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Finding graze time - combining grazing with automatic milking

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Abstract

The introduction of automatic milking systems (AMS) within European dairy farming in the past decades has been accompanied by a decline in grazing and in time spent outdoors by dairy cows. Grazing is a natural behaviour of cattle, and the opportunity to go outdoors is often considered a component of animal welfare. Grazing ruminants can also utilise land unsuitable for human food production, while supplying ecosystem services such as maintaining biodiversity and increasing carbon sequestration. Thus many stakeholders in society want farmers to retain dairy management systems that include grazing. Pasture availability and nutritive quality can fluctuate considerably during the grazing season. This variation, together with lack of accurate methods for cow-side pasture dry matter intake determination as decision support for supplementary feeding, can compromise nutrient supply to high-yielding cows. Therefore farmers often feed high amounts of supplements to maintain milk production level throughout the grazing season. Other constraints, *e.g.* a need for continuous access between pastures and milking unit, areal requirements for larger herds and high costs of grazing infrastructure, can further reduce farmers' enthusiasm for grazing and increase their frustration with statutory grazing requirements.

This thesis examined constraints frequently ascribed to combining grazing with AMS and tested the validity of these associations under experimental and real-life conditions. The results showed that solutions are possible whereby dairy farmers can offer high-yielding cows pasture in their diet, without compromising farm finances through associated yield losses.

Keywords: dairy cattle, automatic milking, milk yield, behaviour, grazing management, part-time grazing, dry matter intake estimate, farmer survey

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Oppdrag beitetid – å kombinera beite med automatisk mjølking

Samandrag

Dei siste tiårs inntog av automatiske mjølkingssystem (AMS) i europeiske mjølkebruk har hatt ein parallell nedgang i utbredelese av beitebruk. Å beite er ei viktig naturleg åtferd for mjølkekyr, og å gje tilgang til utegang vert av mange rekna som eit grunnleggande dyrevelferdstiltak. Vidare kan beitande drøvtyggarar nyttegjera seg av areal elles utilgjengeleg for matproduksjon, og beitebruk er ofte tilskriven positive økosystemteneste-effektar som halde oppe biodiversitet og auka jordkarbonbinding. Det er følgjeleg eit uttrykt ynskje frå fleire interessegrupper å oppretthalda ein mjølkeproduksjon som nyttegjer seg av beiteressursen.

Tilgjengeleg mengde og kvalitet av beite fluktuerer ofte gjennom ein beitesesong og mellom sesongar. Denne variasjonen sett saman med ein mangel på pålitelege estimat av beiteinntak som eit avgjerdsverktøy for berekning av tilleggsrasjon kan gjera sikringa av næringsforsørging av høgavkastande kyr krevjande, og driv ofte produsentar til å gje ein for stor tilskottsrasjon for å sikre at avdråttsnivå vert opprettheldt gjennom beitesesongen. Dette kan, saman med andre utfordringar med beite – t.d. behovet for ein kontinuerleg trafikk mellom fjøs og beite, auka behov for fjøsnære areal ved auka besetningsstorleik, samt kostnadar med vedlikehald av beiteinfrastruktur – gje ei minska motivasjon for å drive med beitebruk, eller endåtil skape mismot over gjeldande lovverk om mosjon og beitebruk.

Denne oppgåva tar utgangspunkt i eit utval utfordringar ofte antatt ha samanheng med det å kombinera AMS og beitebruk og testar gildskapen på disse under kontrollerte forsøk og i felt. Målet har vore å finne brukande løysingar for å kunne inkludera ein monnaleg del beite i rasjonen også til høgtytande mjølkekyr i laktasjon, utan å risikera botnlinja på garden gjennom avdråttstap.

Stikkord: storfe, automatisk mjølking, avdrått, åtferd, beitebruk, beitestell, deltidsbeite, beiteinntaksestimat, beitekrav

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Preface

In my lifetime, the agricultural sector, and dairy farming in particular, have seen tremendous and rapid changes. This has also been the case in Norway, albeit at a different rate and magnitude than in other European countries. In the year of my birth, 1984, there were 22,431 dairy farms in Norway, with an average herd size of 13.4 cows yielding 5,716 kg milk/lactation. By my first year of school little had changed; there were 22,161 dairy farms with an average herd of 12.9 cows yielding 6,264 kg milk/lactation. I started upper secondary school in the same year that the first AMS unit was installed on a Norwegian farm. In that year, there were 18,723 registered dairy farms averaging 14.4 cows and 6,094 kg milk/lactation. When I enrolled in veterinary college four years later, there were 15,271 dairy units in Norway, with an average size of 16.3 cow-equivalents and annual milk yield of 6,469 kg. By graduation, this had become 10,943 farms with 24.2 heads and 7,132 kg yield. As I left the advisory services to enrol at SLU's doctoral school three years later, 9,364 farms remained, averaging 24.8 cow-equivalents and with mean yield of 7,599 kg. At the time of writing this, the most recent census (December 31 2019) recorded 7,598 dairy holdings, with a herd-size of 28.0 and mean yield of 8,120 kg/cow, and a total of 2,558 AMS units.

