestimation of forage yield in the dairy forage system model DAFOSYM. Accurately quantifying HM can increase grazing efficiency and, thereby, the economic benefit of grazing (Holshof *et al.*, 2015; McSweeney *et al.*, 2015). Allocating an adequate amount of grass to the herd may increase grazing efficiency and reduce variations in dry matter intake and hence fluctuations in milk production (Hennessy *et al.*, 2015). To date, however, a considerable amount of farmers still carries out visual assessments and bases grazing management on intuitive decisions (McSweeney *et al.*, 2015).

Cutting and weighing grass is a direct and accurate, but time-intensive and destructive, measurement of HM and, therefore, not used in practice. Currently several tools are available to estimate HM in a non-destructive way. A common, non-destructive and easy to use tool is the rising plate meter (RPM), which measures grass height to estimate HM (Sanderson *et al.*, 2001). The RPM is placed on the sward and measures the resistance of the sward towards the plate, which depends not only on grass length, but also on sward structure (‘t Mannetje, 2000; Fehmi and Stevens, 2009). Grass height is translated into HM in kg DM ha$^{-1}$ by using a calibration equation. Rising plate meter readings can be incorporated into a grassland management programme, and provide farmers with information necessary to the management of forage allowance in grazing systems.

For most RPMs, a standard calibration equation is provided by the manufacturer. When estimating HM with the RPM, however, it is important to use context-specific calibration equations, as standard calibration equations may under- or overestimate HM in practice. Sanderson *et al.* (2001), for example, found an error rate of 26% by comparing estimated HM calculated with a universal RPM equation developed in New Zealand with observed HM in pastures in Pennsylvania, Maryland, and West Virginia (USA). Key factors that affect the relation between RPM and HM are tiller density and vertical flexibility of the sward, which differ across climate, season, grass variety and soil type (Fehmi and Stevens, 2009; Ferraro *et al.*, 2012; Nakagami and Itano, 2013).

As the grazing systems also affects tiller density and vertical flexibility of the grass, we hypothesise that the grazing system might also influence the relation between RPM and HM (Fehmi and Stevens, 2009; Nakagami and Itano, 2013). To the authors knowledge, however, these effects of grazing system have not been studied so far. Therefore, our aim was to analyse the effect of grazing system on the rising plate meter calibration for herbage mass.

To do so, we studied two grazing systems, i.e. compartmented continuous grazing (CCG) and strip grazing (SG), that differ in key grazing characteristics, such as pre- and post-grazing heights and period of regrowth, that may influence tiller density and vertical flexibility of the sward. Both CCG and SG are examples of daily rotational grazing systems suitable for intensive Dutch dairy farms with feed supplementation (Holshof *et al.*, 2018). Especially in intensive grazing systems, accurate HM estimates are critical for feed budgeting as the balance between fresh grass allowance and feed supplementation needs to be correct.

## 2 Materials and methods

### *2.1 Experimental set-up*

The grazing experiment in which we conducted the measurements for this paper was performed at the Dairy Campus research facility in Leeuwarden during the grazing seasons of 2016 and 2017. Sixty dairy cows were allocated to two grazing systems, i.e. CCG and SG, in two replications (Figure 2). Blocks of cows were formed on the basis of equality in parity (first, second and higher parity number), days in milk, milk constituent yield, fat- and protein-corrected milk yield of the animals to assure a balanced distribution of the cows. The cows within the blocks were randomly allocated to one of the four experimental treatments, resulting in a randomized complete block design. All cows calved in the period December – March, prior to the grazing season. In total we used 8 ha of grassland, implying a fixed stocking rate of 7.5 cows per ha of grazing area (classified as intensive grazing). Standard grazing time was from 8:30 until 16:00 h. Cows had access to the pasture between morning and afternoon milking and were housed indoors in a cubicle barn during the rest of the time, where they were supplemented with roughage and concentrates. The botanical composition of the fields was 72% perennial ryegrass (*Lolium perenne* L.), 12% timothy-grass (*Phleum pratense* L.), 11% rough meadow-grass (*Poa trivialis* L.) and 5% other species.

Both CCG and SG are rotational grazing systems in which the cows receive a new grazing area daily. These systems, however, largely differ in pre- and post-grazing heights and period of regrowth, i.e. important factors that characterize grazing systems. The CCG system has been introduced in the Netherlands recently to balance between grassland utilization and labour intensity (Holshof *et al.*, 2018). The available grazing area in a CCG system is divided in blocks for continuous grazing, where each block is subdivided in fixed compartments with a different compartment being grazed each day (Figure 1). Each CCG replicate was two ha and was divided into six 0.33 ha compartments. On a grazing day, therefore, each cow had access to 222 $m^2$ fresh grass allowance. Each SG replicate was two ha and was divided into 31 0.07 ha strips. On a grazing day, each cow had access to 43 $m^2$ fresh grass allowance and the strip of the previous day to provide more space to walk (in total 86 $m^2$).



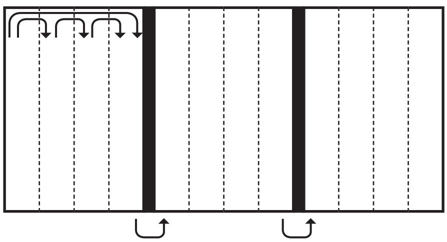

**Figure 1.** *The compartmented continuous grazing system.*

For CCG, five compartments were grazed and the sixth one was cut for silage to remove rejected patches (RP). After regrowth (on average 10 days) the sixth compartment was added to the rotation to provide fresh grass for grazing and the next compartment was selected to produce grass for silage. So during the whole season five of the six compartments were grazed in a five days rotation. Period of regrowth, i.e. days before cows returned to the same compartment, therefore, was four days for CCG. For SG, blocks of four strips were cut for silage and to remove RP after two grazing events. After regrowth, the cut strips were again added to the rotation. Period of regrowth was on average 20 days for SG.

The fresh grass allowance in CCG and SG depended on the grass growth (influenced by weather circumstances), during the period of regrowth. The pre-grazing grass height was on average 75 mm for CCG and 99 mm for SG. The intended post-grazing grass height was 60 mm for CCG and 40 mm for SG throughout the grazing season. Based on the fresh grass allowance the amount of roughage supplementation was adjusted to provide sufficient feed. Fresh grass allowance was measured by performing weekly grass height measurements in all compartments and strips. These measurements were done by walking in a W-shape through the compartments and strips and performing about 60 measurements per compartment or cluster of strips. The clusters of strips were formed based on similar growth stage. Total dry matter intake was set at 21 kg DM $cow^{-1}$ $day^{-1}$ and the concentrate gift was fixed at 5.4 kg DM $cow^{-1}$ $day^{-1}$. Roughage supplementation was at least 5.0 kg DM $cow^{-1}$ $day^{-1}$, existing of maximally 8.0 kg maize silage supplemented with grass silage according to requirements. In addition to the adaptation in supplementary feeding, daily grazing time was reduced with two hours when total grass height was below 60 mm for CCG and when fresh grass allowance was below 4.0 kg DM $cow^{-1}$ $day^{-1}$ for SG.

### *2.2 Calibration measurements*

To calibrate the RPM, we conducted direct measurements on HM by cutting and weighing plots of grass for CCG and SG. Similar to Kennedy *et al.* (2007), plots with an average size of 12 $m^2$ were sampled. For each plot, grass height was measured just before and after cutting, and HM was (directly) determined by weighing. In total there were eight measuring days in 2016 (i.e. 12-5, 19-5, 9-6, 7-7, 14-7, 9-8, 8-9, 15-9) and eight measuring days in 2017 (i.e. 9-5, 17-5, 8-6, 13-6, 11-7, 14-7, 8-8, 11-8). On each measuring day 16 plots were cut in the fields A or B (Figure 2), with eight plots per grazing system. For each grazing system, four plots with relatively high and four plots with relatively low grass heights were cut to maximize the range in grass height (which yields more accurate estimates in the regression calculations that will follow). The cutting height was set at 4 cm to simulate the stubble remaining after grazing (Kennedy *et al.*, 2007). Herbage mass > 4 cm, therefore, was assumed to represent the HM for grazing.

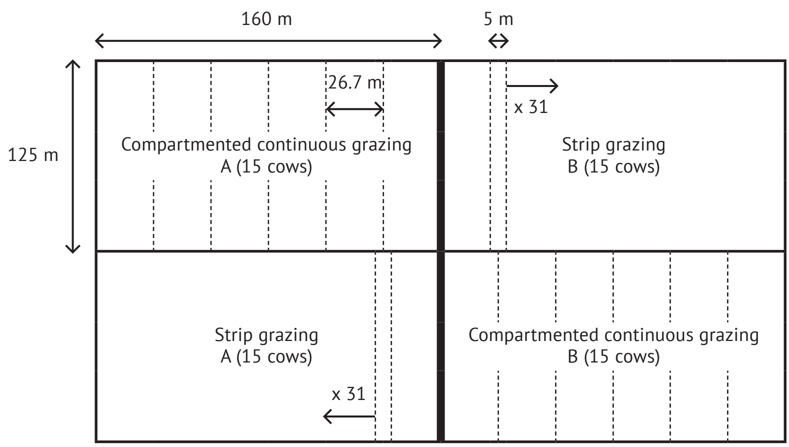


**Figure 2.** *Overview of the grazing experiment with two grazing systems, i.e. compartmented continuous grazing (CCG) and strip grazing (SG) in two replications (A and B).*

Within each of the 16 plots, we conducted 10 grass height measurements before and 10 grass height measurements after cutting. Using these data, we calculated the average grass height above stubble per plot by subtracting the average grass height after cutting from the average grass height before cutting. This average grass height > 4 cm was related to the HM > 4 cm per plot and subsequently expressed per hectare. We did this because we were especially interested in the question if a region-specific calibration equation is accurate across grazing systems above the stubble, since the stubble is not grazed. The Jenquip EC10 (NZ Agriworks Ltd., NZ, diameter 36 cm, average pressure 0.47 g cm$^{-2}$) was used for the grass height measurements before and after cutting in both 2016 and 2017. The same RPM was also used for developing the Dutch standard equation (Holshof and Stienezen, 2016). The EC10 measures the grass height in clicks, with each click representing 0.5 cm (DairyNZ, 2008).

HM > 4 cm was quantified by cutting plots with the Haldrup grass harvester 1500, manufactured in Denmark ('t Mannetje, 2000). The plots had a fixed width of 1.5 m, but a variable length of about 8 m. The precise length of the plots was measured with a measuring tape. The Haldrup automatically collects and weighs the harvested grass per plot. After weighing, a grass sample was taken with a sample drilling cylinder. Grass samples were analysed for dry matter content by drying in an oven at 105 °C for at least 24h (Gabriëls and Berg, 1993).



Since especially differences in tiller density are expected to be pronounced in the HM < 4 cm, differences in HM < 4 cm may (partially) explain differences in HM > 4 cm between both grazing systems. Additional measurements were conducted, therefore, at four out of each eight plots per grazing system to quantify HM < 4 cm. Herbage mass < 4 cm was quantified by clipping 0.09 m$^2$ quadrats to bare ground (0 cm) with electric grass trimmer (HSA 25, Andreas Stihl ag & Co. KG, DE) and scissors. The quadrats were marked with a steel frame of 30 by 30 cm. All HM in the quadrat was carefully collected, weighed, and analysed for dry matter content by drying.

### *2.3 Statistical analyses*

We used linear regression to estimate HM based on grass height measurements with the RPM (i.e. build calibration equations). The sampled and cut plots served as the experimental units in this analysis. The average grass height per plot was the explanatory variable (x-variable), denoted by H, and expressed in cm. The response variable (y-variable) was HM, denoted by y, and expressed in kg DM ha$^{-1}$. Our first interest was the effect of grazing system on the relation between HM and average grass height, so the model comprises effects for grazing system, making the intercept and slope (of height H) depending on the grazing system. In addition, seasonal effects were added, since existing literature shows effects of month and year on the relation between HM and grass height (Ferraro *et al.*, 2012; Nakagami and Itano, 2013). To that end, the eight measurement days per year were classified into months May, June, July, August and September for 2016 and May, June, July and August for 2017. Effects of cow blocks as part of the randomized complete block design were not included in the model, since there is no room for potential block effects in a prediction equation.

Interactions between explanatory variable H and experimental factors for grazing system, month, and year were limited to two-factor interactions. This regression model will be referred to as the full model. Ideally, the full model would include year as a random effect, employing a mixed model analysis. This was not feasible, however, because the component of variance associated with the years cannot be estimated with acceptable accuracy based on two years data only. Year effects therefore were included as fixed effects. This full model was used as a benchmark to compare with a reduced and more practical model that did not include year effects, to see how much unexplained variation in the reduced model is due to years.

The full model reads as follows (Eq. 1):

$$y_{ijkl} = \mu + S_i + M_j + Yr_k + MYr_{jk} + \beta H_{ijkl} + \beta_{S,i} H_{ijkl} + \beta_{M,j} H_{ijkl} + \beta_{Yr,k} H_{ijkl} + \varepsilon_{ijkl} \quad [1]$$

Here, $y_{ijkl}$ is the HM > 4 cm of the $l$-th sampled plot of grazing system $i$, in month $j$, of year $k$, and $H_{ijkl}$ is the corresponding average grass height. $S_i$, $M_j$, $Yr_k$ are main effects of grazing systems, months, and years, and $MYr_{jk}$ are interactions between months and years that affect the intercept. Terms like $\beta_{M,j} H_{ijkl}$ represent interaction between e.g. month and height and affect the slope of height $H$. The random error terms $\varepsilon_{ijkl}$ were assumed to be independently normally distributed around 0 with constant variance $\sigma^2$. The so-called cornerstone representation, a common feature of statistical software, was used, implying that e.g. $\mu$ is the mean HM for system SG, in September in year 2, and effects in the intercept, like $S_i$, are relative to this reference combination. Similarly, $\beta$ is the slope of height for SG in September of 2017 and effects in the slope, like $\beta_{S,i}$ are relative to this reference combination.

We looked into the effects of grazing system upon HM < 4, because such effects may (partially) explain differences in HM > 4. Since height is more or less constant, attention was restricted to a comparison of means by the t-test.

To further disentangle the effects of grazing system and season on the relation between grass height and HM > 4 cm, we analysed the effect of year by comparing the full model (Eq. 1) with a reduced model without year effects (Eq. 2). A similar interpretation of effects as in Eq. 1 holds for the reduced model, where year effects have been omitted.

$$y_{ijl} = \mu + S_i + M_j + \beta H_{ijl} + \beta_{S,i} H_{ijl} + \beta_{M,j} H_{ijl} + \varepsilon_{ijl} \quad [2]$$

We compared the prediction accuracy of our fitted regression equations with the already existing Dutch standard equation translated to HM > 4 cm (Eq. 3). Holshof and Stienezen (2016) developed this calibration equation for Dutch pasture conditions, based on cutting trials in the Netherlands during the growing season of 2014 and 2015. They found the following calibration equation for total HM (kg DM ha$^{-1}$): 845 + 210 × grass height (cm). Since the intercept (845) and the grass height until 4 cm represent the HM in the stubble, we translated the equation into HM > 4 cm as:

HM > 4 cm = 210 × grass height (cm) > 4 cm [3]

The prediction accuracy of the different regression models was expressed in terms of the root mean square error of prediction (RMSEP) (Eq. 4):

$$RMSEP = \sqrt{\tfrac{1}{n}\sum_{ijkl}(\hat{y}_{ijkl} - y_{ijkl})^2} \quad [4]$$



Here, $y_{ijkl}$ is the observed HM and $\hat{y}_{ijkl}$ the corresponding prediction (fitted value), and $n$ is the total number of plots. Roughly, the prediction error is in between plus and minus twice the RMSEP. The RMSEP was determined by leave-one-out cross validation and was calculated from the squared deletion residuals (Montgomery and Peck, 1992).

The statistical program IBM SPSS Statistics for Windows, Version 22.0, was used to perform the regression calculations.

## 3 Results

In Figure 3, HM > 4 cm is plotted against grass height > 4 cm and expressed per hectare, with one measurement representing one cut plot. Grass height > 4 cm varied from 0.4 to 14 cm, with an average of 3.1 cm for CCG and 5.0 for SG. Herbage mass > 4 cm varied from 62 to 3439 kg DM ha$^{-1}$, with an average of 671 kg DM ha$^{-1}$ for CCG and 1113 kg DM ha$^{-1}$ for SG. The actual height of the grass after cutting was on average 3.9 cm. Using the full model, we see that the average increase in HM per cm of grass was smaller ($P < 0.001$; Table 1) for CCG than for SG (163 vs 223 kg DM ha$^{-1}$ cm$^{-1}$, respectively). Using the reduced model, however, we no longer found evidence for differences in slope across grazing systems. In addition, excluding grazing system from the reduced model did not markedly affect the RMSEP. Differences between grazing systems in HM > 4 cm were similar at grass heights < 10 cm (Figure 3).

The HM < 4 cm varied from 744 kg DM ha$^{-1}$ to 3456 kg DM ha$^{-1}$, with an average of 2042 ± 70 kg DM ha$^{-1}$ for CCG and 1676 ± 77 kg DM ha$^{-1}$ for SG. The t-test showed that the grazing system clearly affected the mean HM < 4 cm ($P < 0.001$).

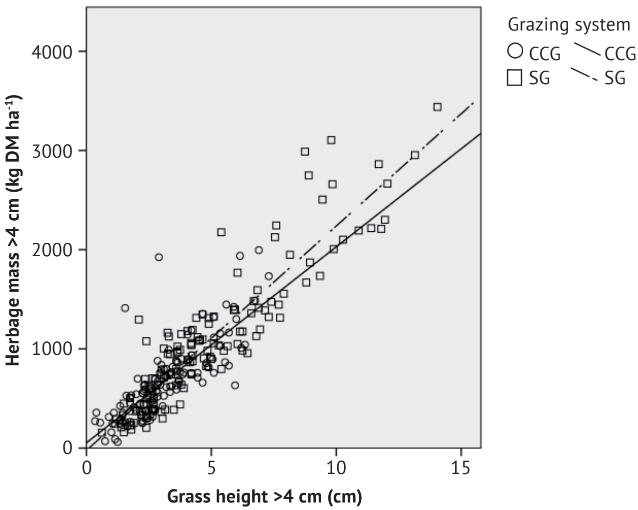


**Figure 3.** *Herbage mass > 4 cm plotted against grass height > 4 cm by grazing system.*

To better understand the effects of grazing system and season on the relation between grass height and HM > 4 cm, we analysed the effect of year by comparing the full model (Eq. 1) with a reduced model without year effects (Eq. 2). Table 1 shows results of the full model with a RMSEP of 231 kg DM ha$^{-1}$. By comparing the years 2016 and 2017, we found that the average intercept was greater ($P < 0.001$) for 2016 than for 2017 (185 vs 19 kg DM ha$^{-1}$, respectively), whereas the average increase in HM per cm was not shown to be affected by year ($P = 0.273$). Differences between months were not the same in the two years ($P < 0.001$).

The RMSEP of the reduced model excluding year effects increased from 231 to 274 kg DM ha$^{-1}$ (Table 1). This leads to an increased prediction error of ± 86 kg DM ha$^{-1}$, which is 10% of the average observed HM > 4 cm (i.e. 892 kg DM ha$^{-1}$). When plotting the deletion residuals from the reduced model against the deletion residuals from the full model we found that the increase in prediction accuracy of the full model is mainly attributable to June estimates (Figure 4a+b).

**Table 1.** *P-values and the root of the mean square error of prediction (RMSEP) for the full regression model with year effects, the reduced regression model without year effects and the reduced regression model without year effects and excluding the June measurements.*

| P-values | Full model | Reduced model | Reduced model without June |
|---|---|---|---|
| **Grazing system** | 0.005 | 0.141 | 0.055 |
| **Year** | < 0.001 | | |
| **Month** | < 0.001 | 0.351 | 0.586 |
| **Year × Month** | < 0.001 | | |
| **Grass height > 4 cm** | < 0.001 | < 0.001 | < 0.001 |
| **Grazing system × Grass height > 4 cm** | < 0.001 | 0.059 | 0.036 |
| **Year × Grass height > 4 cm** | 0.273 | | |
| **Month × Grass height > 4 cm** | 0.018 | 0.877 | 0.707 |
| **RMSEP** | 231 | 274 | 226 |



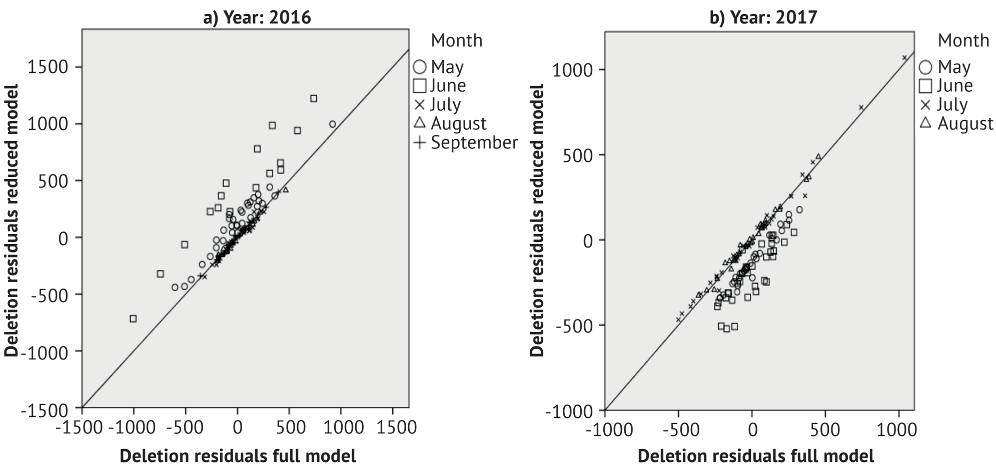


**Figure 4.** *Deletion residuals of the reduced model with year effects plotted against the full model by month for 2016 (a) and 2017 (b).*

Since June was so influential in the model for HM > 4 cm and was known to give inaccurate results with the RPM due to the reproductive stage of grass in this month (Michell and Large, 1983), the reduced model without year effects was analysed again after excluding all June measurements. This model, therefore, cannot be used to translate grass height measurements during the reproductive stage into HM. Table 1 shows the results of this analysis. The RMSEP decreased from 274 to 226 kg DM $ha^{-1}$ compared to the reduced model including June measurements. Although the average increase in HM per cm of grass showed an interaction with grazing system (P = 0.036), excluding grazing system from the model did not affect the RMSEP to any great extent.