When I worked with the advisory services, two of the most frequently asked questions were: "How can I fulfil the imminent legislation making pasture access mandatory, without risking production losses and defaulting on my payment obligations?" (asked by farmers with freestall housing and AMS) and "How can I best plan for grazing without risking production losses?" (asked by farmers still at the planning stage).

My colleagues and I were at a loss for good answers, as technology and modernisation had outpaced our evidence-based knowledge, within less than two years of graduating in my case. I came to believe that this uncertainty was impairing farmer welfare, and I was concerned that creative solutions from farmers or extension services to overcome this challenge and just comply with minimum requirements could risk cow welfare and the intention of the law. Thus, when the opportunity to conduct this project surfaced, I jumped at it.

"No, no! The adventures first, explanations takes such a dreadful time."

– Lewis Carrol

Dedication

To Jarle – for always being my safe harbour.

In loving memory of Katyama – my life buoy. You are sorely missed.

> “Not all those who wander are lost”
> – J. R. R. Tolkien

"He'd mastered the first two rules of writing, as he understood them.

1) Steal some paper.

2) Steal a pencil.

Unfortunately there was more to it than that."

- Terry Pratchett

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List of publications

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I. Kismul H, Spörndly E*, Höglind M, Eriksson T (2018). Morning and evening pasture access – comparing the effect of production pasture and exercise pasture on milk production and cow behaviour in an automatic milking system. Livestock Science, 217, pp. 44-54.

II. Kismul H*, Spörndly E, Höglind M, Næss G, Eriksson T (2019). Nighttime pasture access: Comparing the effect of production pasture and exercise paddock on milk production and cow behavior in an automatic milking system. Journal of Dairy Science, 102 (11), pp. 10423-10438**.

III. Eriksson T*, Jansson T, Höglind M, Kismul H Pasture intake estimated from water intake, urinary output or grazing time combined with recorded individual forage intake rate. (manuscript)

IV. Kismul H*, Torske MO, Eriksson T, Rustas BO, Næss G. Response in production of energy-corrected milk, milk fat and milk protein to pasture turnout on Norwegian farms with different milking systems and different grazing strategies. (manuscript)

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* Corresponding author

** Featured as "Editor's choice"

The contribution of Haldis Kismul to the papers included in this thesis was as follows:

I. Was involved in planning the practical study. Had the main responsibility for conducting the experiment. Cleaned and compiled the data, and performed the statistical analysis in collaboration with the supervisors. Wrote the manuscript with regular input from the supervisors. Revised the manuscript under supervision.

II. Planned the practical study. Had main responsibility for conducting the experiment. Cleaned and compiled the data, and performed the statistical analysis. Wrote the manuscript with regular input from the supervisors. Corresponded with the journal and revised the manuscript under supervision.

III. Was involved in developing the hypothesis together with the supervisors, and was involved in planning and performing the study. Had main responsibility for conducting the experiment. Provided input on the manuscript as a co-author.

IV. Defined problem and research questions to be addressed, in dialogue with the supervisors and project reference group. Designed and tested the questionnaire with regular input from the supervisors and project reference group. Had main responsibility for fulfilment of ethical requirements, collecting data, consecutive communication with respondents and obtaining database access for data linkage. Compiled, cleaned and interpreted the data, and performed statistical analysis. Wrote the manuscript with input from the co-authors.

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(Night vision goggle view of grazing Swedish Holstein)

"Where observation is concerned, chance favours a prepared mind"

- Louis Pasteur

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Abbreviations

AIC	Akaike information criterion
AMS	automatic milking system
BM	bulk milk
CI	confidence interval
CMS	composite milk sample
DIM	days in milk
DM	dry matter
DMI	dry matter intake
ECM	energy-corrected milk
EX	exercise pasture/paddock (experimental group)
LDB	dairy delivery database (Leveransedatabase)
LMM	linear mixed model
ME	metabolisable energy
MLR	multiple linear regression
NDF	neutral-detergent fibre
NDHRS	Norwegian dairy herd recording system
NMSM	Nordic Dairy Associations' Committee for Milk Quality Issues (Nordiske meieriorganisasjoners samarbeidsutvalg for melkekvalitetsarbeid)
PROD	production pasture (experimental group)
RH	relative humidity
SCC	somatic cell count
SH	Swedish Holstein (breed)
SRB	Swedish Red (breed)
THI	Temperature-humidity index

“We all learned by doing, by experimenting (and often failing), and by asking questions “
– Jay Jacob Wind

1. Introduction

Considerable changes in the agricultural sector throughout the 20th century have been important drivers of structural development in Europe. Access to mineral fertilisers and feed concentrates, use of new animal and plant breeds and emergence of new equipment and technology have increased yields substantially, and at the same time reduced the agricultural workforce.