To improve the accuracy of estimating HM in restricted rotational grazing systems in the Netherlands, we compared the RMSEP of the full and the reduced model with the standard Dutch calibration equation (Eq. 3). The RMSEP of the full model, i.e. 231 kg DM $ha^{-1}$, was lower compared to the standard Dutch calibration equation, i.e. 271 kg DM $ha^{-1}$. The reduction in RMSEP, however, was mainly observed around June, which was during the reproductive stage. The RMSEP of the reduced model, i.e. 274 kg DM $ha^{-1}$, was comparable to the RMSEP of the Dutch calibration equation, suggesting that accounting for month and grazing system is not increasing prediction accuracy to a particularly important extent. When we excluded June measurements, however, we found an RMSEP of 226 kg DM $ha^{-1}$ with the reduced model, which is lower compared to the RMSEP of the Dutch calibration equation, i.e. 271 kg DM $ha^{-1}$.

## 4 Discussion

Using the full model, we found that the average increase in HM per cm of grass was smaller for CCG than for SG. The lower slope for CCG might potentially be explained by a higher leaf proportion and a lower dead material proportion in the HM > 4 cm compared to SG, which can be explained by differences in pre- and post-grazing height and period of regrowth. Curran *et al.* (2010) found a higher leaf proportion (< and > 4 cm) and a lower dead proportion (> 4 cm) for a low pre-grazing HM (HM > 0 cm: 1600 kg DM $ha^{-1}$) compared to a high pre-grazing HM (HM > 0 cm: 2400 kg DM $ha^{-1}$), resulting in a lower HM density in kg DM $ha^{-1}$ $cm^{-1}$ for the low pre-grazing HM. Differences between grazing systems, however, were relatively small and including grazing system as a factor in the regression model to explain the increase in HM per cm of grass did not reduce the RMSEP of the model to any important extent.

In contrast, the HM < 4 cm was clearly affected by grazing system. The larger HM < 4 cm for CCG might be explained by a higher tiller density for CCG compared to SG. From November 2016 onwards, tiller density indeed was higher for CCG than for SG ($P < 0.05$) (N. J. Hoekstra, Louis Bolk Institute, Bunnik, The Netherlands, personal communication). This finding is in line with literature, showing an increased tiller density at increasing grazing pressure per grazing event to compensate for a loss in leaf area index (Matthew *et al.*, 1996; Hernández Garay *et al.*, 1999). This difference in HM < 4 cm between grazing systems, however, was not expressed in HM > 4 cm.

By comparing the full model (Eq. 1) with the reduced model (Eq. 2), we found a year effect on the absolute level of HM, but not on the average increase in HM per cm. This suggests that the seasonal pattern may be largely similar for different years, although coefficients are likely to differ to some extent across years. These findings are in line with literature describing year effects (Braga *et al.*, 2009; Ferraro *et al.*, 2012; Nakagami, 2016). Differences between years could easily be explained by differences in weather conditions since they influence the proportion of leaf, stem and dead material in the sward and, thereby, the density in kg DM per cm of grass height (Curran *et al.*, 2010). In principle e.g. covariates for past weather conditions could be included when working on a monthly basis.

When further analysing month effects with the full model (Eq. 1), we found a clear seasonal pattern with a marked decrease in average HM per cm of grass height for June compared to May, July, August and September. This seasonal pattern is in line with findings in literature in cool-season grass swards (Michell and Large, 1983; Ferraro *et al.*, 2012; Nakagami and Itano, 2013). The decrease in slope in June can be explained by the onset of the reproductive stage of perennial ryegrass in the Northern hemisphere (Michell and Large, 1983; Nakagami and Itano, 2013). Reproductive tillers contribute to increasing grass height but without an equivalent increase in HM, since the density of these tillers is low. Compared to vegetative tillers, reproductive tillers contain a larger proportion of stem and dead material and a smaller proportion of leaf material, which is generally more heavy and contains a higher DM% (Curran *et al.*, 2010). We indeed observed an increase in tall rejected grass in the flowering stage in June, especially in the CCG system in 2016. In line with these findings, we found a positive correlation between DM% and intercept ($r = 0.642$; $P = 0.004$) and a negative correlation between DM% and slope ($r = -0.556$; $P = 0.017$). Dry matter content was highest in June 2016, both for CCG (23%) and SG (19.2%).

Our comparison of calibration equations showed that the (modified) Dutch standard equation (Eq. 3) is suitable to estimate HM > 4 cm in CCG and SG, considering both accuracy and feasibility. Including grazing system in the model did not result in a higher prediction accuracy compared to the Dutch calibration equation. Since these systems largely differ in pre- and post-grazing heights, our results indicate that a region-specific calibration equation is accurate across grazing systems. Overall, the calibration equations analysed in this study, however, showed an average error margin of 25 – 31%, expressing the RMSEP as a percentage of the observed HM > 4 cm. This exceeds the 10% that Sanderson *et al.* (2001), proposed as a maximum error margin for estimating fresh grass availability to increase economic benefits of improved forage budgeting. To obtain more a higher prediction accuracy with the Dutch calibration equation, we suggest to include random year effects in the model with data based on a long-term study and to exclude measurements in tall rejected grass during the reproductive stage.

## 5 Conclusions

We found that grazing system clearly affected the HM < 4 cm, with 2042 kg DM $ha^{-1}$ for compartmented continuous grazing (CCG) and 1676 kg DM $ha^{-1}$ for strip grazing (SG). The HM < 4 cm, however, is not used for grazing and this difference was not reflected in the HM > 4 cm. Our results indicate that we can use one region-specific calibration equation across grazing systems, despite relatively large differences in pre- and post-grazing heights and period of regrowth. The average error margin of our calibration equations, however, appeared 25 – 31%, expressed as the RMSEP as a percentage of the observed HM > 4 cm. To obtain more reliable conclusions with the Dutch calibration equation, we suggest to include random year effects in the model with data based on a long-term study and to exclude measurements in tall rejected grass during the reproductive stage.

***Acknowledgments***

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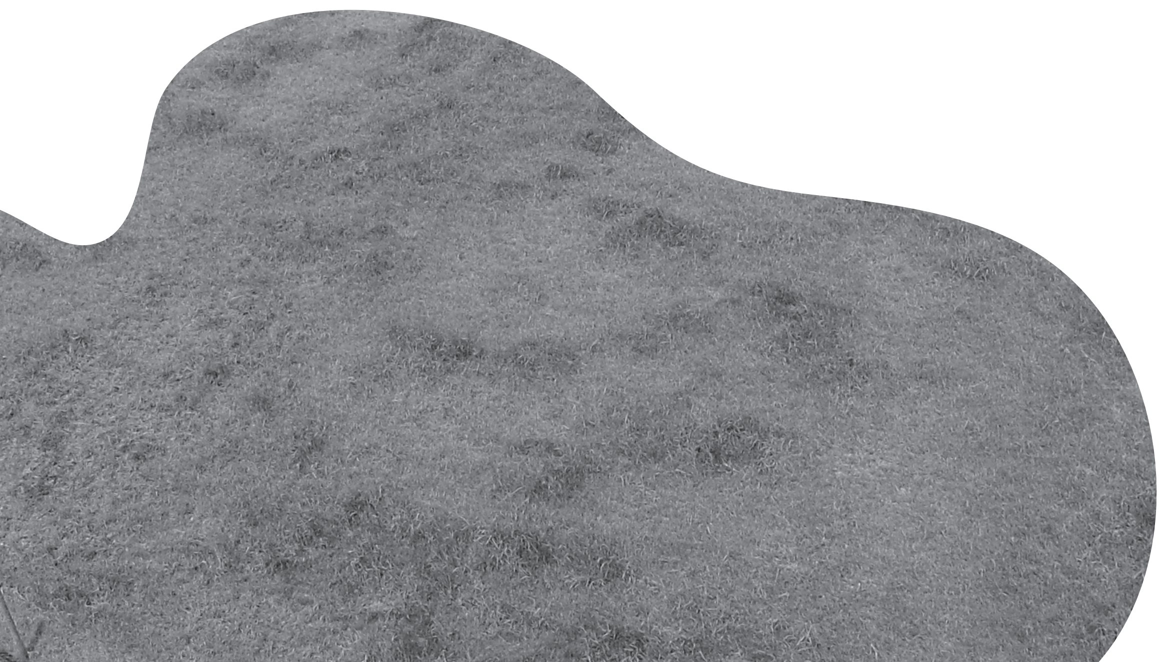
FOLDING PLATE PASTURE METER

# Chapter 4

## *Correcting fresh grass allowance for selective grazing of dairy cows in intensive grazing systems*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## ABSTRACT

Dairy farms with intensive grazing systems combine grazing with supplementary feeding, which can be challenging since an incorrect balance between fresh grass allowance and feed supplementation results in inefficient use of the pasture, a lower feed-efficiency and potential decreases in animal production. When estimating fresh grass allowance, we currently do not correct for the formation of rejected patches (RP) surrounding dung, which can lead to overestimation of the potential fresh grass intake and hampers optimal grazing. In this study, therefore, we aim to quantify the formation of RP in intensive grazing systems and improve the quantification of fresh grass allowance. To do so, we studied two grazing systems, i.e. compartmented continuous grazing and strip grazing, that differ in key grazing characteristics, such as pre- and post-grazing heights and period of regrowth. The experiment was performed from April until October in 2016 and 2017 with 60 dairy cows at a fixed stocking rate of 7.5 cows $ha^{-1}$. Average pre-grazing grass height was measured with a rising plate meter and translated into fresh grass allowance using a Dutch calibration equation. To quantify the formation of RP after grazing, individual grass height measurements were conducted after grazing and classified as RP or not, based on visual assessment. Our analysis showed that the average percentage of grassland covered with RP increased from around 22% at the end of May to around 43% at the end of July/beginning of August, and these percentages do not differ across grazing systems. The percentage of grassland covered with RP should be subtracted from the total grazed area to better estimate fresh grass allowance.


**Key words:** intensive grazing, fresh grass allowance, rejected patches, rising plate meter

## 1 Introduction

In the Netherlands, grazing is a key component of the public opinion about the dairy sector. The Dutch society highly appreciates an open landscape with grazing cows (Van den Pol-van Dasselaar *et al*., 2008; Boogaard *et al*., 2010) and associates grazing with sustainable milk production and animal welfare (Blokland *et al*., 2017). In addition to societal benefits, grazing can also have economic benefits. Various Dutch milk processors pay a higher milk price to farmers who graze their cows on pasture (Doornewaard *et al*., 2017). Furthermore, several studies have shown that the economic benefit of grazing increases with an increase in fresh grass intake per cow, due to lower costs for supplementary feed and contract labour (Finneran *et al*., 2012; Meul *et al*., 2012; Van den Pol-van Dasselaar *et al*., 2014b).

A reliable prediction of the fresh grass allowance can increase farm profit by optimizing the grazing regime. In an optimal grazing regime, fresh grass allowance matches the requirements of the herd, which may increase grazing efficiency and reduce variations in dry matter intake and hence fluctuations in milk production (Hennessy *et al*., 2015). Fresh grass allowance is determined by stocking rate and available herbage mass (HM) on the grazing platform (Stockdale and King, 1983). The stocking rate on the grazing platform can be calculated by dividing the number of cows by the available hectares of grassland available and accessible for grazing. Herbage mass can be indirectly measured with the rising plate meter (RPM) (Sanderson *et al*., 2001), which is used in practice to measure grass height before grazing and is subsequently translated to HM by using a prediction equation. In practice, however, the offered fresh grass is not homogenously grazed down due to selective grazing, resulting in grazing losses.

Dung is the major cause of selective grazing as cows refuse to graze grass contaminated by dung due to the smell, which results in the formation of rejected patches (RP) (Dohi *et al*., 1991; Bosker *et al*., 2002; Verwer *et al*., 2016). Marten and Donker (1964) found that 93% of the non-grazed areas contained dung from previous grazing events. In addition, 81% of the dung patches, deposited three to four weeks before grazing, was rejected by dairy cows during grazing. When estimating fresh grass allowance, we currently do not correct for the formation of RP. This overestimates the fresh grass allowance and, thereby, the potential fresh grass intake of dairy cows, which can undermine optimal grazing.

The formation of RP is shown to be influenced by stocking rate (Arnold and Holmes, 1958), because it influences the possibility for selective grazing. The stocking rate on the grazing platform has increased in the Netherlands. This has resulted in reduced (daily) fresh grass allowance per cow and the need to increase feed supplementation. In this study, therefore, we aim to quantify the formation of RP in intensive grazing systems and improve the quantification of fresh grass allowance. To do so, we studied two grazing systems, i.e. compartmented continuous grazing (CCG) and strip grazing (SG), that differ in key grazing characteristics, such as pre- and post-grazing heights and period of regrowth. In addition, these two systems are examples of daily rotational grazing systems suitable for intensive Dutch dairy farms with feed supplementation (Holshof *et al.*, 2018).

## 2 Materials and methods

### *2.1 Grazing systems*

The grazing experiment in which we conducted our measurements was performed at the Dairy Campus research facility in Leeuwarden in 2016 and 2017. Sixty dairy cows were allocated to two different grazing systems, i.e. CCG and SG, in two replicates (Figure 1). Blocks of cows were formed on the basis of equality in parity (first, second and higher parity number), days in milk, milk constituent yield, fat- and protein-corrected milk yield of the animals to assure a balanced distribution of the cows. The cows within the blocks were randomly allocated to one of the four experimental treatments, resulting in a randomized complete block design. All cows calved in the period December – March, prior to the grazing season. In total we used 8 ha of grassland, implying a fixed stocking rate of 7.5 cows per ha of grazing area (classified as intensive grazing). Standard grazing time was from 8:30 until 16:00 h. Cows had access to the pasture between morning and afternoon milking and were housed indoors in a cubicle barn during the rest of the time, where they were supplemented with roughage and concentrates. The botanical composition of the fields was 72% perennial ryegrass (*Lolium perenne* L.), 12% timothy-grass (*Phleum pratense* L.), 11% rough meadow-grass (*Poa trivialis* L.) and 5% other species on all four blocks.

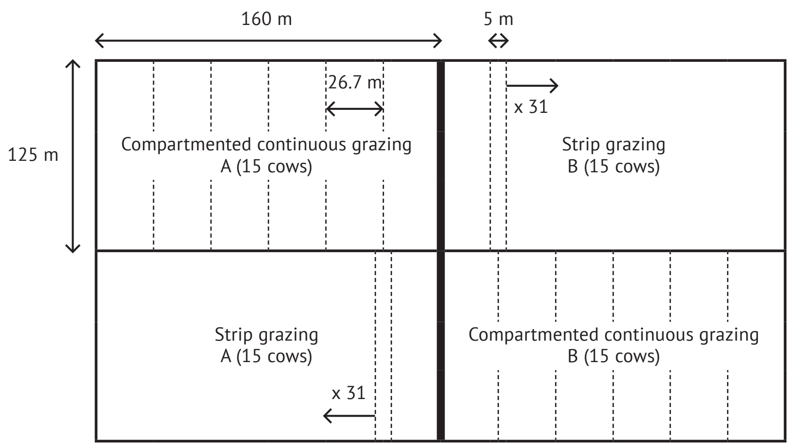



**Figure 1.** *Overview of the grazing experiment with two contrasting grazing systems, i.e. compartmented continuous grazing (CCG) and strip grazing (SG) in two replicates (A and B).*

Both CCG and SG are rotational grazing systems in which the cows receive a new grazing area daily. These systems, however, largely differ in key grazing characteristics, such as pre- and post-grazing heights and period of regrowth. Each CCG replicate was two ha and was divided into six 0.33 ha compartments. On a grazing day, therefore, each cow had access to 222 $m^2$ of fresh grass. Each SG replicate was also two ha and was divided into 31 strips of 0.07 ha each. On a grazing day, each cow had access to 43 $m^2$ of fresh grass and the strip of the previous day to provide more space to walk (in total 86 $m^2$).

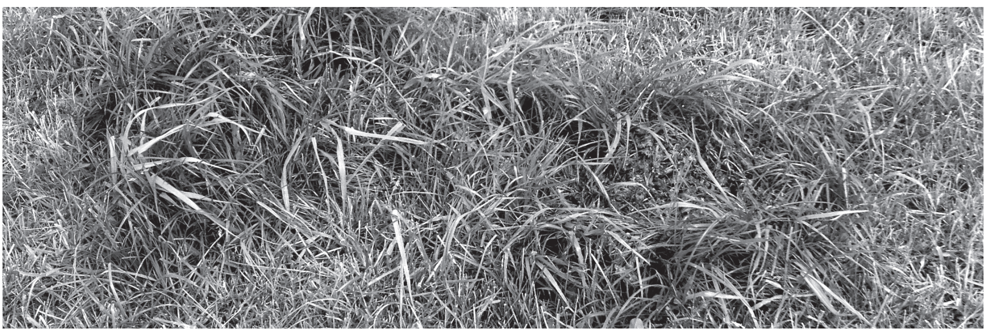
For CCG, five compartments were grazed and (random) the sixth one was cut for silage to remove RP. After regrowth (on average ten days) the sixth compartment was added to the rotation to provide fresh grass for grazing and a next compartment was selected to produce grass for silage. So during the whole season five of the six compartments were grazed in a five days rotation. Period of regrowth, i.e. days before cows returned to the same compartment, therefore, was four days for CCG. For SG, blocks of four strips were cut for silage and to remove RP after two grazing events. After regrowth, the cut strips were again added to the rotation. Period of regrowth was on average 20 days for SG.



The fresh grass allowance in CCG and SG depended on the grass growth (influenced by weather circumstances), during the period of regrowth. The measured pre-grazing grass height was on average 75 mm for CCG and 99 mm for SG. The intended post-grazing grass height was 60 mm for CCG and 40 mm for SG throughout the grazing season. Based on the fresh grass allowance the amount of roughage supplementation was adjusted to provide sufficient feed. Fresh grass allowance was measured by performing weekly grass height measurements in all compartments and strips. These measurements were done by walking in a W-shape through the compartments and strips and performing about 60 measurements per compartment or cluster of strips. The clusters of strips were formed based on similar growth stage. Total dry matter intake was set at 21 kg DM $cow^{-1}$ $day^{-1}$ and the concentrate gift was fixed at 5.4 kg DM $cow^{-1}$ $day^{-1}$. Roughage supplementation was at least 5.0 kg DM $cow^{-1}$ $day^{-1}$, existing of maximally 8.0 kg DM maize silage supplemented with grass silage according to requirements. In addition to the adaptation in supplementary feeding, daily grazing time was reduced with two hours when total grass height was below 60 mm for CCG and when fresh grass allowance was below 4.0 kg DM $cow^{-1}$ $day^{-1}$ for SG.

### *2.2 Quantifying fresh grass allowance with RP correction*

Since the formation of RP occurs during grazing, we analyzed the percentage of grassland covered with RP after grazing to correct fresh grass allowance before grazing. We recorded grass heights in recently grazed fields and indicated for each individual measurement whether or not it corresponded to an RP (yes/no) based on visual assessment. An RP was identified as an ungrazed spot due to dung patches (Bao *et al.* (1998). The percentage of grassland measurements related to a RP was determined by the mean proportion of RP and non-RP according to the visual assessment. In total we analysed nine fields for CCG and eight fields for SG. Proportions RP per field were analysed with a logistic regression model. This model comprised main effects and interactions for the two systems and for three time periods (1 = May, 2 = July and 3 = August) on the logit scale. A multiplicative overdispersion parameter was included in the binomial variance function. Parameters on the logit scale were estimated by maximum quasi-likelihood (MCcullagh and Nelder, 1989). The overdispersion parameter was estimated by Pearson's chi-square statistic divided by its degrees of freedom. A test for interaction and tests for main effects (within the additive model without interaction) were based on the quasi-likelihood ratio test. P-values were derived from an approximation with an F-distribution (with denominator degrees of freedom associated with Pearson's chi-square from the largest model). Pairwise comparisons between time points, within the additive model, were based on quasi-Wald tests, with P-values derived from an approximation with the t-distribution. Calculations were performed with generalized linear model facilities of Genstat (VSN International, 2017).



### *2.3 Grass height measurements*

To assure a reliable representation of the RP formation per field we used the following protocol. The fields served as experimental units and were either a compartment of CCG or two adjacent strips of SG. For CCG, one compartment measured 26.7 by 125 meters (3333 $m^2$). In this compartment, we marked the long side at about every 15 meters with a stick and walked through the compartment in a W-pattern, taking 30 measurements in each of the four W-shapes covering 30 meters (Figure 2A), resulting in 120 measurements. Measurements were triplicated to have a total of 360 measurements per compartment. For SG, two adjacent strips measured a total size of 10 by 125 meters. In these strips, we marked the long side in between the two strips at about every 15 meters with a stick and walked through the middle of each strip straight from the beginning until the end, taking about 15 measurements per 30 meter (Figure 2B). Measurements were triplicated to have a total of 360 measurements per two strips.

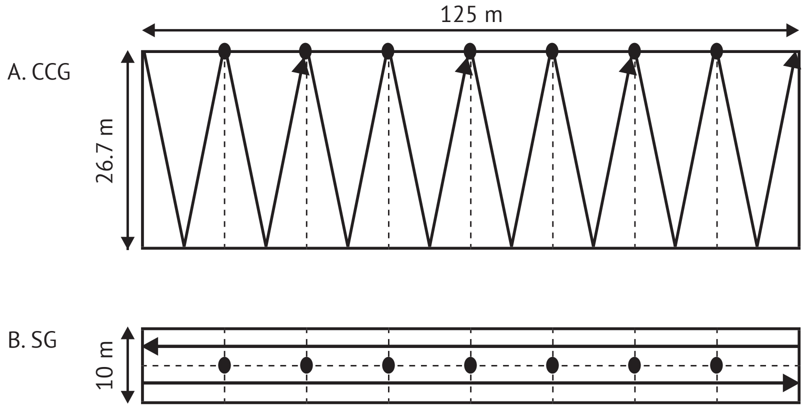



**Figure 2.** *Sampling technique for representative grass height measurements in two grazing systems, A) CCG = compartmented continuous grazing and B) SG = strip grazing, with the black dots indicating the sticks as reference points.*

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In total we conducted 6,120 grass height measurements in 17 recently grazed fields, from the end of May until the beginning of August in 2017. We calculated the average grass height for RP and non-RP for in total nine fields for CCG and eight fields for SG and performed a Wilcoxon's signed rank test to compare the grass height of RP and non-RP for CCG and SG separately. All grass height measurements were conducted by the same operator using the Jenquip EC20 (NZ Agriworks Ltd., NZ), which is developed in New Zealand. This RPM enables to record each individual grass height measurement in mm and is connected with an Android Pasture Meter App via a Bluetooth connection.

### *2.4 Quantifying the required number of grass height measurements per field*

The current advice in practice is to take 30 measurements per field before grazing to estimate fresh grass allowance. To determine whether 30 measurements is sufficiently accurate to estimate HM in intensive grazing systems, we analysed the effect of number of grass height measurements on the accuracy of estimating the average grass height in the field. Eq. 1 was used to quantify the effect of within-field variance on the number of measurements needed per field to estimate the average grass height with a predefined, accepted accuracy (i.e. error). Since the accepted error in mm depends on the average grass height and the aim of measuring, we varied the accepted error from 1 until 20 mm.

$$n = \frac{1.96^2 \times \sigma^2}{E^2} \qquad [1]$$

Here, $\sigma^2$ is the within-field variance between measurements and E is the error margin in grass height.

To determine the number of measurements needed to estimate grass height before grazing (eq. 1), we need an estimate of the within-field variance in grass height for both CCG and SG. Since the average grass height to quantify HM is measured before grazing in practice, we needed a representative within-field variance for before grazing. For both systems, therefore, we conducted additional measurements in three fields that were not grazed since the last mowing activity, with 360 measurements per field. For CCG, the within-field variation in grass height before and after grazing is not so different, since the period of regrowth is only four days. In addition, the within-field variation in grass height increases with the number of grazing events. Therefore, we also included the within-field variation of the fields after grazing providing an average within-field variance after 0 to 18 grazing events for CCG. Since we argue that the fresh grass allowance should be corrected for RP, we excluded RP from this analysis.

## 3 Results and discussion

### *3.1 Fresh grass allowance with RP correction*

Figure 3 shows the variation in grass height per recently grazed field for non-RP and RP, for each grazing system separately. For non-RP, average grass height per field was 64 mm (58-70 mm) for CCG and also 64 (49-80 mm) for SG. For RP, average grass height per field after grazing was higher than for non RP ($P < 0.001$), i.e. 142 mm (97190 mm) for CCG and 106 mm (86128) for SG. The large contrast in grass height between non-RP and RP supports that we could distinguish them based on visual assessment. The contrast we found in grass height of non-RP and RP is comparable with results of Bao *et al.* (1998), who showed an average post-grazing grass height of 60 mm for non-RP and 100 mm for RP in a 20-day rotational system with a stocking rate of 4.9 cows $ha^{-1}$. Schwinning and Parsons (1999) argued that instead of having two alternative stable states, a grazing system in which there is preference for short patches (non-RP) is likely to result in a bimodal frequency distribution with short (non-RP) and tall (RP) patches. In line with this, Bao *et al.* (1998) mention that the extent to which tall patches are defoliated seems likely to be influenced by the grazing pressure. Cows first tend to graze on non-RP, but then turn to RP gradually in proportion to the availability when the sward is further grazed down (Bao *et al.*, 1998). The shift towards RP is likely dependent on the proportion of available leaf to stem material, since cows prefer leaf over stem material. The RP in CCG likely contain more stem material since they are refused for multiple grazing events without mowing in between.

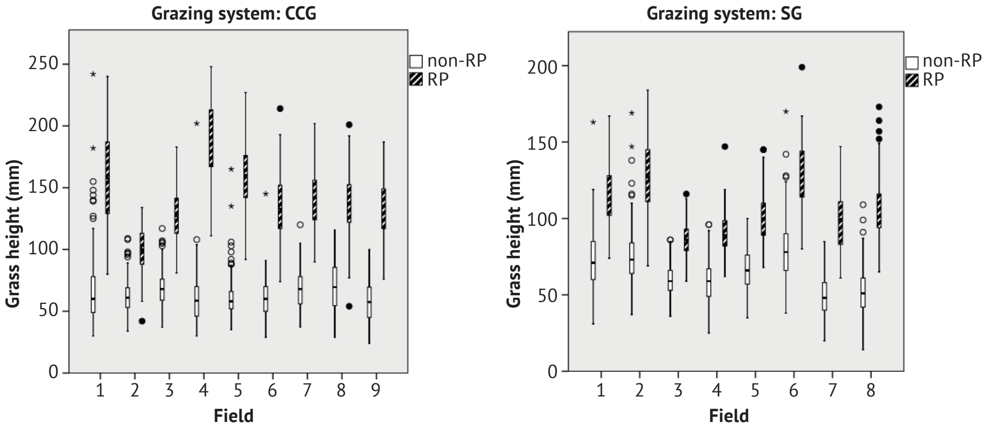


**Figure 3.** *Range in grass height (mm) per recently grazed field distinguishing between non-rejected patches (non-RP) and rejected patches (RP) split up for 2 grazing systems, i.e. CCG = compartmented continuous grazing and SG = strip grazing.*

4

Our analysis showed that the average percentage of grassland covered with RP increased from around 22% at the end of May to around 43% at the end of July/beginning of August (Figure 4). The logistic regression model showed that the development of proportion of RP in time did not differ across grazing systems (P = 0.33). Time showed an effect on the proportion of RP (P < 0.001), while grazing system did not (P = 0.33). Pairwise comparisons between time points revealed that the proportion of RP was lower in May compared to both July and August (P < 0.001), but that the difference between July and August was not significant (P = 0.37). These results indicate that after a period of increase in grassland covered with RP a maximum seems to be reached in July. MacLusky (1960) also described an equilibrium state after an increase in RP formation, which can be explained by a balance between formation of RP and reduction of RP due to breakdown of dung. Our results do not suggest that the percentage of grassland covered with RP is influenced by grazing system under intensive grazing. The time it takes before the equilibrium state is reached as well as the percentage of grassland covered with RP, however, will likely depend on grazing intensity, weather conditions and whether the sward is trimmed or mowed (Tonn *et al.*, 2018).

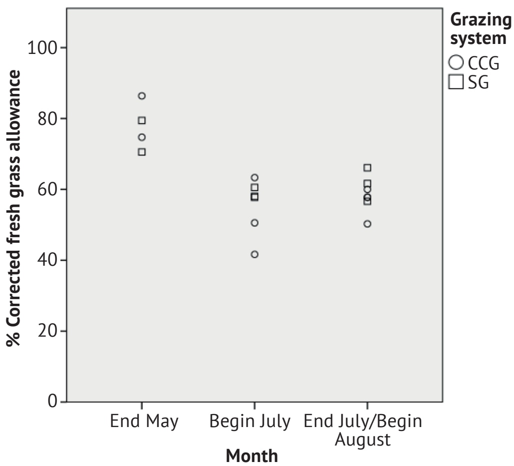


**Figure 4.** *The percentage of fresh grass allowance remaining after correction for rejected patches (RP) at the end of May, beginning of July and end of July/beginning of August for continuous compartmented grazing (CCG) and strip grazing (SG).*

Sanderson *et al.* (2001), concluded that measuring within 10% error margin can improve forage budgeting by allocating an adequate amount of grass to the herd. An average error margin of 38% in predicting fresh grass allowance is substantial and can result in an imbalance with the rest of the ration and subsequently a reduction in milk production. If the fresh grass allowance is insufficient in the CCG system the grass height will decrease below the intended 60 mm. This means that there will be less grass left for the next grazing and this will increase the need for supplementary feeding. The SG system is even less flexible because the fresh grass intake cannot be compensated below 40 mm, which requires a fast increase in supplementary feeding. Therefore, it is necessary to correct fresh grass allowance for RP formation under intensive grazing. The fresh grass allowance can be corrected by subtracting the surface covered with RP from the total grazed area. If the RP can already be visually distinguished before grazing, they should be excluded from the grass height measurements to get a reliable estimate of the remaining grazing area without RP. This is more relevant for grazing systems with a short grazing interval since the contrast in grass height between non-RP and RP reduces with an increase in period of regrowth.

### *3.2 The required number of grass height measurements per field*

Table 1 shows the effect of number of grass height measurements on the accuracy of average grass height estimates per field for CCG and SG. The number of necessary grass height measurements reduces with a decrease in within-field variance and with an increase in accepted error. The within-field variance in grass height before grazing was 544 $mm^2$ for CCG and 618 $mm^2$ for SG. The current advice in practice is to take 30 measurements per field before grazing to estimate fresh grass allowance. The corresponding errors in estimations of the average grass height per field are 8-9 mm for both CCG and SG. The error in estimating the average grass height should in general be as small as possible since the calculation from average grass height to HM already comes with an error margin of 25-31% under CCG and SG (Klootwijk *et al.*, 2019b). Since most of the grass height meters measure grass height in clicks, which corresponds with 5 mm, this might be accepted as a maximal error. To achieve a maximal error of 5 mm, our results indicate that we need to take minimally 84 measurements per field in CCG, when excluding visible RP, and 95 measurements per field in SG.

**Table 1.** *Number of grass height measurements needed in fields for compartmented continuous grazing (CCG), including and excluding rejected patches, and strip grazing (SG).*

| Accepted error (mm grass) | CCG | SG |
|---|---|---|
| 1 | 2089 | 2375 |
| 2 | 522 | 594 |
| 3 | 232 | 264 |
| 4 | 131 | 148 |
| 5 | 84 | 95 |
| 6 | 58 | 66 |
| 7 | 43 | 48 |
| 8 | 33 | 37 |
| 9 | 26 | 29 |
| 10 | 21 | 24 |
| 11 | 17 | 20 |
| 12 | 15 | 16 |
| 13 | 12 | 14 |
| 14 | 11 | 12 |
| 15 | 9 | 11 |



## 4 Conclusions

This study shows that estimates of grass height should be corrected for RP formation in intensive grazing systems to better estimate potential fresh grass allowance. Our analysis showed that the average percentage of grassland covered with RP increased from around 22% at the end of May to around 43% at the end of July/beginning of August at a fixed stocking rate of 7.5 $cow^{-1}$ $ha^{-1}$, and these percentages do not differ across grazing systems. The percentage of grassland covered with RP should be subtracted from the total grazed area to better estimate fresh grass allowance. Our results suggest that the percentage of grassland covered with RP is not markedly influenced by grazing system under intensive grazing. If the RP can already be visually distinguished before grazing, they should be excluded from the grass height measurements to get a reliable estimate of the remaining grazing area without RP. This is more relevant for grazing systems with a short grazing interval since the contrast in grass height between non-RP and RP reduces with an increase in period of regrowth. Excluding RP reduces variation in grass height in a field, implying that less measurements are needed for a sufficiently accurate estimate of average grass height in a field.

### *Acknowledgments*

This work is part of the research programme which is financed by the Province of Fryslân. In addition, this work was carried out within the framework of the Amazing Grazing project (www.amazinggrazing.eu), which is financed by ZuivelNL, LTO, NZO and the Dutch Ministry of Agriculture, Nature and Food Quality. We would like to thank the financers of this research and the employees at Dairy Campus for their assistance during the field work.

# Chapter 5

## *The potential of multispectral images to correct fresh grass allowance for selective grazing*

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## ABSTRACT

Accurate estimates of fresh grass allowance are central to improve the economic and environmental performance of pasture-based dairy farms. To accurately quantify fresh grass allowance, we should correct total available herbage mass (HM) for the occurrence of rejected patches (RP) that are formed due to selective grazing. The rapid advances in precision technology create new opportunities for automated recordings of HM, for example via spectral images. The aim of this study was to explore whether spectral images can be used to correct fresh grass allowance for selective grazing. To do so, we performed measurements in a grazing experiment including two grazing systems, namely compartmented continuous grazing and strip grazing. We created one overview drone image of all fields on three dates (i.e. July 19, August 10 and 25) using an eBee Ag, which was equipped with a multispectral, and recorded green, red, red edge and near-infra red wavelengths. We also recorded the full visible red-green-blue (RGB) spectrum using a colour camera. We estimated HM using the Normalised Difference Vegetation Index (NDVI), which is based on the fraction of reflected NIR and the red wavelengths. To understand the predictive value of our automated recordings, we first regressed NDVI recordings on grass height measurements obtained with a rising plate meter, which included RP. We found a quadratic relation between grass height and NDVI, which was influenced by the day of measurement and grazing interval ($P<0.001$; RMSEP of 10.2%; $R^2$ of 0.78). We were able to identify RP by estimating threshold values in NDVI using visual interpretation of RGB images (out of sampling error of -9% to 15%). Correcting NDVI values for RP resulted in an average reduction of NDVI values of 11%, irrespective of the grazing systems. Our results provide first indications that NDVI could be used to quantify fresh grass allowance for grazing, but research is necessary to further explore the relation between NDVI and HM under different grazing management practices.

**Key words:** spectral analysis, NDVI, herbage mass, grazing management, dairy cows

## 1 Introduction

The economic and environmental sustainability of pasture-based dairy farms is largely driven by grassland utilisation (Shalloo *et al.*, 2018). To improve grassland utilisation it is necessary to accurately quantify fresh grass allowance (McSweeney *et al.*, 2015). Fresh grass allowance is the amount of pasture offered to the cow in kg dry matter (DM) per cow per grazing day, and is determined by the stocking rate and available herbage mass (HM) on the grazing platform. To accurately calculate fresh grass allowance, we should correct total HM for the occurrence of rejected patches (RP) that are formed due to selective grazing (Klootwijk *et al.*, 2019a). Especially in intensive grazing systems, accurate estimates of fresh grass allowance are critical for feed budgeting since an incorrect balance between fresh grass allowance and feed supplementation results in inefficient use of the pasture, a lower feed-efficiency and potential decreases in milk production. In this paper, therefore, fresh grass allowance is defined as the allowance including a correction for RP.

The most validated and internationally adopted method to quantify HM in practice is the use of the rising plate meter (RPM). The RPM measures grass height, which is subsequently used in a calibration equation to estimate HM. Herbage mass estimates based on the RPM are commonly used as an input in decision support tools to assist in grazing management and have been shown to improve pasture utilisation (Creighton *et al.*, 2011; Hanrahan *et al.*, 2017). The disadvantage of measuring grass height with an RPM, however, is that it is quite labour intensive as the farmer needs to measure all paddocks at least weekly. Moreover, quantifying the percentage of grassland covered with RP to improve accuracy of fresh grass allowance is possible with an RPM (Klootwijk *et al.*, 2019a), but, again, this is labour intensive.



The rapid advances in precision technology create new opportunities for automated recordings of HM, for example via spectral images (McSweeney *et al.*, 2015). Although widely adopted in arable production, the use of spectral images is still in its infancy in grass-based dairy farming systems (Shalloo *et al.*, 2018). Some preliminary studies show the potential of using near-surface hyperspectral images to estimate HM in mowing trials (Geipel and Korsaeth, 2017; Davids *et al.*, 2018; Hoving *et al.*, 2018). Moeckel *et al.* (2017) mention that there are some indications that the accuracy of spectral sensors reduces with increasing grass maturity because of a relatively high fraction of senescent material. The effect of grazing on the relation between vegetation indices and HM, however, is yet to be discovered (Moeckel *et al.*, 2017).

A recent paper used spectral images to detect trends in existence of short and tall RP under very lenient to moderate grazing intensities (Tonn *et al.*, 2018). This indicates that we might be able to identify RP under selective grazing to correct fresh grass allowance. To our knowledge, spectral images have so far not been utilized to quantify fresh grass allowance. The aim of this study, therefore, was to explore whether spectral images can be used to correct fresh grass allowance for selective grazing. To do so, we performed measurements in a grazing experiment, including two grazing systems, i.e. compartmented continuous grazing (CCG) and strip grazing (SG).

## 2 Materials and methods

### *2.1 Experimental set-up*

The grazing experiment in which we conducted our measurements was performed at the Dairy Campus research facility in Leeuwarden, the Netherlands, during the grazing season of 2017 that lasted from April until September. Standard grazing time was from 8:30 until 16:00 h. The botanical composition of the fields was 72% perennial ryegrass (*Lolium perenne* L.), 12% timothy-grass (*Phleum pratense* L.), 11% rough meadow-grass (*Poa trivialis* L.) and 5% other species.

Sixty dairy cows were allocated to two grazing systems, i.e. CCG and SG, in two replicates (Figure 1). In total we used 8 ha of grassland, implying a fixed stocking rate of 7.5 cows per ha of grazing area. Both CCG and SG are rotational grazing systems in which the cows receive a new grazing area daily. These systems, however, largely differ in key grazing characteristics, such as pre- and post-grazing heights and period of regrowth. Each CCG replicate was two ha and was divided into six compartments of 0.33 ha. On a grazing day, therefore, each cow had access to 222 $m^2$ fresh grass. Each SG replicate was two ha and was divided into 31 strips of 0.07 ha. On a grazing day, each cow had access to 43 $m^2$ fresh grass and the strip of the previous day to provide more space to walk (in total 86 $m^2$).

For CCG, five compartments were grazed in rotation and the sixth one was cut for silage to remove RP. After regrowth the sixth compartment was added to the rotation to provide fresh grass for grazing and the next compartment was selected to produce grass for silage. So during the whole season five of the six compartments were grazed in a five days rotation. Period of regrowth, i.e. days before cows returned to the same compartment, therefore, was four days for CCG. For SG, blocks of four strips were cut for silage and to remove RP after two grazing events. After regrowth, the cut strips were again added to the rotation. Period of regrowth was on average 20 days for SG. Due to the differences in period of regrowth between grazing systems and fields this experimental set-up provides a heterogeneous field, which is relevant to explore the possibility of drone images to quantify fresh grass allowance.

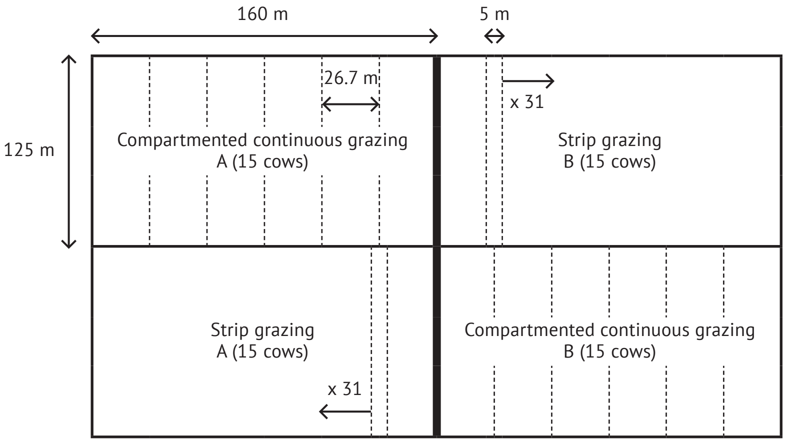



**Figure 1.** *Overview of the grazing experiment with two contrasting grazing systems, i.e. compartmented continuous grazing (CCG) and strip grazing (SG) in two replicates (A and B).*

### *2.2 Drone recordings*

Drone images were taken with the eBee Ag equipped with a multispectral camera (multiSPEC 4C) recording the green (mean of 550 nm), red (mean of 660 nm), red edge (mean of 735 nm) and near-infra red (NIR; mean of 790 nm) wavelengths (AIRINOV, 2019). In addition, we used a colour camera (canon S110 RGB) to record the full visible red-green-blue (RGB) spectrum. On the $19^{th}$ of July (1), $10^{th}$ of August (2) and $25^{th}$ of August (3) multispectral and RGB recordings were taken of all fields in one overview image. Based on the fraction of reflected NIR and the red wavelengths, we calculated the Normalised Difference Vegetation Index (NDVI) based on equation 1.

$$NDVI = (NIR - red) / (NIR + red) \quad [1]$$

The NDVI is widely used to analyse vegetation based on satellite imagery. The NDVI value is always in between -1 and 1. A value around 1 means the highest possible density of green leaves, implying that all visible light is absorbed. We used the program QGIS version 2.18.2 to calculate the average NDVI per field. We first identified the fields in the drone images, using latitude and longitude measurements of all field corner points taken with a Global Positioning Systems (GPS) device (Garmin GPSMAP 64S). Second, we created a separate polygon for each field, which is a basic feature in QGIS to represent complex shapes in digital format. We saved these polygons in a vector layer, which represents a basic type of data structure in a geographic information system. Third, we used this vector layer as input for the zonal statistics software in the QGIS geo-algorithm toolbox to calculate the average NDVI per field.

### *2.3 Relating HM estimates from drone recordings with grass height measurements*

Grass height measurements obtained with the RPM served as a validation for HM estimation based on the drone recordings. We performed grass height measurements in all fields close to the dates of the drone recordings, i.e. on the 18th of July (one day before), the 8th of August (two days before) and 23th of August (two days before). The fields that were grazed or mowed in between the grass height measurements and the drone recordings were excluded from the dataset. Grass heights were measured by walking in a W-shape through all fields, using an RPM. For CCG the average grass height per compartment was noted, whereas for SG the average grass height was noted per cluster of maximally four fields in similar growth stage. In line with the average grass height estimates, the average NDVI for CCG was calculated per compartment and the average NDVI for SG was calculated for the same clusters of maximally four fields. The compartments and clusters of strips served as the experimental units for relating NDVI with grass height and will be referred to as 'subfields'.

### *2.4 Regression analysis of NDVI recordings on grass height in field*

To understand the relation between NDVI recordings and grass height measurements, we defined a regression model with grass height being the dependent variable, and NDVI being the explanatory variable [2]. Since literature shows a non-linear relationship between ground measurements of HM and spectral reflectance (Hoving *et al.*, 2018; Lussem *et al.*, 2018), we introduced NDVI also as a quadratic term in the regression analysis.

$$y_{ijkl} = \mu + S_i + D_j + F_k + \beta_1 I_{ijkl} + \beta_2 N_{ijkl} + \beta_3 N^2_{ijkl} + \beta_{2,i} N_{ijkl} + \beta_{3,i} N^2_{ijkl} + \beta_{2,j} N_{ijkl} + \beta_{3,j} N^2_{ijkl} + \beta_{2,k} N_{ijkl} + \beta_{3,k} N^2_{ijkl} + \varepsilon_{ijkl} \quad [2]$$

Here, $y_{ijkl}$ is the grass height in cm of the $l$-th sampled subfield of grazing system $i$, on date of measurement $j$, on field $k$, $I_{ijkl}$ is the grazing interval (i.e. period of regrowth), and $N_{ijkl}$ is the corresponding average NDVI per subfield. $S_i$, $D_j$, $F_k$ are main effects of grazing system, measurement date, and fields. Terms like $\beta_{2,i} N_{ijkl}$ represent interaction between e.g. grazing system and NDVI and affect the slope of NDVI $N$. The random error terms $\varepsilon_{ijkl}$ were assumed to be independently normally distributed around 0 with constant variance $\sigma^2$.

The statistical program IBM SPSS Statistics for Windows, Version 22.0, was used to perform the regression calculations. The prediction accuracy of the regression model was expressed in terms of the root mean square error of prediction (RMSEP) [3].

$$RMSEP = \sqrt{\frac{1}{n} \sum_{ijkl} (\hat{y}_{ijkl} - y_{ijkl})^2} \quad [3]$$

Here, $y_{ijkl}$ is the observed grass height in cm and $\hat{y}_{ijkl}$ the corresponding prediction (fitted value), and $n$ is the total number of subfields. Roughly, the prediction error is in between plus and minus twice the RMSEP. The RMSEP was determined by leave-one-out cross validation and was calculated from the squared deletion residuals (Montgomery and Peck, 1992).

### *2.5 Identifying rejected patches*

Klootwijk *et al.* (2019a) showed a clear contrast in grass height between non-RP and RP under intensive grazing. Using the RPM, they found an average grass height of 64 mm for non-RP for CCG and SG, and an average grass height of 142 mm for RP in CCG, and of 106 mm for RP in SG. We hypothesised that due to this contrast it should be possible to identify RP based on the difference in average NDVI of the field and the NDVI of the RP. We also hypothesised, however, that it is only possible to identify RP in fields that have been recently grazed, since the contrast in grass height becomes indistinguishable after regrowth. Since we could visually distinguish RP up until ten days after grazing, mowed fields and fields that were grazed more than ten days before the recording were excluded to identify RP. The remaining fields served as the experimental units to identify RP.

First, RP per field were visually identified by using the NDVI and RGB raster layers of the 19$^{th}$ of July. The relation between the minimum NDVI of the visually identified RP per field was compared to the average NDVI per field [4] to see if the labour intensive manual identification of RP could be automated. Second, Eq. 4 was used to determine RP for the images of the other two measurement dates, while four random fields were checked for out of sample errors by comparing the amount of visually identified RP with the amount of RP identified with Eq. 4.

$$\text{Minimum NDVI RP} = a \times \text{average NDVI} + b \qquad [4]$$

### *2.6 Analysing the effect of rejected patches on fresh grass allowance*

Based on the RP identification described above we set the minimum field specific NDVI of the RP as a threshold value to create binary raster layers, representing the non-RP grazing area, for each field. First, we used these raster layers to calculate the percentage of grassland covered with RP. Subsequently, we used these raster layers to calculate the average NDVI of the non-RP, representing the fresh grass allowance per field. Finally, we compared the NDVI of the non-RP with the average NDVI of the field, representing the HM. To quantify the change in NDVI after excluding RP, we expressed the difference in NDVI as a percentage of the range in NDVI per system.

# 3 Results and discussion

### *3.1 Grass heights vs NDVI*

Figure 2 shows an example of two stacked spatial layers, one raster layer representing NDVI values based on one drone image and one vector layer representing the experimental unit, i.e. subfields, based on the GPS measurements. In general, we can say that the lighter the colour, the higher the NDVI value, and the more HM. The average NDVI values per subfield in the three images varied from 0.81 to 0.94, whereas the average grass heights per subfield varied from 6 until 14 cm (Figure 3). Regression analysis showed that the quadratic relation between grass height and NDVI is influenced by the day of measurement ($P< 0.001$; Table 1). This is in line with literature showing that the relation between HM and NDVI is influenced by growing season (Hoving *et al.*, 2018). In addition, we found an expected relation between grazing interval (i.e., period of regrowth) and grass height ($P< 0.001$; Table 1). The regression analysis resulted in an RMSEP of 0.9 cm (10.2%) and a coefficient of determination ($R^2$) of 0.78.

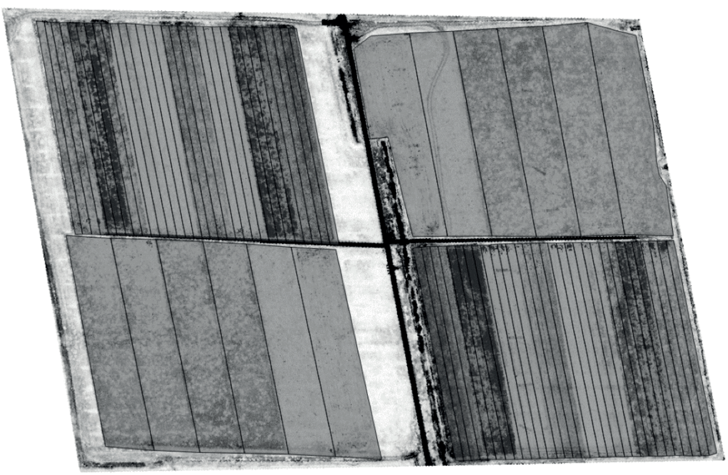


**Figure 2.** *Example of two stacked layers, one raster layer representing NDVI values based on one drone image and one vector layer representing the fields based on Global Positioning System (GPS) coordinates.*

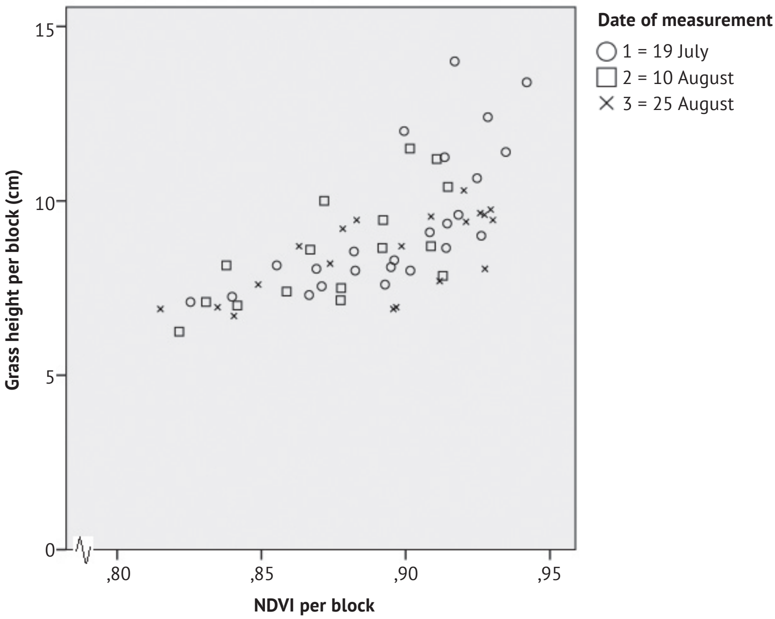



**Figure 3.** *Grass height in cm plotted against NDVI per subfield and split up for date of measurement.*



**Table 1.** *P-values and the root of the mean square error of prediction (RMSEP) for the regression model with grass height as dependent variable.*

| | P-values |
|---|---|
| **Intercept** | 0.290 |
| **Date of measurement** | 0.001 |
| **Grazing interval** | < 0.001 |
| **NDVI**[1] | 0.295 |
| **NDVI**[1] | 0.336 |
| **Date of measurement × NDVI**[1] | < 0.001 |
| **RMSEP** | 0.9 |

[1]Normalised Difference Vegetation Index.

### *3.2 Identifying rejected patches*

We found a linear relation ($R^2$= 0.81) between the threshold values for RP based on visual interpretation of RGB images and the average NDVI values per field (Equation [5], Figure 4). This means that the threshold value for RP selection increases with an increase in average NDVI. In other words, the grass height of the RP increases with an increase in the overall grass height, affecting the threshold to identify RP based on NDVI.

Minimum NDVI RP = 0.77 × NDVI + 0.23 [5]

We found an out of sample error varying from -9% to 15% when comparing the count of visually identified RP with RP identified with Eq. 4 (Table 1). This shows potential to identify RP based on NDVI threshold values, although effects of grazing system, seasonality and days since grazing should be further explored. The advantage of such a relatively easy selection method is that it would not require advanced geographic information software, which might not be feasible for on-farm application.

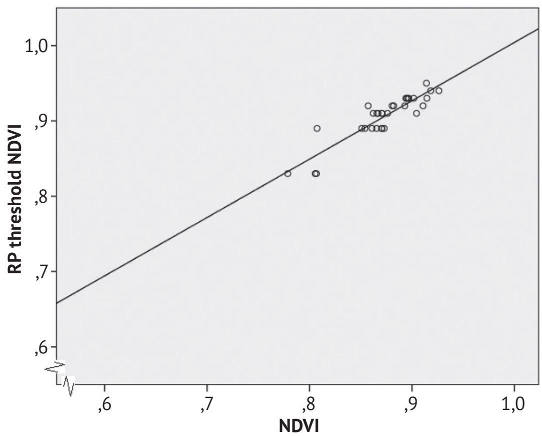



**Figure 4.** *Visually identified threshold values for rejected patches (RP) plotted against the average NDVI per field.*

**Table 1.** *Out of sample error (%) for identifying rejected patches (RP) based on NDVI threshold for two grazing systems (GS) and two measurement dates.*

| Image | GS | Days since grazing | % out of sample error |
|---|---|---|---|
| **10-8** | CCG | 1 | -7 |
| **10-8** | CCG | 4 | 8 |
| **10-8** | SG | 9-11 | 14 |
| **10-8** | SG | 9-11 | 10 |
| **25-8** | CCG | 1 | -9 |
| **25-8** | CCG | 1 | -5 |
| **25-8** | SG | 1-2 | -4 |
| **25-8** | SG | 3-6 | 15 |

### *3.3 The effect of rejected patches on fresh grass allowance*

Figure 5 shows results of the average percentage of RP for CCG and SG per field. On July 19, the percentage of RP was 19 ± 6 % for CCG and 27 ± 7 % for SG, whereas on August 10 it was 21 ± 6 % for CCG and 24 ± 10% for SG, and on August 25 it was 15 ± 3 % for CCG and 22 ± 11 % for SG. The large variation between fields of the same grazing system can be explained by the varying grazing interval, the amount of grazing events since the last mowing event and seasonality. Klootwijk *et al.* (2019a) found an increase in percentage of RP from around 22% in May to around 43% in the beginning of August in fields that were grazed until a maximum of four days before the measurement. The lower average RP proportion in this study, with measurements in July and August, can be explained by only including those fields that were grazed up to ten days before the measurement.

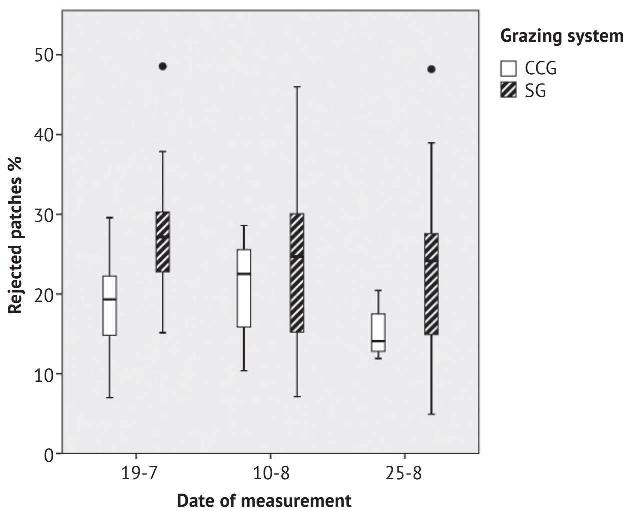



**Figure 5.** *Average percentage of rejected patches and individual variation between fields for compartmented continuous grazing (CCG) and strip grazing (SG) based on NDVI values.*



In line with Klootwijk *et al.* (2019a), the fresh grass allowance can be corrected by subtracting the surface covered with RP from the total area available for grazing. Klootwijk *et al.* (2019a) showed that if the RP can already be visually distinguished before grazing, they should be excluded from the grass height measurements to get a reliable estimate of the remaining grazing area without RP. We argue, therefore, that this will also be necessary when using a vegetation index as measure for HM. For CCG, NDVI values with RP ranged from 0.84 to 0.93, with an average of 0.89, whereas NDVI values without RP ranged from 0.82 to 0.92, with an average of 0.88. This reduction in average NDVI value of 0.01 seems rather small, but equals 11% of the range in NDVI with RP (0.09). For SG, NDVI with RP ranged from 0.67 to 0.90, with an average of 0.82, whereas NDVI without RP ranged from 0.67 to 0.90, with an average of 0.80. This reduction in average NDVI values also equals 11% of range in NDVI with RP The difference between NDVI with and without RP decreased with an increasing amount of days since grazing, which is expected since the detection of RP becomes more difficult when grass height of RP and non-RP increases. These results show that when using a vegetation index as measure for HM, RP should also be excluded to get a reliable estimate of the fresh grass allowance. This is especially relevant for grazing systems with a short grazing interval since the contrast in grass height between non-RP and RP reduces with an increase in period of regrowth.

Excluding RP resulted in a smaller percentage reduction in terms of NDVI values (i.e. 11%) than in terms of area (range from 15% to 27%). A potential explanation for this is that the NDVI values of the RP are less accurate than the values of the non RP. This hypothesis is underlined by Moeckel *et al.* (2017), who indicate that the accuracy of spectral sensors reduces with an increase in grass maturity because of an increasing proportion of senescent material. Rejected patches generally contain a larger proportion of stem and senescent material and a smaller proportion of leaf material. This is also known to influence the relation between grass height and HM and to result in a low prediction accuracy of HM around the reproductive stage (Klootwijk *et al.*, 2019b). Since our aim, however, is to quantify fresh grass allowance by excluding RP, the actual HM of the RP is not of interest to us. Rather, excluding RP in our quantification of HM controls for the influence of selective grazing. It would be interesting to analyse the relation between grass height and NDVI after excluding RP, because this relation might change based on these results. However, our database was too small (n = 36) after using the selection criteria of the subfields for the regression analysis and the fields for the RP identification to show the effects of excluding RP on the relation between grass height and NDVI. Ultimately, the interest would be in the relation between NDVI and HM. Our recommendation would be to account for RP when analysing this relation under grazing management.

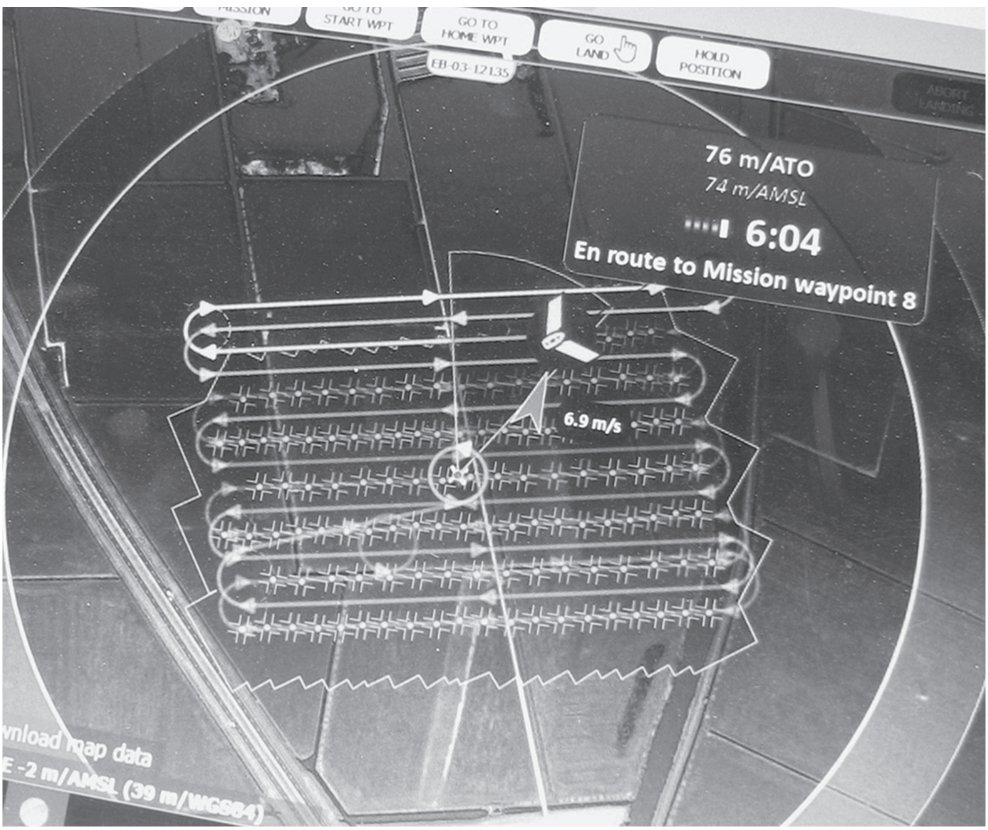
Sanderson *et al.* (2001) concluded that measuring within 10% error margin can improve forage budgeting by allocating an adequate amount of grass to the herd. Correctly estimating fresh grass allowance can increase grassland utilization and improve feed budgeting, which can maintain milk production at the desired level. The use of drones has the potential to reduce the labour associated with grassland management, since one overview image can replace all necessary grass height measurements per field. The potential of this precision technology extends beyond estimating fresh grass allowance as the spectral images can be used for multiple purposes, e.g. to analyse the pattern of RP in relation to infrastructure. In addition, these images could be used to quantify herbage quality, and to reveal between-field and within-field variation in terms of nutrient requirements of the grass (Shalloo *et al.*, 2018). At the moment, a potential drawback for practical implementation of drones for grassland management is the relatively high costs. Costs of these types of technologies, however, have drastically reduced over the last decade and are expected to further reduce. To maximise accuracy, drone measurements should be done at least once a week.

## 4 Conclusions

We demonstrated a relatively easy method to identify RP for two intensive grazing systems based on spectral images. By subtracting the surface covered with RP from the total area available for grazing, fresh grass allowance can be corrected for selective grazing. Similarly, when using a vegetation index to estimate HM, RP should be excluded. Our results provide first indications that NDVI could be used to quantify fresh grass allowance for grazing, but research is necessary to further explore the relation between NDVI and HM under different grazing management practices.

***Acknowledgments***

This work is part of the research programme which is financed by the Province of Fryslân. In addition, this work was carried out within the framework of the Amazing Grazing project (www.amazinggrazing.eu), which is financed by ZuivelNL, LTO, NZO and the Ministry of Agriculture, Nature and Food Quality. We would like to thank the employees at Dairy Campus for their assistance during the field work.



# Chapter 6

## *Economic and environmental consequences of grazing strategies with different levels of fresh grass intake and milk production*

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## ABSTRACT

The aim of this study was to quantify the economic and environmental performance of grazing strategies, defined by a difference in grazing hours per day, at different levels of milk production and for a situation where grazing management appears difficult (high-yielding cows, high stocking rate, automatic milking system). We modelled three grazing strategies differing in daily grazing hours: strategy 1 with 6 grazing hours day$^{-1}$; strategy 2 with 9 grazing hours day$^{-1}$, and strategy 3 with 15 grazing hours day$^{-1}$, and three levels of milk production: 7,000, 8,000 and 9,000 kg milk cow$^{-1}$ year$^{-1}$. A whole-farm linear programming model was used, simulating a Dutch dairy farm on sandy soil. The objective function of the model maximized labour income. We combined the model with a farm nutrient balance and life-cycle assessment to determine surpluses of nitrogen (N) and phosphate ($P_2O_5$) per hectare of farm land, and greenhouse gas (GHG) emission per kg fat-and-protein-corrected milk (FPCM). Results showed that at each level of milk production, labour income increases with an increase in grazing hours. The increase in income varied from €4,056 to €7,189 going from strategy 1 to strategy 3. This equals an average increase of about €1,000 per extra kg DM fresh grass cow$^{-1}$ day$^{-1}$. GHG results showed that the emission intensity (kg $CO_2$ equivalent kg$^{-1}$ of FPCM) increased with about 5-7% going from strategy 1 to strategy 3. Surpluses of N and $P_2O_5$ were generally quite comparable across grazing strategies. Increasing grazing losses from 16% to 25%, as a measure for the effectiveness of grassland utilization, showed a decrease in labour income, varying from about €1,979 at 6 hours of grazing and 7,000 kg milk cow$^{-1}$ day$^{-1}$ to €10,985 at 15 hours of grazing and 9,000 kg milk cow$^{-1}$ day$^{-1}$. GHG emissions remained similar or slightly increased after increasing grazing losses, while the N and $P_2O_5$ surpluses per ha increased. Abovementioned results showed that regardless of milk production level, increasing fresh grass intake can improve the economic performance of farms. Improving grassland utilization, furthermore, has the potential to increase both the economic and environmental performance of grazing strategies.

## 1 Introduction

Grazing management on large-scale farms with high-yielding cows, a large herd size and a high stocking density appears difficult and requires sophisticated skills of the farmer (Parsons *et al.*, 2004). This has resulted in a decline in grazing on dairy farms in several North-Western European countries. Dairy farmers increasingly choose for a zero-grazing system, which enables them to better control cattle diets, optimize grassland utilization, increase milk production, improve labour efficiency and lower nutrient losses (Meul *et al.*, 2012). In addition, grazing area scarcity in the close proximity of the farm and the use of an automatic milking system (AMS) appear main reasons for choosing a zero-grazing system. Abovementioned trends affect important sustainability issues of milk production, including economic, environmental and social issues.

Farm profitability appears a key issue affecting the economic performance of dairy farms (Van Calker *et al.*, 2005). Generally, zero-grazing dairy farms feed higher amounts of supplements to increase milk production, which results in higher revenues from milk but also in higher feed costs (Meul *et al.*, 2012). Several studies have shown positive effects of grazing on the farm profitability of dairy farms (Dillon *et al.*, 2005; Evers *et al.*, 2008; Van den Pol-van Dasselaar *et al.*, 2014b). The economic benefit of grazing, however, highly depends on the fresh grass intake and associated achieved milk production of dairy cows (Evers *et al.*, 2008; Van den Pol-van Dasselaar *et al.*, 2014b).

These key characteristics inherently differ across grazing systems. Van Vuuren (1993), for example, argued that in theory even the best quality roughage can only support production levels of about 27 L of milk per cow per day, if no additional concentrates are fed. Milk production levels on full roughage diets, however, often peak at 20 to 22 L of milk per cow per day in practice (Van Vuuren, 1993), because roughage is not optimally used in terms of quantity or quality, implying that there is room for improvement.



To further increase milk production in grazing systems, concentrates are needed to fulfil the required extra energy demand (Kristensen *et al.*, 2005). An incorrect balance between fresh grass allowance and feed supplementation can reduce grassland utilization, and increase variations in dry matter intake and hence fluctuations in milk production (Hennessy *et al.*, 2015). Achieving a high grassland utilization is especially challenging when grazing is combined with supplementary feeding, since cows are less motivated to graze when alternative feed is offered. In addition, the increasing use of automatic milking systems raises the question whether it is still possible to gain economic benefit from grazing at high production levels. Van den Pol-van Dasselaar *et al.* (2013) indicate that it requires more management skills, but that it is possible to gain economic benefit from grazing on highly productive dairy farms with AMS.

From an environmental perspective, grazing can have both positive as well as negative effects. Generally, the higher feed supplementation of zero-grazing dairy farms does not lead to a similar increase in milk yield and, therefore results in higher nutrient surpluses (Meul *et al.*, 2012). N losses in the form of ammonia volatilization are most apparent during housing, slurry storage, and slurry application (Bussink and Oenema, 1998). The higher volatilization of ammonia from slurry storage compared to grazing occurs because the urease enzyme in the manure can mix freely with the urea in the urine. Grazing systems, on the other hand, show higher N losses in the form of nitrate leaching than zero-grazing systems (Di and Cameron, 2002). The risk of nitrate leaching while grazing results from the high local concentrations of N in urine and manure patches, which exceeds grass requirements (Vellinga *et al.*, 2011).

Lorenz *et al.* (2019) show that an increasing milk yield, grass intake and feed efficiency decrease the carbon footprint per unit of milk, independent of the production system. They, however, did not find a difference in carbon footprint across production systems (i.e. pasture, mixed, confinement).

Above described existing studies either focused on the economic and/or environmental performance of grazing and zero-grazing systems. Differences in sustainability performance across commercial farms, however, do not only result from differences in grazing strategies, but also from differences in, for example, farm size, grazing area, or farm management. Although several studies mention that improved grassland management can improve both the economic and environmental performance of grazing systems, a consistent analysis of the interlinked effects of grazing strategies, feed supplementation and milk production on farm profitability and environmental performance is missing.

The aim of this study, therefore, was to quantify farm profitability and environmental performance of grazing strategies, differing in fresh grass intake, feed supplementation, milk production and grassland utilization in situations where grazing management appears difficult (high-yielding cows, high stocking rate, and an automatic milking system). To this end, we used a whole-farm optimization model, which enables an analysis of the impact of grazing strategies on economic and environmental farm performance (Van Middelaar, 2014). We used the Netherlands as a case study for high productive dairy farms.

## 2 Materials and methods

### *2.1 The dairy farm model*

To analyse the differences in economic and environmental consequences between several grazing strategies, we used a whole-farm linear programming (LP) model. Linear programming is a mathematical technique to find an optimal strategy given a certain objective and a set of limited resources and/or other constraints (Kay *et al.*, 2012). Optimization models include a guiding principle (e.g. maximizing farm income) that guarantees an optimal solution before and after implementing a strategy, in this case a grazing strategy. Our analysis is based on the objective to maximize labour income. Economic optimization was used as economic incentives are one of the important drivers in management decisions of farmers.

The whole-farm optimization model that is used, was originally developed by Berentsen and Giesen (1995) to calculate the impact of institutional, technical and price changes on farm management, economic results and nutrient losses of dairy farms on sandy soils. The model includes activities and constraints to allow the optimization process to optimize management decisions regarding farm structure and feeding strategies. The LP model has been further developed through the years (Berentsen *et al.*, 2000; Van Middelaar *et al.*, 2014), and recently updated by Klootwijk *et al.* (2016). They further developed the model to evaluate the effect of milk quota abolition and the accompanied new manure policy to limit phosphate production on farm structure, management, labour income, N and phosphorus (P) losses and greenhouse gas (GHG) emissions of a Dutch dairy farm on sandy soil.

The central element of the LP model is an average Holstein Friesian dairy cow. The model distinguishes a summer (182 days) and a winter period (183 days). Based on a fixed milk production level, dietary requirements of the average cow are calculated using the bio-economic model of Groen (1988). Feed requirements concern energy, rumen degradable protein (RDP) balance, true protein digested in the small intestine, and phosphorus. In addition, dry matter intake (DMI) capacity is limited, based on Jarrige (1988). Dietary choices include fresh grass (only summer), grass silage, maize silage and three types of concentrates (i.e. standard, medium and high protein). Available land can be used for grass and silage maize production, whereas maize silage and concentrates can be purchased. One hectare of silage maize yields 16.5 t of DM $yr^{-1}$, which equals 108 GJ of net energy for lactation ($NE_L$). Grassland yield depends on the level of nitrogen fertilization, which can vary from 100 to 500 kg $ha^{-1}$ $yr^{-1}$. Based on 225 kg of N $ha^{-1}$ $yr^{-1}$, 1 ha of grassland yields 75 GJ of $NE_L$ $yr^{-1}$. Based on feed restrictions, the model matched the feed requirements of the cow with on-farm feed production and purchased feed.

The latest manure legislation in the Netherlands as included in the model is described in detail by Klootwijk *et al.* (2016). In short, if the annual excretion of the dairy herd exceeds the total amount of manure that may be applied on on-farm land, the farm has to deal with a manure surplus according to the Dutch 'Dairy Act'. This extra manure surplus, which is expressed in a phosphate ($P_2O_5$) surplus, needs to be removed from the farm. An increase in surplus, comes with a step-wise increase in requirements for removal; the first part of the surplus only needs to be disposed to an arable farm, the second part needs to be processed, whereas the third part needs to be justified with additional farm land. In addition, total $P_2O_5$ production per farm is limited, based on the number of cows present on the farm in July 2015, and a fixed $P_2O_5$ excretion per cow. In line with previous studies using this model, model inputs are representing a typical Dutch dairy farm on sandy soils. The following sections describe the changes made to the model to analyse economic and environmental consequences of different grazing strategies.

### *2.2 Prices and costs*

Prices and costs were set according to long-term expectations (2014-2024) based on (KWIN-V, 2014). Milk price was set at 360 € $t^{-1}$ and includes a Dutch grazing premium of 150 cent per 100 kg of milk. Regarding the AMS yearly costs of €33,310 for an AMS with 2 boxes and €45,178 for an AMS with 3 boxes were included in the model. These costs were calculated based on replacement costs of €165,000 for an AMS with 2 boxes and €225,000 for an AMS with 3 boxes with a depreciation rate of 10%, a maintenance rate of 8% and an interest rate of 4.5% (KWIN-V, 2014). Because we combine grazing and automatic milking, a selection gate is needed to facilitate efficient cow traffic from the milking robot to the pasture in terms of milk production. Therefore, we included €1,012 in the model as yearly costs for this selection gate (KWIN-V, 2014).

### *2.3 Environmental impacts*

The model uses a nutrient balance to quantify the N and $P_2O_5$ surplus per hectare of on-farm agricultural area, being used as an indicator for the local environmental pressure related to N and $P_2O_5$ losses. Inputs of N and $P_2O_5$ are in the form of concentrates, maize silage, fertilizer, and atmospheric deposition, whereas outputs are in the form of milk, culled animals, and, potentially, manure. A positive N balance implies that N is potentially lost to the environment through volatilization of ammonia or nitrous oxide, or through runoff and leaching of dissolved nitrate. A positive $P_2O_5$ balance implies that phosphate can accumulate in the soil and is potentially lost to the environment through leaching and runoff, contributing to eutrophication of ground and surface waters (Sharpley, 1995).

In addition to the N and $P_2O_5$ balance, the model calculates the GHG emission intensity per kg fat-and-protein corrected milk (FPCM). Based on a life-cycle approach, emissions of the three major GHGs, carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$) are estimated from cradle to farm-gate. Processes included are the extraction of raw materials to produce farm inputs, the manufacturing and distribution of these inputs, and all processes on the dairy farm. Emission calculations have been described in detail by Van Middelaar (2014) and were updated in the most recent model by Klootwijk *et* *al.* (2016). Greenhouse gases were summed based on their equivalence factor in terms of $CO_2$: 1 for $CO_2$, 28 for biogenic $CH_4$, 30 for fossil $CH_4$, and 265 for $N_2O$ (IPCC, 2013). To express emissions per ton FPCM, we used economic allocation to allocate emissions between milk and meat.

### *2.4 Modelling different grazing strategies*

Grazing strategies were modelled for a typical Dutch dairy farm with a fixed land area of 50 hectares. In the Netherlands, farmers often do not have the option to acquire additional land. Especially when it comes to grazing, land also should be in close proximity to the farm and reachable by dairy cows. Housing capacity was set at 83 cow places with additional necessary space for young stock, with the option to purchase extra barn capacity at yearly costs of €558 per cow place including young stock. The LP model was used for economic optimization of the farm (i.e., herd size, feeding, manure application, land use) under different grazing strategies and different milk production levels as described below.

### *2.5 Grazing strategies*

Based on Philipsen *et al.* (2016), we defined three grazing strategies that differ in the amount of daily grazing hours: strategy 1 with 6 grazing hours day$^{-1}$; strategy 2 with 9 grazing hours day$^{-1}$, and strategy 3 with 15 grazing hours day$^{-1}$. The amount of grazing hours determined the maximum fresh grass intake. At farms with an AMS, the intake is less than 1 kg DM per cow per hour grazing, since the cows do not spend all hours of grazing outside, they regularly walk to the AMS. Therefore, the grazing strategies equalled 4 kg DM cow$^{-1}$ day$^{-1}$ for strategy 1; 6 kg DM cow$^{-1}$ day$^{-1}$ for strategy 2, and 10 kg DM cow$^{-1}$ day$^{-1}$ for strategy 3 (Philipsen *et al.*, 2016). We additionally modelled a relation between manure patches in the pasture and grazing losses, resulting from grass rejection surrounding these manure patches. Based on the amount of grazing hours, we determined the fraction of manure excreted in pasture, i.e. 0.25 for strategy 1, 0.38 for strategy 2 and 0.63 for strategy 3. Patch areas resulted from an assumed average size of manure patches of 0.067 $m^2$ (Cindy Klootwijk, unpublished data), in combination with an average cow defecating 16 times per 24 hours (Aland *et al.*, 2002). The areas with rejected grass patches was computed as six times the grassland area covered with manure based on MacLusky (1960). Grazing was only applicable in the summer period. Young stock had unlimited access to pasture for all grazing strategies.

### *2.6 Cow production traits and feed requirements*

To analyse the effect of milk yield on economic and environmental performance of the different grazing strategies, we modelled three different milk yields for each strategy, i.e. 7,000, 8,000 and 9,000 kg milk cow$^{-1}$ year$^{-1}$, with a fat content of 4.4% and a protein content of 3.5% (KWIN-V, 2014). The capacity of the AMS was set at 70 dairy cows per milking box. The number of milking boxes was determined in the optimization process, i.e. 2 boxes with a capacity of 140 dairy cows or 3 boxes with a capacity of 210 dairy cows. Based on literature, we assumed an increase in energy requirements of 1% per hour of grazing (Groen, 1988).

### *2.7 The effect of grassland utilization*

Since several studies hypothesize that grassland management has an important impact on the economic and environmental performance of grazing strategies, we tested the effect of an increase in grazing losses as a measure for suboptimal grassland utilization. As explained before, for the basis situation grazing losses were estimated based on the area of rejected grass patched which was determined by hours of grazing and the number of cows. The basis situation, therefore, represents a scenario with minimal grazing losses. Based on Klootwijk *et al.* (2019a), grazing losses were fixed at a relatively high rate of 25% for all grazing strategies and production levels, representing a situation in which fresh grass allowance exceeds fresh grass requirements. Differences between the basis situation and this scenario show the importance in terms of labour income, GHG emission intensity, and area based N and P surplus of suboptimal grassland utilization under different grazing strategies.

## 3 Results and discussion

### *3.1 The effects of grazing strategies on farm structure*

Table 1 shows the farm structure and management of an average Dutch dairy farm for each grazing strategy at the three milk production levels. Grazing strategies will be compared within each milk production level, starting with 7,000 kg cow$^{-1}$ yr$^{-1}$. Subsequently, the impact of milk production will be assessed by comparing results across levels.

For each of the grazing strategies at 7,000 kg cow$^{-1}$ yr$^{-1}$, grassland area is 40 ha or 80% of total farm land, being the minimum area that allows a manure N gift of 230 kg ha$^{-1}$ instead of 170 kg for farms with <80%. For each strategy, furthermore, fresh grass intake in summer was maximized at, respectively, 4, 6 and 10 kg DM, since fresh grass is the cheapest source of feed. In case of strategy 1 (6h of grazing), and strategy 2 (9h of grazing) summer diets were supplemented with a maximum of roughage (grass- and maize silage) and a small amount of concentrates to meet requirements for rumen degradable protein and energy within the limiting dry matter intake capacity of the cow. The summer diet of strategy 3 (15h of grazing), contained relatively low amounts of roughage and large amounts of concentrates compared to strategy 1 and 2. This can be explained by the high share of fresh grass in the diet in combination with an increase in the number of dairy cows, which left no grass silage for the summer diet. The winter diet was similar across all strategies. The amount of grass silage was based on the amount of grass remaining after summer. Maize silage and concentrates were added to meet requirements for energy and rumen degradable protein.

For grazing strategy 1 and 2 at 7,000 kg milk $cow^{-1}$ $day^{-1}$, the number of dairy cows was restricted by the phosphate application room of 4,200 kg $P_2O_5$ on own land. Increasing the number of cows would require manure disposal to an arable farm, increasing the variable cost per cow. In case of strategy 1 and 2, the revenues of an extra cow did not outweigh the costs for manure disposal, in combination with costs for, e.g., extra barn capacity and feed. The small decrease in the number of cows when going from grazing strategy 1 to 2 can be explained by an increase in nutrient content of the manure due to an increase in the share of fresh grass in the diet.

In case of strategy 3, the revenues of an extra cow did outweigh the costs of manure disposal as well as processing, in combination with other costs (Table 1). In this case, the number of cows was restricted by the availability of own labour. This means that the revenues of an extra cow did not outweigh the extra costs of hiring labour, in combination with other costs. Differences between strategies at 7,000 kg milk $cow^{-1}$ $yr^{-1}$ show that increasing grazing time to the highest level reduces feeding costs per additional cow to an extent that it compensates the increasing costs for manure disposal and processing related to herd extension.

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For all grazing strategies at milk production levels of 8,000 and 9,000 kg $cow^{-1}$ $yr^{-1}$, the revenues of an extra cow also outweigh the extra costs of manure disposal and processing in combination with other cost. Similar to strategy 3 at 7,000 kg milk $cow^{-1}$ $yr^{-1}$, the number of cows was restricted by the availability of own labour in each of those cases. The lower number of cows in strategy 3 at 8,000 kg milk, and in strategy 2 and 3 at 9,000 kg milk, is explained by the higher grassland area on those farms, and the fact that grassland is more labour intensive than maize land. The grassland area is increased to maximize fresh grass intake in summer, while at the same time enough grass is left for a required amount of grass silage in the winter diet given the feeding requirements. For all strategies at 8,000 and 9,000 kg milk $cow^{-1}$ $yr^{-1}$, diets are based on the same principle as under grazing strategy 3 at 7,000 kg milk $cow^{-1}$ $yr^{-1}$. Differences in diets within milk production level are explained by the difference in the share of fresh grass in summer and the number of cows.

### *3.2 The effects of grazing strategies on labour income*

The last row of Table 1 shows the difference in labour income across grazing strategies at different production levels. Results show that labour income increases with an increase in grazing hours, regardless milk production level. The change in labour income differed between €4,056 (9,000 kg milk $cow^{-1}$ $yr^{-1}$) to €7,189 (8,000 kg milk $cow^{-1}$ $yr^{-1}$) going from strategy 1 (6h of grazing $day^{-1}$) to strategy 3 (15h of grazing $day^{-1}$). This equals an average increase of about €1,000 per extra kg DM fresh grass $cow^{-1}$ $day^{-1}$. Results show that regardless the level of milk production, increasing fresh grass intake increases economic results.

### *3.3 The effects of grazing strategies on GHG emissions and nutrient surpluses*

Table 2 shows the environmental performance in terms of GHG emissions and nutrient surpluses for each of the grazing strategies at different production levels. Comparing results within each milk production class shows that the emission intensity (i.e., kg $CO_2$eq $kg^{-1}$ of FPCM) increases with an increased share of fresh grass in the diet, mainly due to an increase in emissions from manure and enteric fermentation. Manure emissions increased due to a larger share of manure deposited during grazing, contributing to $N_2O$ emissions, while emissions from enteric fermentation increases with an increasing share of fresh grass in the diet. Emission intensity increased with about 5-7% going from strategy 1 (6h grazing) to strategy 3 (15h grazing). Comparing results across milk production levels shows that an increase in milk production generally reduces emission intensity due to dilution of maintenance, i.e. emissions are diluted over a higher amount of milk.

In case of the area based surplus, varying from 179 to 199 kg N $ha^{-1}$ and from 0.3 to 3.3 kg $P_2O_5$ $ha^{-1}$ (Table 2), there does not seem to be a clear effect of grazing strategy. There is, however, a clear relation between the area based surplus and farm intensity (kg milk $ha^{-1}$; Table 1), with the latter depending on the number of cows and milk production level. The higher the farm intensity, the larger the input of off-farm feed products (nutrients), and the higher the area based surplus.

**Table 1.** *Farm structure and management of an average Dutch dairy farm with three different grazing strategies; 1 = 6 hours of grazing, 2 = 9 hours of grazing and 3 = 15 hours of grazing, at three milk production levels.*

| | | 7,000 kg $cow^{-1}$ $year^{-1}$ | | | 8,000 kg $cow^{-1}$ $year^{-1}$ | | | 9,000 kg $cow^{-1}$ $year^{-1}$ | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Grazing strategy** | **Unit** | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** |
| **Farm structure** | | | | | | | | | | |
| Dairy cows | No. | 98 | 96 | 113 | 115 | 115 | 109 | 115 | 113 | 108 |
| Young stock | No. | 51 | 51 | 59 | 61 | 61 | 57 | 59 | 59 | 57 |
| Total milk production | t $yr^{-1}$ | 725,963 | 710,239 | 834,382 | 972,141 | 975,466 | 922,398 | 1,090,543 | 1,071,892 | 1,026,711 |
| Total farmland | Ha | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| Grassland[1] | % | 80 | 80 | 80 | 80 | 80 | 87 | 80 | 85 | 88 |
| Maize land | % | 20 | 20 | 20 | 20 | 20 | 13 | 20 | 15 | 12 |
| $N_{min}$ application on grassland[2] | kg of N $ha^{-1}$ $yr^{-1}$ | 225 | 225 | 250 | 250 | 250 | 250 | 250 | 250 | 250 |
| Farm intensity | kg of milk $ha^{-1}$ | 13,731 | 13,434 | 15,782 | 18,387 | 18,450 | 17,447 | 20,627 | 20,274 | 19,420 |
| **Diet dairy cows: summer** | kg of DM $cow^{-1}$ $day^{-1}$ | | | | | | | | | |
| Grass | | 4.0 | 6.0 | 10.0 | 4.0 | 6.0 | 10.0 | 4.0 | 6.0 | 10.0 |
| Grass silage | | 7.7 | 6.3 | 0.1 | 4.3 | 3.6 | 1.4 | 4.5 | 4.5 | 1.8 |
| Maize silage | | 5.7 | 5.5 | 3.2 | 5.2 | 4.4 | 4.6 | 6.9 | 5.4 | 5.2 |
| Concentrates | | 2.1 | 2.2 | 6.5 | 7.0 | 7.0 | 5.9 | 7.0 | 7.0 | 6.9 |
| Diet restricted by[3] | | E,D,R | E,D,R | E,R | E,R | E,R | E,R | E,R | E,R | E,D,R |
| **Diet dairy cows: winter** | kg of DM $cow^{-1}$ $day^{-1}$ | | | | | | | | | |
| Grass silage | | 6.4 | 6.3 | 5.7 | 7.3 | 5.9 | 6.8 | 7.3 | 6.6 | 6.9 |

| | | 7,000 kg $cow^{-1}$ $year^{-1}$ | | | 8,000 kg $cow^{-1}$ $year^{-1}$ | | | 9,000 kg $cow^{-1}$ $year^{-1}$ | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Grazing strategy** | **Unit** | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** |
| **Diet dairy cows: winter** | kg of DM $cow^{-1}$ $day^{-1}$ | | | | | | | | | |
| Maize silage | | 2.4 | 2.3 | 2.4 | 4.7 | 4.6 | 3.6 | 5.2 | 5.4 | 4.2 |
| Concentrates | | 6.5 | 6.6 | 7.0 | 4.8 | 6.1 | 6.2 | 5.7 | 6.0 | 6.9 |
| Diet restricted by[3] | | E,R | E,R | E,R | E,R,T | E,R | E,R,T | E,R,T | E,R | E,R,T |
| **External inputs** | | | | | | | | | | |
| Purchased maize silage | t of DM $yr^{-1}$ | 43 | 32 | 18 | 117 | 97 | 122 | 165 | 171 | 152 |
| Purchased concentrates | t of DM $yr^{-1}$ | 166 | 167 | 297 | 266 | 294 | 259 | 284 | 285 | 288 |
| **Manure management** | | | | | | | | | | |
| N content | % | 4.04 | 4.23 | 4.46 | 4.44 | 4.54 | 4.73 | 4.75 | 4.78 | 4.99 |
| $P_2O_5$ content | % | 1.32 | 1.39 | 1.48 | 1.42 | 1.46 | 1.53 | 1.49 | 1.52 | 1.61 |
| Manure application restricted by[4] | | P | P | $N_{min}$ | $N_{min}$,P | $N_{min}$,P | $N_{min}$,$N_{org}$,P | $N_{org}$,P | $N_{org}$,P | $N_{org}$,P |
| Total excretion | kg of phosphate $yr^{-1}$ | 4,200 | 4,200 | 5,275 | 5,147 | 5,342 | 5,230 | 5,346 | 5,416 | 5,459 |
| Applied on own land | kg of phosphate $yr^{-1}$ | 4,200 | 4,200 | 4,133 | 4,200 | 4,200 | 4,305 | 4,204 | 4,274 | 4,317 |
| Manure disposal | kg of phosphate $yr^{-1}$ | 0 | 0 | 560 | 560 | 560 | 560 | 560 | 560 | 560 |
| Manure processing | kg of phosphate $yr^{-1}$ | 0 | 0 | 582 | 387 | 582 | 365 | 582 | 582 | 582 |
| Purchased phosphate quota | kg of phosphate $yr^{-1}$ | 0 | 0 | 372 | 243 | 438 | 327 | 443 | 512 | 555 |
| **Labour income** | € $yr^{-1}$ | -5,139 | -2,542 | 1,577 | 18,585 | 20,437 | 25,774 | 42,568 | 43,982 | 46,624 |

[1]derogation to apply 230 kg N $ha^{-1}$ instead of 170 kg N $ha^{-1}$ with min. 80% grassland.
[2]$N_{min}$ = N mineral.
[3]D = dry matter intake capacity, E = energy requirements, R = rumen-degradable protein balance, T = true protein digested in the small intestine.
[4]$N_{min}$ = N mineral, $N_{org}$ = N organic, P = phosphate.

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**Table 2.** *Environmental performance of three different grazing strategies at three milk production levels.*

| *In $CO_2$-eq $t^{-1}$ of FPCM* | **7,000 kg $cow^{-1}$ $year^{-1}$** | | | **8,000 kg $cow^{-1}$ $year^{-1}$** | | | **9,000 kg $cow^{-1}$ $year^{-1}$** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Grazing strategy[1]** | **1** | **2** | **3** | **1** | **2** | **3** | **1** | **2** | **3** |
| **Animal emissions** | | | | | | | | | |
| Enteric $CH_4$ dairy cows | 442 | 448 | 445 | 411 | 416 | 432 | 397 | 405 | 418 |
| Enteric $CH_4$ young stock | 83 | 83 | 83 | 74 | 74 | 74 | 66 | 66 | 66 |
| Manure | 123 | 124 | 138 | 113 | 118 | 124 | 105 | 109 | 117 |
| **On-farm feed production** | | | | | | | | | |
| Grassland | 177 | 174 | 161 | 149 | 144 | 154 | 129 | 136 | 139 |
| Maize land | 37 | 37 | 27 | 24 | 24 | 17 | 23 | 18 | 15 |
| **Off-farm feed production** | | | | | | | | | |
| Concentrates | 156 | 160 | 242 | 181 | 201 | 193 | 169 | 179 | 194 |
| Maize | 10 | 8 | 4 | 21 | 17 | 23 | 26 | 28 | 26 |
| **Total GHG emissions** | 1,027 | 1,034 | 1,101 | 972 | 994 | 1,017 | 916 | 941 | 974 |
| *In kg $ha^{-1}$* | | | | | | | | | |
| **N surplus** | 183 | 179 | 185 | 193 | 194 | 191 | 199 | 197 | 191 |
| **$P_2O_5$ surplus** | 3.2 | 3.3 | 0.3 | 1.6 | 1.8 | 1.5 | 1.9 | 1.8 | 1.7 |

[1]grazing strategy; 1 = 6 hours of grazing, 2 = 9 hours of grazing and 3 = 15 hours of grazing.

### *3.4 The effect of grassland utilization*

In the basis situation, grazing losses were based on the area of manure patches which was directly related to grazing hours and the number of cows on the farm. Similarly, maximum fresh grass intake per cow was based on grazing hours. As the maximum fresh grass intake was met in each scenario, grazing losses were found to be similar at a level of about 16% across all grazing strategies and production levels. As these grazing losses were inevitable due to the rejection of surrounding manure patches (MacLusky, 1960), the basis situation represents a situation with optimal grassland utilization.

Figure 1 shows the economic and environmental consequences of an increase in grazing losses from 16% in the basis situation (solid lines) to 25% under suboptimal grassland utilization (dotted lines) for the different grazing strategies and levels of milk production. Increasing grazing losses to 25% decreased labour income for all grazing strategies and at all milk production levels, with the decrease becoming more pronounced when the dietary share of fresh grass increases (Figure 1a). The difference in labour income per year varied from €1,979 for strategy 1 at 7,000 kg milk $cow^{-1}$ $yr^{-1}$, to €10,985 for strategy 3 at 9,000 kg milk $cow^{-1}$ $yr^{-1}$. The differences increased not only with an increase in fresh grass intake, but also with an increase in milk yield. This result related to the fact that an increase in grazing losses resulted in a decrease in the number of cows per farm, and at higher milk production levels, the economic consequences of reducing the number of cows is larger. The results also show that increasing the number of grazing hours from 9 to 15 at a production level of 9,000 kg milk cow$^{-1}$ yr$^{-1}$ and 25% grazing losses is economically not attractive anymore. The reason is that the maximum intake of fresh grass of 10 kg DM cow$^{-1}$ day$^{-1}$ in this situation cannot be realised anymore, because that would lead to a suboptimally low amount of available silage grass in relation to the total feed requirement of the herd. This indicates that there is an upper limit to grazing from an economic point of view.

The GHG emission intensity slightly increased (1% on average) with an increase in grazing losses (Figure 1b), mainly due to an increasing reliance on off-farm feed. Similarly, the area based N surplus (Figure 1c; average increase 13 kg ha$^{-1}$, or 7%) and $P_2O_5$ surplus (Figure 1d; average increase of 5 kg ha$^{-1}$, or 680%) increased with an increase in grazing losses. In case of N, the increase was more pronounced at higher milk production levels, while for $P_2O_5$ the increase was more pronounced at higher levels of fresh grass intake. Differences between N and $P_2O_5$ are explained by the fact that the N content is relatively similar across different feed types, while the $P_2O_5$ content of feed products varies. As a result, $P_2O_5$ losses increased at higher levels of fresh grass intake (and subsequent feed substitution) wile N losses only increased with an increase in milk production level.

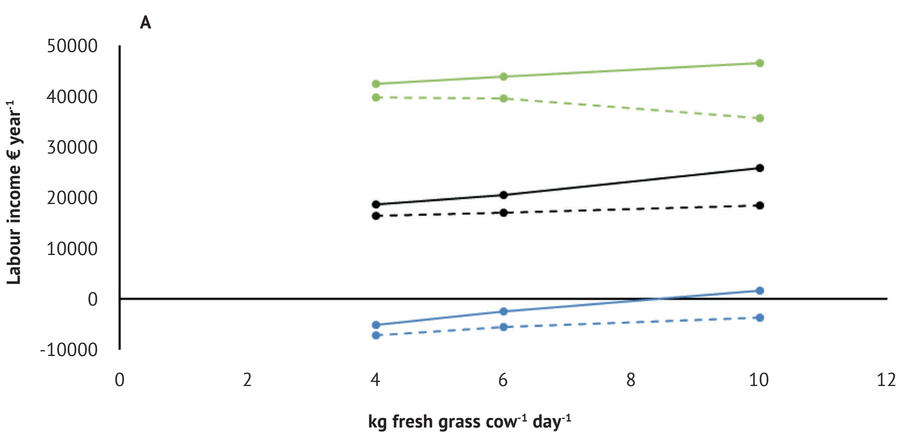


**Figure 1.** *Economic (panel a) and environmental (panel b-d) consequences of an increase in grazing losses from 16% in the basis situation (solid lines) to 25% under suboptimal grassland utilization (dotted lines) at different milk production levels and at different levels of fresh grass intake. Milk production levels: 7,000 kg cow$^{-1}$ yr$^{-1}$ (**blue**), 8,000 kg cow$^{-1}$ yr$^{-1}$ (**black**), and 9,000 kg cow$^{-1}$ yr$^{-1}$ (**green**).*

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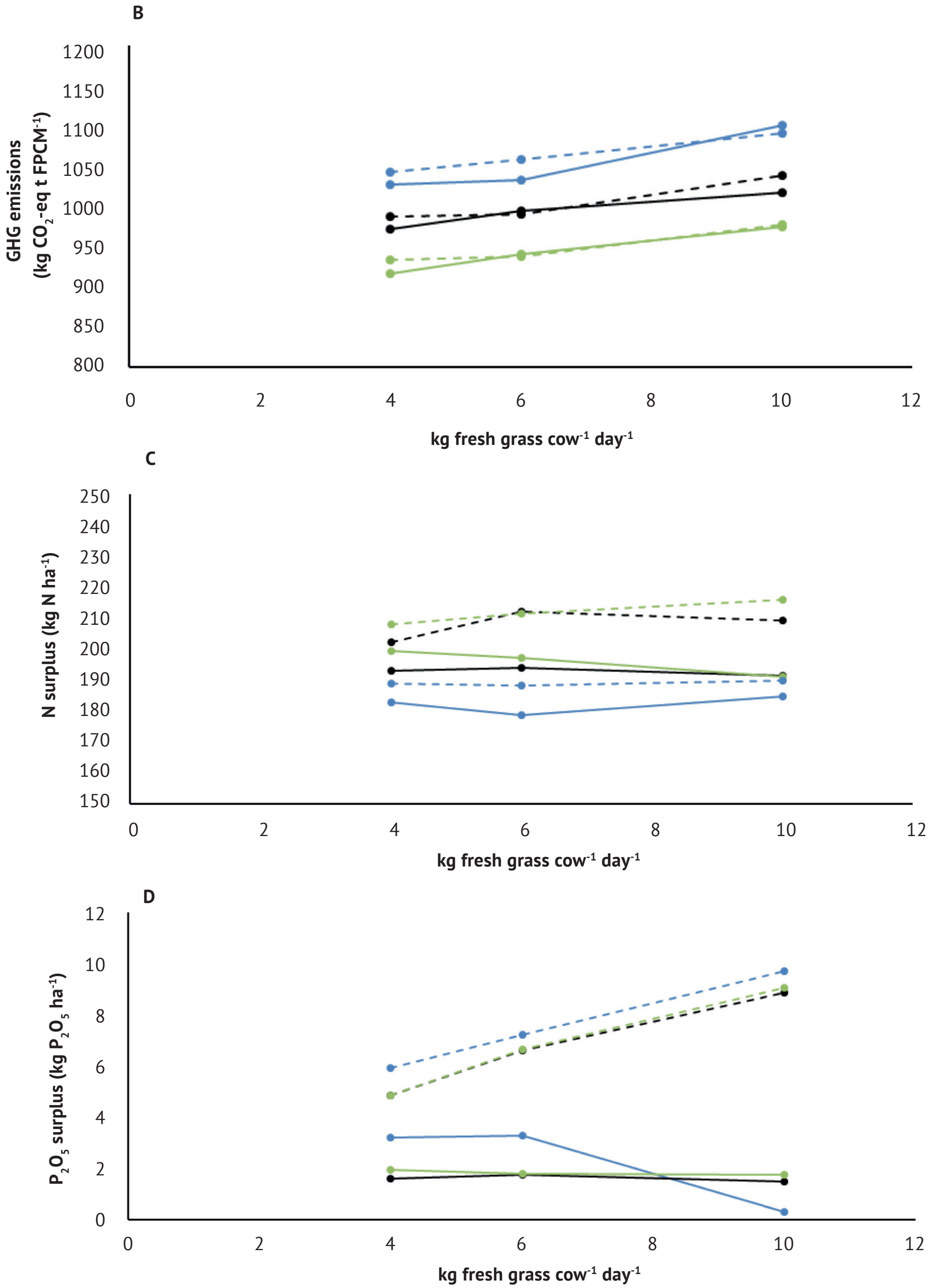


**Figure 1.** *(continued) Economic (panel a) and environmental (panel b-d) consequences of an increase in grazing losses from 16% in the basis situation (solid lines) to 25% under suboptimal grassland utilization (dotted lines) at different milk production levels and at different levels of fresh grass intake. Milk production levels: 7,000 kg cow$^{-1}$ yr$^{-1}$ (**blue**), 8,000 kg cow$^{-1}$ yr$^{-1}$ (**black**), and 9,000 kg cow$^{-1}$ yr$^{-1}$ (**green**).*

Results show that reducing grazing losses through improving grassland utilization is an effective way to improve both the economic and environmental performance of grazing strategies. It should be noted, however, that especially dairy farms with a high share of fresh grass in the diet and a high milk production level per cow can experience difficulties to achieve a high grassland utilization. In general, it is more difficult to motivate dairy cows to graze when they are offered alternative feed indoors. This means that, for example, in practice we might observe the 25% grazing losses at 9,000 kg milk $cow^{-1}$ $year^{-1}$ and 16% grazing losses at 8,000 kg milk $cow^{-1}$ $year^{-1}$, which results in more comparable performance in terms of labour income and GHG emissions across different milk production levels. This can explain why studies based on empirical data, therefore, often show overlap in the economic or environmental performance of different grazing strategies, e.g. Lorenz *et al.* (2019).

## 4 Conclusions

This study showed that increasing daily grazing hours of dairy cows can improve the economic performance of dairy farms, at various levels of milk production. The average increase in income per extra kg dry matter fresh grass $cow^{-1}$ $day^{-1}$ was about €1,000 per year. Increasing grazing hours from 6 to 15h $day^{-1}$, however, also increased greenhouse gas emissions per kg milk by 5-7%, while the area based surplus of N and $P_2O_5$ didn't change substantially. Further evaluation showed that improving grassland utilization is an important step to improve the economic performance of grazing strategies, while reducing the nutrient surplus per hectare of farmland.

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***Acknowledgments***

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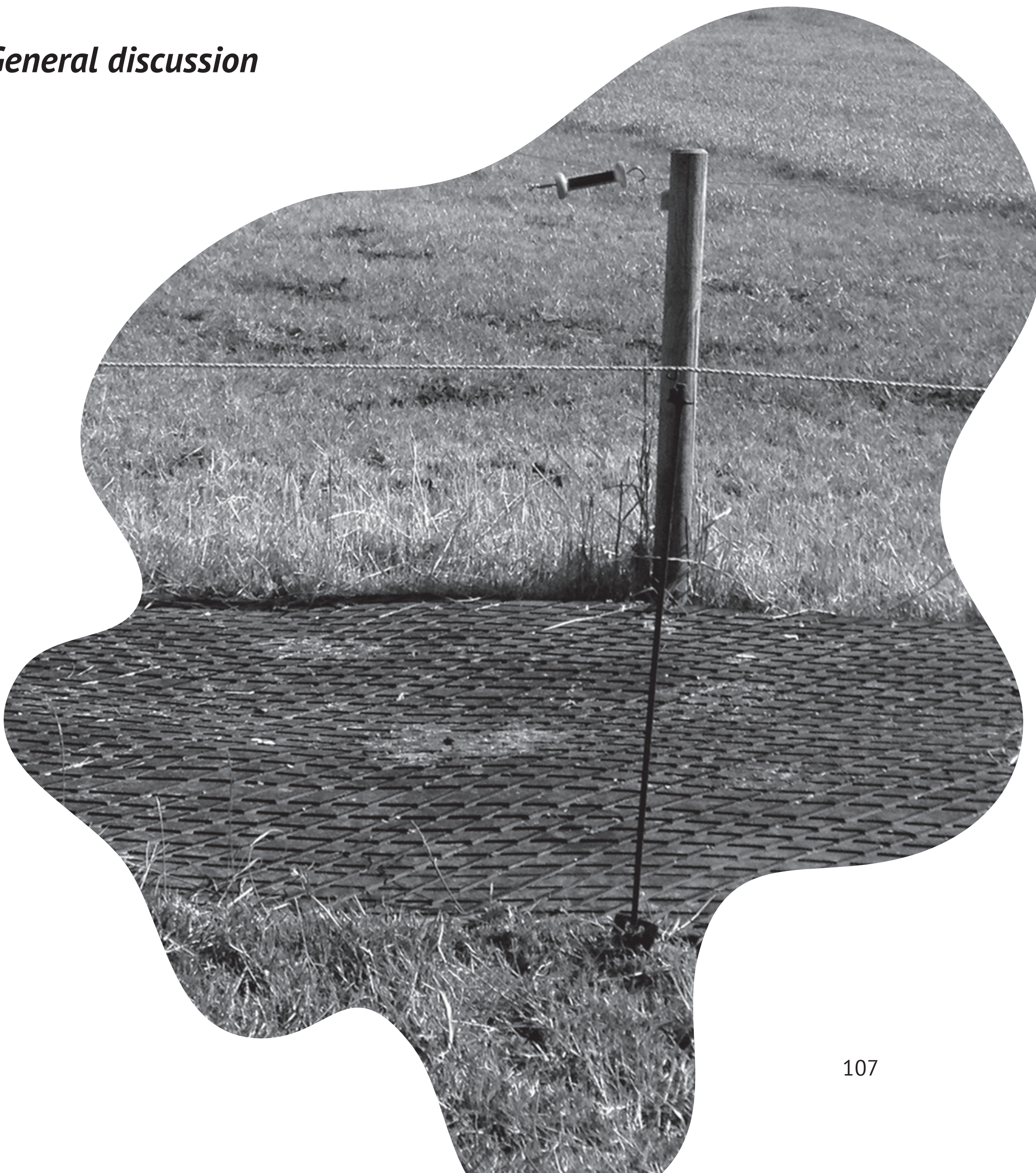
# Chapter 7

## *General discussion*



## 1 Introduction

In response to the rising global demand for food, dairy production systems have been intensified in North-West Europe over the past decades, leading to less grazing and more supplementary feeding. In order to maintain grazing at highly productive dairy farms (i.e. farms with a high stocking density on the available grazing area), farmers start to change from traditional continuous and rotational grazing to compartmented continuous grazing (CCG) and strip grazing (SG) (for a detailed explanation of the systems see page 10). Unlike the traditional grazing systems, CCG and SG are rotational systems in which cows receive a new grazing area each day. Daily rotational systems are hypothesized to increase grass yield, reduce grazing losses from trampling or selective grazing, and reduce clustering of excreta by forcing a more even distribution of manure. Van den Pol-van Dasselaar *et al.* (2014a) indicated the importance of these technical parameters (grass yield, grazing losses and grass utilization) for the sustainability performance of grazing systems. Creighton *et al.* (2011) also highlighted the potential of improved grassland utilization to improve the economic and environmental performance of grazing systems. A complete overview of the interlinked effect of grazing strategies, grassland utilization and cow productivity on the economic and environmental performance of highly productive farms, however, is missing. This lack of knowledge hinders decision-making regarding optimal grazing management. In order to quantify economic and environmental consequences of improved grazing strategies, such as CCG and SG, for dairy farms, we need detailed insights in the technical performance of these systems. The aim of this thesis, therefore, was to quantify the technical performance of improved grazing strategies, such as CCG and SG, in order to determine the economic and environmental consequences for dairy farms.

## 2 Grassland and cow productivity at grazing



Results as described in chapter 3, 4 and 5 were obtained as part of a larger grazing experiment of the project 'Amazing Grazing' at the Dairy Campus, during 2016 and 2017. The Amazing Grazing project aimed to find grazing strategies suitable for highly productive dairy farms (Schils *et al.*, 2018b). Amazing Grazing yielded additional knowledge on grassland and cow productivity which, if relevant, is incorporated into the discussion of the findings in this thesis in the following sections.

### *2.1 Utilizing fresh grass for grazing*

The annual gross grass yield in the grazing experiment at the Dairy Campus with intensive grazing of 7.5 cows $ha^{-1}$ was 10,163 kg dry matter (DM) $ha^{-1}$ for CCG and 11,575 kg DM $ha^{-1}$ for SG ($P = 0.05$). The higher annual gross grass yield for SG was expected and could be explained by a longer grazing interval compared to CCG. These gross grass yields were in the range of simulated Dutch grass yields. Based on an empirical grass growth model, Schils *et al.* (2018a) simulated Dutch yields using 25 years of weather data from five weather stations. For 18 soil types, they found an average annual actual gross grass yield of 10,800 kg DM ha$^{-1}$ in a combined cutting and grazing regime that is common in the Netherlands. Schils *et al.* (2018a) also simulated a water and nutrient-limited potential yield of 12,800 kg DM ha$^{-1}$, indicating that there might be potential to gain even higher grass yields.

In both CCG and SG, fresh grass intake was about 7,800 kg DM ha$^{-1}$ (Holshof *et al.*, 2018), which equalled 77% of the annual gross grass yield for CCG and 67% for SG. This resulted in a fresh grass intake of on average 6 kg DM cow$^{-1}$ day$^{-1}$ and shows that, also with a stocking density of 7.5 cows ha$^{-1}$, it is possible to achieve a substantial fresh grass intake. The additional 23-33% of the annual gross grass yield was cut for silage making and included grazing losses. Grazing losses might result from selective grazing due to manure patches, but also result from inaccurate measurements of daily fresh grass allowance.

In the grazing experiment at the Dairy Campus, we used the rising plate meter to match daily fresh grass allowance with daily cow requirements and feed supplementation (i.e. forage budgeting). The rising plate meter is used in practice to measure grass height before grazing, which is subsequently translated to herbage mass (HM) by using a prediction equation. We have shown that despite relatively large differences in pre- and post-grazing heights and period of regrowth, one region-specific calibration equation can be used across grazing systems (chapter 3). At present, however, farmers do not correct estimates of fresh grass allowance measured with a rising plate meter for the formation of rejected patches (RP) surrounding dung, which can lead to overestimation. In chapter 4, we showed that the average percentage of grassland covered with RP increased from around 22% to around 43% during the grazing season, independent of the grazing system. We, therefore, concluded that the percentage of grassland covered with RP should be subtracted from the total grazed area to better estimate fresh grass allowance. Accurate estimates of fresh grass allowance are essential in daily rotational grazing systems. When there is insufficient fresh grass available in the CCG system, grass height will decrease below the intended 60 mm, implying that less grass is available for the next grazing which increases the need for supplementary feeding. The SG system is even more dependent on accurate estimates of fresh grass allowance, because inaccurate estimates cannot easily be compensated by additional fresh grass intake below 40 mm, but requires additional supplementary feeding.

Clearly, also under intensive grazing, grassland utilization depends on manure patches and the rejected area surrounding these manure patches. The percentage of grassland covered with manure can be influenced by grazing hours and stocking density. As mentioned in chapter 6, we found an average size of manure patches of 0.067 $m^2$, based on surface measurements of 200 manure patches in both CCG and SG (Cindy Klootwijk, unpublished data). On average, a cow defecates 16 times per 24 hours (Aland *et al.*, 2002), which results in about 5 manure patches in the pasture with 8 grazing hours. Per grazing day, therefore, the maximal area covered with manure patches is 0.357 $m^2$ $cow^{-1}$. With a stocking density of 7.5 cows $ha^{-1}$ and 183 grazing days, this results in a maximum area covered with manure patches of 489 $m^2$ per ha, which is only 4.9% of the total grazing area. MacLusky (1960), however, showed that the total area of RP is about six times the area covered with manure patches, implying that the area with RP would equal about 29%. This estimate of 29% is within the range of results in our study. We found a range in percentage of grassland covered with RP from 22 to 43% on fields that were grazed until a maximum of four days before the measurement.

A potential way to reduce grazing losses might be to reduce the size of the rejected area surrounding manure patches. Literature shows that mainly the smell of manure patches affects the rejected area (Verwer *et al.*, 2016). Bosker *et al.* (2002) provided some first indications that feeding strategy might affect the smell of manure patches, and hence the size of RP. The grazing system can also affect the size of RP. First indications, for example, show that the 'Kurzrasen' system, a system with a pre-grazing grass height of 30 to 50 mm, results in smaller RP (Hoekstra *et al.*, 2017). Due to the lower pre-grazing grass height, however, grass yield reduced with 25% compared to SG. These might be interesting topics to explore in future research to further improve grassland utilization under grazing.

### *2.2 Converting fresh grass into milk*

The key challenge of grazing systems is to achieve a high grassland utilization while at the same time maintain milk production levels during the grazing season. For this, it is important to find the correct balance between fresh grass allowance and feed supplementation. An incorrect balance between fresh grass allowance and feed supplementation, namely, not only results in inefficient use of the pasture, but also in a lower feed-efficiency and a potential decrease in milk production. This is especially relevant for highly productive dairy farms with high levels of feed supplementation. It is in fact more difficult to motivate dairy cows to graze when alternative feed is offered. Zom *et al.* (2018) hypothesized that reducing the protein content in concentrates might motivate dairy cows to increase their fresh grass intake, as grass has a high protein content. This hypothesis was based on literature showing that dairy cows are able to balance the rumen degradable protein (RDP) level in their ration (Tolkamp *et al.*, 1998). Results of Zom *et al.* (2018) showed, however, that cows balanced their RDP level by reducing their maize silage intake instead of by increasing their fresh grass intake. This resulted in a lower total DM intake and, subsequently, a lower milk yield. It might be interesting to further explore potential feeding strategies to motivate dairy cows to graze at high levels of feed supplementation. One approach could be to change the time of pasture allocation, as grazing behaviour differs between the morning and late afternoon. Gregorini (2012), for example, showed an increase in nutrient intake and utilization due to pasture allowance during late afternoon instead of morning.

In the grazing experiment, we varied the feed supplementation according to the fresh grass availability. As a result, both the fresh grass intake and the supplementary feed varied throughout the grazing season. Based on this varying diet with an average fresh grass intake of 6 kg DM $cow^{-1}$ $day^{-1}$, we were able to maintain an average milk production of 28.0 kg FPCM $cow^{-1}$ $day^{-1}$ for CCG and 27.4 kg FPCM $cow^{-1}$ $day^{-1}$ for SG, with no significant difference between the two grazing systems. Cows reached this average daily milk production of 27-28 kg FPCM despite indications for a lower nitrogen (N) digestibility of the grass than expected, i.e. the average N digestibility in 2016 was 64% (Klootwijk *et al.*, 2018). This lower N digestibility might have reduced the milk production or increased the need for feed supplementation. Correct insight into N digestibility of grass is essential for optimal grass utilization and nitrogen use efficiency under grazing. The lower N digestibility, however, also might have been due to the measurement method (alkane technique) and in particular to the assumptions related to the recovery rate of the alkanes used to quantify the manure production per cow.

### *2.3 Improving technical performance of grazing*

A balanced diet contributes to both improving grassland utilization and maintaining the desired milk production. To provide a balanced diet that matches daily feed requirements, it is important to know the fresh grass availability. When it comes to grazing in the Netherlands, therefore, an important improvement in practice is to perform grassland production measurements. As mentioned previously, we have shown that farmers can use one generic calibration equation to translate grass height measures from the rising plate meter into fresh grass allowance across grazing systems. In chapter 4, we showed the importance of correcting this estimate of fresh grass allowance for the formation of RP surrounding dung. In chapter 5, we found a more labour-friendly method to quantify fresh grass allowance, which can take into account RP, using drone technology. Due to variability in weather circumstances leading to differences in grass growth, accurate estimates of fresh grass allowance requires weekly measurements. Grassland data can subsequently be used as an input in management programmes like ‘Grip op Gras’, that can assist in choosing which paddocks to use for grazing and which for cutting, and the exact timing of these activities (Stienezen *et al.*, 2018).

## 3 Economic and environmental performance of grazing

### *3.1 Economic and environmental consequences of recent policy changes*

Before focussing on developing key grazing strategies for dairy farms, we first wanted to evaluate the effects of recent policy changes, such as the abolishment of milk quota and new manure policy on farm structure, management, income and environmental impact of an average Dutch dairy farm (chapter 2). To do so, we used a whole-farm optimization model in 2015 to simulate an average farm before and after quota abolition and the introduction of new manure policy. As described in detail in chapter 2, the Dutch manure policy prescribes how dairy farmers should handle their on-farm manure surplus, which comes with costs for disposal, processing and buying or renting extra land. In addition, the Dutch manure policy limits the total on-farm phosphate ($P_2O_5$) production. We estimated that the increase in milk production per ha of Dutch dairy farms would be restricted to 4 to 20% due to the newest Dutch manure policy. Results showed that this increase in farm intensity would slightly increase nutrient losses per hectare. Greenhouse gas emissions per unit of milk would barely change, so at a given milk production per cow, total GHG emissions would increase linearly with an increase in the number of cows. These results indicated that a further intensification of dairy farms would be halted by regulations to reduce the environmental impact of milk production. Today, four years after the abolishment of the milk quota, the total milk production in the Netherlands has indeed stabilised in the range as described in chapter 2.

In chapter 2, we modelled restricted grazing with a maximum daily fresh grass intake during grazing of 10 kg DM cow$^{-1}$ (Taweel *et al.*, 2004; Abrahamse, 2009; Kennedy *et al.*, 2009). The modelling results showed that the fresh grass content in the summer diet was maximized because it was the cheapest feed resource. In this analysis, however, we did not yet analyse the effect of different grazing strategies on the economic and environmental performance of dairy farms. For example, we did not include the effect of different levels of fresh grass intake. In the next section we will elaborate on how we included different grazing strategies in the optimization model and discuss economic and environmental consequences of these grazing strategies for dairy farms.



### *3.2 Economic and environmental consequences of increasing fresh grass intake*

Although multiple studies have mentioned economic and environmental benefits from improved grassland management, a consistent analysis of the interlinked effects of grazing strategy, feed supplementation and milk production on farm profitability and environmental performance was missing. In chapter 6, therefore, we determined economic and environmental consequences of different grazing strategies, defined by a difference in grazing hours per day, at different levels of milk production, for highly productive dairy farms, using empirical data from grazing experiments as described in chapter 2, 3 and 4.

We argued that regardless of the grazing system (i.e. CCG and SG), a key parameter for efficient grassland utilization is fresh grass intake. Based on Philipsen *et al.* (2016), who studied grazing systems for farms with an automated milking system (AMS), we defined three grazing strategies that differ in the amount of daily grazing hours: strategy 1 with 6 grazing hours day$^{-1}$; strategy 2 with 9 grazing hours day$^{-1}$, and strategy 3 with 15 grazing hours day$^{-1}$. The amount of grazing hours determined the maximum fresh grass intake. At farms with an AMS, the average intake is less than 1 kg DM per cow per hour grazing, since cows do not spend all hours of grazing outside as they regularly walk to the AMS. The maximal fresh grass intake, therefore, equalled 4 kg DM cow$^{-1}$ day$^{-1}$ for strategy 1; 6 kg DM cow$^{-1}$ day$^{-1}$ for strategy 2, and 10 kg DM cow$^{-1}$ day$^{-1}$ for strategy 3 (Philipsen *et al.*, 2016). To analyse the effect of milk production, we modelled three different milk yields per cow for all three grazing strategies, i.e. 7,000, 8,000 and 9,000 kg cow$^{-1}$ yr$^{-1}$, with a fat content of 4.4% and a protein content of 3.5%. As mentioned before, we found that also under intensive grazing, grassland utilization depends on manure patches and the rejected area surrounding these manure patches. Therefore, we incorporated the relation between manure patches, i.e. being dependent on the number of cows and hours of grazing, and grazing losses, i.e. resulting from grass rejection surrounding these patches.

Results showed that increasing fresh grass intake of dairy cows can improve the economic performance of dairy farms, at various levels of milk production. The average increase in income per extra kg dry matter fresh grass cow$^{-1}$ day$^{-1}$ was about €1,000 per year. We did not find a clear effect of fresh grass intake on the nitrogen and phosphorus surpluses ha$^{-1}$. The GHG emissions per kg of FPCM (i.e. further referred to as GHG intensity), on the other hand, increased with about 5-7% across production levels when increasing the share of fresh grass in the diet from 4 to 10 kg DM cow$^{-1}$ day$^{-1}$. This can be explained by an increase in emissions from manure due to a larger share of manure deposited during grazing, contributing to $N_2O$ emissions, while emissions from enteric fermentation increases with an increasing share of fresh grass in the diet. These results show a trade-off between economic benefit and GHG emissions with an increase in fresh grass intake.

Like Meul *et al.* (2012), we also found that an increase in milk production per cow increased labour income per farm and nutrient surpluses per ha, but reduced GHG intensity. The latter results from the dilution of emissions related to maintenance (i.e. emissions are diluted over a higher amount of milk). Moreover, comparing GHG emissions across milk production levels also implies that we have to handle differences in ratio of milk over meat production. We used economic allocation to attribute GHG emissions to milk production, which favours GHG intensity of high producing cows (Zehetmeier *et* *al.*, 2012). If we would have used system expansion, the GHG intensity might not be that different across different milk production levels, especially when producing meat with potential to substitute beef produced by beef cattle.

### *3.3 Economic and environmental consequences of grazing losses*

Several studies hypothesized that grazing losses influence both the economic and environmental consequences of grazing strategies (Creighton *et al.*, 2011; Van den Pol-van Dasselaar *et al.*, 2014a). Increasing grazing losses from 16 to 25% resulted in an increase in the area per cow used to produce grass for grazing, which equalled a decrease in stocking density from 8.8 to 7.3 cows $ha^{-1}$ for 6 hours of grazing per day, from 5.9 to 4.9 cows $ha^{-1}$ for 9 hours of grazing per day and from 3.5 to 2.9 cows $ha^{-1}$ at 15 hours of grazing per day, regardless of milk production level. These results show that at similar grass intake, the number of cows that can be fed on the same grazing area decreases with about 20% when grazing losses increase from 16 to 25%.

Increasing grazing losses from 16% to 25%, as a measure for the effectiveness of grassland utilization, resulted in a decrease in labour income varying from €4,056 (9,000 kg milk $cow^{-1}$ $yr^{-1}$) to €7,189 (8,000 kg milk $cow^{-1}$ $yr^{-1}$) going from strategy 1 (6h of grazing $day^{-1}$) to strategy 3 (15h of grazing $day^{-1}$). The GHG emission intensity slightly increased (1% on average) with an increase in grazing losses, mainly due to an increasing reliance on off-farm feed. Similarly, the N (7% on average) and $P_2O_5$ (680% on average) surpluses per ha increased after increasing the grazing losses. These results show that improving grassland utilization is an important step to improve the economic and environmental performance of grazing strategies.

## 4 Key to sustainable grazing

Overall, we have shown that improving grassland utilization by using grazing systems such as CCG and SG can increase labour income, while at the same time decrease the nutrient surplus per ha of farmland, and the GHG intensity. It should be noted that especially dairy farms with high milk production and supplementary feeding levels experience difficulties to achieve a high grassland utilization in practice. As mentioned before, it is more difficult to motivate dairy cows to graze when they are offered alternative feeds indoors. This might explain why grazing systems in practice show comparable performances in terms of labour income and GHG emissions despite differences in the share of fresh grass in the diet. Our grazing experiment linked most closely to grazing strategy 2 of chapter 6, with a fresh grass intake of around 6 kg DM $cow^{-1}$ $day^{-1}$ and a stocking density of 7.5 cows $ha^{-1}$. Results showed that it is possible to achieve a substantial fresh grass intake at this high stocking density with both the

CCG and the SG system. In addition, we found no significant differences in average fresh grass intake and milk production between CCG and SG. Abrahamse *et al.* (2008) showed that fresh grass intake and milk production can be simultaneously increased by applying a daily rotation instead of a four-day rotation, which underlines the benefits of CCG and SG in terms of grassland utilization compared to traditional rotational grazing systems. Since CCG requires less labour this system shows to be a promising strategy to balance grassland utilization and labour input.

Although the daily rotational grazing systems were designed to match daily fresh grass allowance with feed requirements and reduce selective grazing by limiting the daily grazing area, grazing losses were still substantial and did not differ between the systems. According to our hypothesis, the grass yield was indeed higher for SG compared to CCG. This higher yield, however, did not result in a higher fresh grass intake in the SG system, which might have been due to inaccurate estimates of fresh grass allowance because of RP, which is especially relevant in SG (see chapter 4). Especially in these daily rotational systems that are designed to improve grassland utilization, correctly matching daily fresh grass allowance with feed requirements is essential for good grazing management. Interestingly, we found a higher DM yield in the stubble for CCG compared to SG. This might not immediately be beneficial for grazing, but a denser sward, for example, might improve the carrying capacity of the soil during wet circumstances and prevent trampling damage and associated grazing losses. Furthermore, it might result in the possibility to start grazing earlier in spring and to end grazing later in autumn, leading to an extended grazing season and an associated increased annual fresh grass intake. Clearly, not only the grazing system but also the grazing management is essential to increase grassland utilization.

We however also found a clear relation between the area based nutrient surplus and farm intensity (kg milk $ha^{-1}$). The higher the farm intensity, the larger the dependency on off-farm feed products, and the higher the nutrient surpluses and, therefore, potential nutrient losses, per ha. This dependency on off-farm feed products moreover potentially introduces feed-food competition, since the current concentrates contain ingredients that are also edible by humans. Van Zanten *et al.* (2016) argue that farm animals should not consume human-edible feed, but convert grass biomass and by-products from the food system into valuable food, manure and other ecosystem services. In this way, we value the potential of ruminants to convert biomass which is not edible for humans into high quality food products thereby contributing to net food security. By converting grass products and by-products from the food system, ruminants recycle biomass and nutrients into the food system, that otherwise would have been lost for food production (van Zanten *et al.*, 2016).

The Dutch dairy sector also increasingly values this role of dairy cows in the circular food system, and, therefore, focusses on strategies to reduce feed supplementation levels. The sector has formulated goals related to the source of feed for dairy farms (Commissie grondgebondenheid, 2018). In 2025, dairy farmers should produce 65% of the protein in their feed on own land or land close by the farm, and reduce off-farm feed inputs by two-thirds. In addition, the grazing area near the farm should provide sufficient possibility for grazing. Several actors of the dairy chain, including companies, government and community organisations, moreover set the goal that at least 81.2% of the Dutch dairy farms should graze in 2020, due to the large social demand for grazing related to the typical Dutch landscape and the image of the Dutch dairy sector (Boogaard *et al.*, 2010).

Grass yields and utilization, therefore, are key parameters for our future dairy sector. Feeding mainly grass biomass and co-products to ruminants, however, also requires a transition towards lower average annual milk production levels. Lower average milk production levels per ha of land might open doors to combine milk production with other ecosystem services, such as biodiversity conservation. In chapter 6, we showed that reduced milk production levels have a financial trade-off and, therefore, provision of other ecosystem services like biodiversity conservation requires a financial reward system for farmers. In our search towards sustainable grazing, therefore, we might need to also include other functions of grassland, and explore the value of mixing grasses in time and space.

## 5 Conclusions

This study provides an overview of the interlinked effects of grazing strategies, grass-land utilization and cow productivity on the economic and environmental performance of highly productive dairy farms. Overall, we showed in a grazing experiment that it is possible to achieve substantial fresh grass intake at high stocking densities, while maintaining high milk production levels. Both CCG and SG proved suitable systems for highly productive dairy farms with a high stocking density on the available grazing area. According to our hypothesis grass yield was indeed high for SG than for CCG. This higher grass yield, however, did not results in a higher fresh grass intake, which might have been due to inaccurate estimates of fresh grass allowance because of RP, which is especially relevant in SG. CCG was less labour intensive due to fixed fencing. Since fresh grass intake and milk production level were not significantly different for the two systems, CCG is a promising strategy to balance grassland utilization and labour input.



Our modelling results showed that increasing fresh grass intake of dairy cows can improve the economic performance of dairy farms, at various levels of milk production. The average increase in income per extra kg dry matter (DM) fresh grass cow$^{-1}$ day$^{-1}$

was about €1,000 per year. Increasing fresh grass intake from 4 to 10 kg DM $cow^{-1}$ $day^{-1}$, however, also increased greenhouse gas emissions per kg milk by 5-7%, while the nutrient surplus $ha^{-1}$ hardly changed. Reducing grazing losses, furthermore, has the potential to improve both the economic and the environmental performance of dairy farms.

Although daily rotational grazing systems have been designed to improve grass utilization, and hence reduce grazing losses, grazing losses were still substantial and did not differ between CCG and SG. Accurate grassland measurement, therefore, remains important in order to match fresh grass allowance with supplementary feeding and feed requirements in daily rotational systems.

We also found that farms with a higher milk production per hectare purchased more off-farm feed, and had a higher nutrient surplus per ha of land. This dependency on off-farm feed potentially introduces feed-food competition. Moreover, reducing grazing losses might become more difficult with high levels of stocking density and feed supplementation, since it is more difficult to motivate dairy cows to graze when they are offered alternative feeds indoors. These arguments are in favour of feeding less concentrates, but mainly grass biomass and by-products to ruminants. Besides food production, other non-provisional ecosystem services of grasslands need to be included in our context-specific choice for a grazing system. In our search towards sustainable grazing, therefore, we need to also include these other functions of grassland, and explore the value of mixing grasses in time and space.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# Summary

In order to maintain grazing at highly productive dairy farms (i.e. farms with a high stocking density on the available grazing area), farmers start to change from traditional continuous and rotational grazing systems to compartmented continuous grazing (CCG) and strip grazing (SG). Unlike the traditional grazing systems, CCG and SG are grazing systems in which cows receive a new grazing area each day. Daily rotational systems are hypothesized to increase grass yield, reduce grazing losses from trampling or selective grazing, and reduce clustering of excreta by forcing a more even distribution of manure.

A complete overview of the interlinked effects of grazing strategies, grassland utilization and cow productivity on the economic and environmental performance of highly productive farms was missing. This lack of knowledge hinders decision-making regarding optimal grazing management. In order to quantify economic and environmental consequences of improved grazing strategies, such as CCG and SG, we need detailed insights in the technical performance of these systems. The aim of this thesis, therefore, was to quantify the technical performance of improved grazing systems, such as CCG and SG, in order to determine the economic and environmental consequences for dairy farms.

To determine the economic and environmental consequences of improved grazing strategies, two building blocks were required. First, I needed insight into the effect of recent policy changes, such as the abolishment of milk quota and new manure policy, on farm structure, management, income and environmental impact. To do so, we used an optimization model that combines bio-economic optimization modelling and life cycle assessment modelling and used the Netherlands as a case study (chapter 2). In chapter 2, we showed that the new manure policy will likely limit farm expansion of Dutch dairy farms up to an increase in milk production per ha of 4 to 20%, mainly due to additional costs of manure processing, land purchases, and phosphate quota. Labour income as well as environmental impacts can increase slightly due to this increase in farm intensity.

Second, I needed insight in the technical performance of grazing strategies. These technical data were collected in a large grazing experiment as part of the project 'Amazing Grazing'. This grazing experiment aimed at quantifying technical performance of CCG and SG for farms with a high stocking density (7.5 cows $ha^{-1}$) on the grazing area. For this thesis, we focused on measurements related to grass yield, grazing losses and grass utilization since we hypothesized that these technical parameters influence both the economic and environmental performance of grazing systems.

In chapter 3, we analysed the effect of grazing system on the rising plate meter calibration for herbage mass. The rising plate meter is used to measure grass height, which subsequently is used in a calibration equation to estimate herbage mass, being

an important parameter to optimize feed management in grazing systems. Our results indicate that, despite relatively large differences in pre- and post-grazing heights and period of regrowth, one region-specific calibration equation can be used across grazing systems.

When estimating fresh grass allowance, dairy farmers currently do not correct for the formation of rejected patches (RP) surrounding dung, which can lead to overestimation. Also under intensive grazing, grassland utilization depends on manure patches and the rejected area surrounding these manure patches. In chapter 4, we showed that the average percentage of grassland covered with RP increased from around 22% to around 43% during the grazing season, irrespective of the grazing system being CCG and SG. The percentage of grassland covered with RP should be subtracted from the total grazed area to better estimate fresh grass allowance.

In chapter 5, we demonstrated the potential of a relatively easy method to identify RP for two intensive grazing systems based on spectral images. By subtracting the surface covered with RP from the total area available for grazing, fresh grass allowance can be corrected for selective grazing. Results provide first indications that the Normalised Difference Vegetation Index (NDVI) could be used to quantify fresh grass allowance for grazing, but further research is necessary to explore the relation between NDVI and herbage mass under grazing management. Drone technology might be an interesting strategy to reduce labour related to grassland measurements.

Overall, we showed in the grazing experiment that it is possible to achieve substantial fresh grass intake at high stocking densities, while maintaining high milk production levels. Both CCG and SG proved suitable systems for highly productive dairy farms. According to our hypothesis, the grass yield was indeed higher for SG compared to CCG. This higher yield, however, did not result in a higher fresh grass intake in the SG system, which might have been due to inaccurate estimates of fresh grass allowance because of RP, which is especially relevant in SG. CCG was less labour intensive due to fixed fencing. Since fresh grass intake and milk production levels were not significantly different for the two systems, CCG is a promising strategy to balance grassland utilization and labour input.

The technical data as collected during the grazing experiment, together with already existing literature, fed into the model as used for chapter 2 and results were discussed in chapter 6. We showed that increasing fresh grass intake of dairy cows can improve the economic performance of dairy farms, at various levels of milk production. The average increase in income per extra kg dry matter (DM) fresh grass $cow^{-1}$ $day^{-1}$ was about €1,000 per year. Increasing fresh grass intake from 4 to 10 kg DM $cow^{-1}$ $day^{-1}$, however, also increased greenhouse gas emissions per kg milk by 5-7%, while the nutrient surplus per ha of land hardly changed. Reducing grazing losses furthermore has the potential to improve both the economic and the environmental performance of dairy farms.

Although daily rotational grazing systems have been designed to improve grassland utilization, and hence grazing losses, grazing losses were still substantial and did not differ between CCG or SG. Accurate grassland measurement remains important in order to match fresh grass allowance with supplementary feeding and feed requirements in daily rotational grazing systems.

We also found that farms with a higher milk production per hectare purchased more off-farm feed, and had a higher nutrient surplus per ha of land. This dependency on off-farm feed potentially introduces feed-food competition. Moreover, reducing grazing losses might become more difficult with high levels of stocking density and feed supplementation, since it is more difficult to motivate dairy cows to graze when they are offered alternative feeds indoors. These arguments are in favour of feeding less concentrates, but mainly grass biomass and by-products to ruminants. Besides food production, other non-provisional ecosystem services of grasslands need to be included in our context-specific choice for a grazing system. In our search towards sustainable grazing, therefore, we need to also include these other functions of grassland, and explore the value of mixing grasses in time and space.

S

## Samenvatting

Om weidegang op hoogproductieve melkveebedrijven te behouden (i.e. bedrijven met een hoge veedichtheid op het beweidbaar oppervlak), schakelen veehouders over van traditioneel standweiden en omweiden naar systemen als roterend standweiden (RS) en strip grazen (SG). In tegenstelling tot de traditionele systemen, krijgen koeien bij RS en SG dagelijks vers gras aangeboden. De hypothese is dat het dagelijks aanbieden van vers gras de grasopbrengst verhoogt, beweidingsverliezen door vertrapping en selectief grazen verlaagt en clustering van mest en urine vermindert door geforceerde verspreiding. Er mist echter volledig overzicht van de samenhangende effecten van beweidingsstrategieën, graslandbenutting en melkproductie op de economische- en milieutechnische prestatie van hoogproductieve bedrijven. Gebrek aan kennis maakt het voor veehouders lastig keuzes te maken aangaande een optimaal beweidingsmanagement. Om de economische- en milieutechnische prestatie van nieuwe beweidingsstrategieën, zoals RS en SG, te kunnen doorrekenen, is kennis over het technische resultaat van nieuwe beweidingsstrategieën nodig. Het doel van dit onderzoek is het kwantificeren van het technische resultaat van nieuwe beweidingsstrategieën, zoals RS en SG, om zo de economische en milieutechnische prestatie door te kunnen rekenen.

Hiervoor waren twee bouwstenen nodig. Allereerst moest inzicht verkregen worden in het effect van recente veranderingen in de wetgeving (zoals het afschaffen van het melkquotum en de nieuwe mestwetgeving) op de bedrijfsstructuur, het management, het inkomen van veehouders en het milieu. Hiervoor is een optimalisatiemodel gebruikt waarin bio-economisch modelleren wordt gecombineerd met een levenscyclusanalyse, met Nederland als testcase (hoofdstuk 2). Met behulp van het optimalisatiemodel hebben we aangetoond dat de nieuwe mestwetgeving een verdere schaalvergroting van Nederlandse melkveebedrijven zal beperken tot een groei in bedrijfsintensiteit van ongeveer 4 tot 20% in melkproductie per hectare. Deze beperking wordt voornamelijk veroorzaakt door extra gemaakte kosten gerelateerd aan mestverwerking, aankopen van extra land en het fosfaatquotum. Bij een bovengenoemde groei in bedrijfsintensiteit kunnen ook het arbeidsinkomen en de milieu-impact een lichte stijging vertonen.

Ten tweede, hadden we inzicht nodig in het technische resultaat van beweidingsstrategieën. Deze data hebben we verzameld met behulp van een omvangrijke beweidingsproef, onderdeel van het project 'Amazing Grazing'. Het doel van de beweidingsproef was het kwantificeren van het technische resultaat van RS en SG, voor bedrijven met een veedichtheid van 7.5 koe ha$^{-1}$ beweidbaar oppervlak. Onze hypothese is dat graslandopbrengst, graslandbenutting en beweidingsverliezen zowel de economische- alsook de milieutechnische prestatie beïnvloeden. Om die reden hebben we voor dit proefschrift gefocust op metingen gerelateerd aan bovengenoemde, technische parameters.

In hoofdstuk 3 hebben we getoetst of het type beweidingssysteem effect heeft op de kalibratie van de grashoogtemeter om beschikbare biomassa voor beweiding te schatten. Met de grashoogtemeter worden grashoogtes gemeten. Vervolgens wordt middels een kalibratieformule een schatting gemaakt van de beschikbare biomassa, een belangrijke parameter in de optimalisatie van het voermanagement van beweidingssystemen. Onze resultaten laten zien dat, ondanks relatief grote verschillen in grashoogte voor- en na beweiden, en verschillen in de periode van hergroei tussen de beweidingssystemen, er één regiospecifieke kalibratieformule gebruikt kan worden voor verschillende beweidingssystemen.

In de huidige praktijk corrigeren melkveehouders veelal niet voor bosvorming rondom mestplekken bij het schatten van het grasaanbod. Bosvorming ontstaat doordat koeien selectief grazen rondom mestplekken door een afkeur voor de mestgeur. De totale hoeveelheid vers gras die daadwerkelijk beschikbaar is voor beweiding kan hierdoor makkelijk overschat worden. In hoofdstuk 4 laten we zien dat voor zowel RS als SG, het gemiddelde percentage met bossen bedekt grasland gedurende het beweidingsseizoen toeneemt van circa 22% naar 43%. Om tot een realistischere inschatting te komen van het beschikbare grasaanbod, moet het percentage met bossen bedekt grasland in mindering gebracht worden op het totale beweidingsoppervlak.

In hoofdstuk 5 demonstreren we de potentie van het kwantificeren van bosvorming rondom mestplekken met behulp van multispectraal beelden. Deze beelden gebruikten we om de Normalised Difference Vegetation Index (NDVI) te berekenen; een maat voor biomassa. Onze resultaten vormen een eerste indicatie dat de Normalised Difference Vegetation Index (NDVI) gebruikt kan worden om vers grasaanbod voor beweiding te kwantificeren. Vervolgonderzoek naar de relatie tussen de NDVI en biomassa is echter nodig bij verschillende variaties op het beweidingsmanagement. Tevens kan de inzet van drones de arbeidsintensiteit van graslandmanagement verminderen.

In ons beweidingsexperiment hebben we aangetoond dat het mogelijk is om, met behoud van hoge melkproductieniveaus, een substantiële vers grasopname te behalen bij een hoge veedichtheid op het beweidbaar oppervlak. Zowel RS als SG zijn daarmee geschikt bevonden voor hoogproductieve melkveebedrijven. In lijn met onze hypothese ontdekten we tevens dat de grasopbrengst bij SG hoger was dan bij RS. De hogere opbrengst in het SG-systeem leidde echter niet tot een hogere vers grasopname. Dit kan mogelijk verklaard worden doordat bij de inschatting van het grasaanbod niet gecorrigeerd is voor bosvorming rondom mestplekken; een probleem wat met name bij het SG-systeem speelt. RS is door de aanwezigheid van vaste omheining echter arbeidsextensiever. Doordat de vers grasopname en de melkproductie tussen de verschillende beweidingssystemen niet significant verschilde, is RS een veelbelovende strategie om graslandbenutting en arbeid te optimaliseren.

De technische data verzameld tijdens de beweidingsproef vormden, samen met bestaande literatuur, input voor het model zoals gebruikt in hoofdstuk 2. De resultaten van het model worden besproken in hoofdstuk 6. We hebben voor verschillende melkproductieniveaus aangetoond dat een hogere vers grasopname de economische prestatie van melkveebedrijven kan verbeteren. De gemiddelde inkomenstoename per extra kg drogestof (DS) vers grasopname per koe per dag was ongeveer €1.000 per jaar. Een toename in vers grasopname van 4 naar 10 kg DS koe$^{-1}$ dag$^{-1}$ leidde echter ook tot een toename in broeikasgasemissies van 5-7% per kg melk. Het nutriëntenoverschot per hectare land veranderde nauwelijks. Verlagen van beweidingsverliezen heeft echter de potentie om zowel de economische- als de milieutechnische prestatie van melkveebedrijven te verbeteren.

Ondanks het feit dat beweidingssystemen waarbij koeien dagelijks vers gras krijgen aangeboden speciaal zijn ontwikkeld om de graslandbenutting te verbeteren, en daarmee beweidingsverliezen te verlagen, zijn de beweidingsverliezen nog altijd substantieel. Het is daarom van belang, om ook in beweidingssystemen met dagelijks vers grasaanbod nauwkeurige graslandmetingen uit te voeren. Dit om het grasaanbod af te kunnen stemmen op de bijvoeding en de voederbehoeften van het vee.

Onze resultaten tonen bovendien aan, in lijn met de literatuur, dat bedrijven met een hogere melkproductie per hectare, meer voer aankopen en een hoger nutriëntenoverschot hebben per hectare land dan melkveehouders die per hectare minder melk produceren. De afhankelijkheid van aangekocht voer introduceert een mogelijke voer/voedselcompetitie. Daarnaast is het verlagen van beweidingsverliezen mogelijk moeilijker bij een hogere veebezetting en bij een hoog bijvoedingsniveau. Koeien zijn immers lastiger te motiveren om te grazen wanneer zij op stal alternatief voer ter beschikking hebben. Deze argumenten pleiten ervoor minder krachtvoer aan te wenden en het gebruik van gras-en bijproducten voor herkauwers te stimuleren. Naast voedselproductie zijn er ook nog andere niet-voergerelateerde ecosysteemdiensten die meegenomen dienen te worden in de keuze voor een contextspecifiek beweidingssysteem. We adviseren daarom in de zoektocht naar duurzamere beweiding andere graslandfuncties mee te nemen en de waarde van het mengen van grassoorten in tijd en ruimte verder te exploreren.

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## About the author

Cindy Klootwijk was born on the 17th of September 1991 in Roermond, the Netherlands. She obtained her BSc degree (2012) and MSc degree (2014) in Animal Sciences from Wageningen University (both Cum Laude).

During her study, she specialized in sustainability assessment of animal production systems at the Animal Production Systems (APS) group of Wageningen University & Research. For her BSc thesis at APS, she investigated ways to reduce the assessment time of the Welfare Quality protocol to assess the on-farm welfare of dairy cows. For her MSc thesis at APS, she developed a novel approach to assess efficiency of land use by livestock to produce human food. For a second MSc thesis, she assessed the nitrogen and phosphorus use efficiency on dairy farms (Farming Systems Ecology group, Wageningen University & Research). For her internship, she studied the nutritional value and environmental impact of black soldier fly (Hermetia illucens) prepupae as an alternative protein source for animal feed (Faculty of Bioscience Engineering, Ghent University, Belgium).

After graduation, Cindy started her PhD at APS. Her research focussed on assessing the economic and environmental performance of grazing strategies for dairy farms. This required the collection of grassland data in a grazing experiment at Dairy Campus (Leeuwarden, the Netherlands), for which she collaborated with the 'Amazing Grazing' project. She was awarded with the Stapledon Memorial Trust to attend the European Grassland Federation (EGF) conference in 2015 and 2018.

Cindy is currently working at the Animal Nutrition department of Wageningen Livestock Research as researcher grassland, forages and grazing.

# Publications

## Refereed scientific journals

H.H.E. Van Zanten, H. Mollenhorst, **C.W. Klootwijk**, C.E. Van Middelaar, I.J.M. De Boer. 2015. Global food supply: land use efficiency of livestock systems. Int J of Life Cycle Assess 21:747–758. doi.org/10.1007/s11367-015-0944-1

**C.W. Klootwijk,** C.E. Van Middelaar, P.B.M. Berentsen and I.J.M. De Boer. 2016. Dutch dairy farms after milk quota abolition: Economic and environmental consequences of a new manure policy. J. Dairy Sci. 99:8384–8396. doi.org/10.3168/jds.2015-10781

T. Spranghers, M. Ottoboni, **C.W. Klootwijk**, A. Ovyn, S. Deboosere, B. De Meulenaer, J. Michiels, M. Eeckhout, P. De Clercq and S. De Smet. 2016. Nutritional composition of black soldier fly (Hermetia illucens) prepupae reared on different organic waste substrates. J. Sci. Food Agric. doi.org/10.1002/jsfa.8081

**C.W. Klootwijk**, G. Holshof, K. Van Helvoort, A. Van den Pol-Van Dasselaar, C.E. Van Middelaar and I.J.M. De Boer. 2018. The effect of grazing system on the rising plate meter calibration for herbage mass. J. Dairy Sci. Submitted

**C.W. Klootwijk**, G. Holshof, A. Van den Pol-Van Dasselaar, C.E. Van Middelaar and I.J.M. De Boer. 2018. Correcting fresh grass allowance for selective grazing of dairy cows in intensive grazing systems. J. Dairy Sci. Submitted

## Abstracts in conference proceedings

H. Mollenhorst, **C.W. Klootwijk**, C.E. Van Middelaar, H.H.E. Van Zanten and I.J.M. De Boer. 2014. A novel approach to assess efficiency of land use by livestock to produce human food. In: Book of Abstracts of the 65th Annual Meeting of the European Federation of Animal Science, Wageningen, The Netherlands.

H. Mollenhorst, **C.W. Klootwijk**, C.E. Van Middelaar, H.H.E. Van Zanten and I.J.M. De Boer. 2014. A novel approach to assess efficiency of land use by livestock to produce human food. Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector, LCA Food 2014, San Francisco, California, USA.

**C.W. Klootwijk**, C.E. Van Middelaar, A. Van den Pol-Van Dasselaar, P.B.M. Berentsen and I.J.M. De Boer. 2015. The economic and environmental performance of grazing and zero-grazing systems in a post-quota era. In: Book of abstracts of the 66th Annual Meeting of the European Federation of Animal Science, Warschau, Polen.

**C.W. Klootwijk**, C.E. Van Middelaar, A. Van den Pol-Van Dasselaar, P.B.M. Berentsen and I.J.M. De Boer. 2016. The effect of grass yield on economic and environmental performance of dairy farms. In: Book of abstracts of the 67th Annual Meeting of the European Federation of Animal Science, Belfast, UK.

C.E. Van Middelaar, **C.W. Klootwijk**, P.B.M. Berentsen and I.J.M. De Boer. 2016. Economic and environmental consequences of milk quota abolition in the Netherlands. In: Book of abstracts of the 67th Annual Meeting of the European Federation of Animal Science, Belfast, UK.

## Refereed conference paper

**C.W. Klootwijk**, R.L.G. Zom, A. Van den Pol-Van Dasselaar, C.E. Van Middelaar, G. Holshof and I.J.M. De Boer. 2018. Amazing Grazing; N use efficiency of sixty individual dairy cows under intensive grazing. Pages 81-83 in Proc. Grassland Science in Europe 23.

G. Holshof, R.L.G. Zom, A.P. Philipsen, A. Van den Pol-Van Dasselaar and **C.W. Klootwijk**. 2018. Amazing grazing; Substantial fresh grass intake in restricted grazing systems with high stocking rates. Pages 234-236 in Proc. Grassland Science in Europe 23.

R.L.M. Schils, A.P. Philipsen, G. Holshof, R.L.G. Zom, I.E. Hoving, C.G. Van Reenen, J.T.N. Van der Werf, P.J. Galama, L. Sebek, **C.W. Klootwijk**, N.J.M. Van Eekeren, N.J. Hoekstra, M.W.J. Stienezen and A. Van den Pol-Van Dasselaar. 2018. Amazing Grazing; science in support of future dairy systems. Pages 336-338 in Proc. Grassland Science in Europe 23.

## Other publications

P.B.M. Berentsen, **C.W. Klootwijk**, C.E. Van Middelaar and I.J.M. De Boer. 2015. Fosfaatrechten vormen pas een barrière om uit te breiden wanneer mestverwerking of grond goedkoper worden - Uitbreiden ondanks nieuwe wetgeving? Veeteelt, 02-11-2015.

# Education certificate

Completed training and supervision plan[1]

| **The basic package** | **3 ECTS** |
|---|---|
| WIAS Introduction day | 2014 |
| Course philosophy of science and/or ethics | 2014 |
| Course essential skills | 2014 |
| **Disciplinary competences** | **11 ECTS** |
| Writing research proposal | 2014-2015 |
| Course design of experiments | 2015 |
| Course environmental impact assessment of livestock systems | 2015 |
| Course orientation on mathematical modelling in biology | 2016 |
| Course shaping future animal systems | 2017 |
| Course grazing management techniques (Teagasc, Ireland) | 2018 |
| **Professional competences** | **9 ECTS** |
| Workshop Bas Haring | 2013 |
| Course effective behaviour in your professional surroundings | 2013 |
| Autumn school valorisation of your research | 2013-2014 |
| Chairing WIAS Science Day committee & member of WAPS council | 2013 |
| Organising PhD course shaping future animal systems | 2013 |
| Course supervising MSc thesis work | 2014 |
| Course scientific writing | 2014 |
| **Presentation skills** | **4 ECTS** |
| Poster, WIAS Science day, Wageningen, the Netherlands | 2015-2016 |
| Theatre, EAAP, Warschau, Poland | 2015 |
| Theatre, EAAP, Belfast, United Kingdom | 2016 |
| Theatre, EGF, Cork, Ireland | 2018 |
| Theatre, WIAS Science Day, Wageningen, the Netherlands | 2019 |
| **Teaching competences** | **6 ECTS** |
| Supervision practicum students 2 courses | 2016-2017 |
| Supervision 2 BSc & 3 MSc thesis students | 2016-2017 |
| **Education and training total** | **33 ECTS** |

[1]With the educational activities listed, the PhD candidate has complied with the educational requirements set by the graduate school Wageningen Institute of Animal Sciences (WIAS) of Wageningen University & Research. One ECTS equals a study load of 28 hours.

**Colophon**
The research presented in this thesis is part of a research programme which is financed by the Province of Fryslân and Melkveefonds (LTO and Wageningen University & Research). In addition, this work was carried out within the framework of the Amazing Grazing project (www.amazinggrazing.eu), which is financed by ZuivelNL, LTO, NZO and the Dutch Ministry of Agriculture, Nature and Food Quality.

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