In parallel with the intensification of agriculture, the past century has seen de-agrarianisation of the European continent, first through industrial employment and expansion of care professions, later by an emerging service industry and increased self-actualisation. As a result the majority of the population are distant from, and unfamiliar with, primary production.

The climate and society of the Nordic region shape its dairy farming. The long, harsh winters call for advanced and costly animal housing, and the high cost of wages makes automation of farming more financially competitive than hiring permanent staff. These traits have created a dairy sector characterised by fewer and larger herds, a growing proportion of national herds milked in automatic milking systems (AMS) and increased milk yield per cow.

With the reduction in the agricultural workforce, Nordic dairy farming has become more centralised in terms of closeness of infields and settlements. With the increased demand for nearby farmland and abandonment of transhumance traditions, outdoor grazing of dairy cows has decreased. However, consumer concerns about animal welfare and political motives for maintaining cultural landscapes and traditions have resulted in grazing legislation being pushed through in several Nordic countries. Combining the traditional grazing system of extensive farming with the intensive management commonly associated with AMS has not been without its hurdles. This thesis is the product of a joint Swedish-Norwegian research project designed to tackle some of the most relevant issues within this research area, particularly by examining various applicable and low-cost solutions to optimise inclusion of pasture in the diet of high-yielding cows without inflicting yield losses.

2. Background

2.1 A century of change

During the past 100 years, European agriculture has undergone dramatic intensification and rationalisation. Food production has gone from engaging a large proportion of the population to being a minority occupation in most European countries, including those in Scandinavia (Statistics Norway, 2020a; Emanuelsson, 2009; Almås, 2002).

Although the nations of the Scandinavian Peninsula differ greatly in terms of geography, history, and current affairs, there are also great similarities. Characteristic of the whole region are long winters, a short growing season with long daylight hours, high cost of living and high labour costs. Other similarities are that a majority of the population is physically and culturally removed from agriculture, but with a strong interest in animal welfare, environmental protection, biodiversity preservation and maintenance of landscape beauty. Against this background, Norway is used below as an example and as the starting point in describing the context of this thesis work.

2.1.1 Norwegian agriculture

Norway is characterised by a long coastline deeply indented with fjords and scattered with some 50,000 islands, rugged mountains, high plateaus, numerous glaciers and even vast areas with permafrost. Arable land is scarce, around 3.2% of total land area, and highly segmented (Statistics Norway, 2015). The country lies between 57 and 71 degrees north (Statistics Norway, 2015), so the climate is characterised by a long winter with low sun or no sunlight and a short growing season. Mean annual precipitation is high, while mean annual temperature is low (Norwegian Meteorological Institute, 2020).

However, the presence of the warm Gulf stream allows for vital agriculture farther north than would otherwise be possible.

Only a very few restricted areas are suitable for production of cash crops, such as grains and vegetables. However, with its long hours of daylight in the growing season and long-term average temperatures and precipitation levels suitable for temperate grasses, Norway is a nation of grass. In fact, about 45% of mainland land mass is considered to be suitable for grazing, *i.e.* of sufficient quality to support growth in grazing animals, with 10% classified as high-value pasture land (Asheim & Hegrenes, 2006).

For thriving agricultural production and population spread across the nation to be possible, farm units were traditionally small-scale and versatile; in coastal areas, pastoral agriculture was combined with fishing, and in forested areas with forestry. Traditionally, infield-outfield farming was practised, *i.e.* grazing animals on mountains, in forests and on islands and harvesting winter fodder for the same animals from the same grazing land by outfield haymaking and pollarding. This way, even small patchworks of fenced-in infields near settlements could give sufficient hay and crop yields to sustain a family.

When World War II ended, industrial activity and job opportunities off-farm increased, and agriculture could no longer compete with the salary and benefits of full-time industrial employment. Previously hired hands, tenant farmers and their families migrated from the countryside to factories for jobs. Family members outside the core farming family quickly followed. Those left had to either adjust to the new normal, coping with the agricultural workload with fewer hands and disappearance of social infrastructure in the countryside, or follow the majority and change their farm boots for factory overalls (Almås, 2002)

A swift and all-embracing process of modernisation introduced modern technology, machinery, animal breeding, plant breeding and formal education into agriculture, for the purpose of rationalisation and to improve efficiency. It was no longer sufficient for a farm to be self-supporting for a family – agriculture had to feed the masses. Horses were replaced with tractors and hand-spreading of manure and fertilisers with mechanical muck spreaders. Scythemen and child labour gave way to hay dolly, harvester, grass silage, combine and concentrate feed. With expansion of the electrical grid and mains water supply to farms with livestock, dairymen and dairymaids were replaced with vacuum milking units. In the house, maids were replaced with washing machines and vacuum cleaners. Soon, farms provided employment for only one person, while still remaining the family home (Almås, 2002). Mechanisation took over most of the tasks traditionally considered to be women's work on the farm, at a time when there was a growing demand for workers in public healthcare and schools. Thus, farm wives typically took outside employment, while the men remained on the farm (Almås, 2002).

By 1969, the total number of agricultural holdings in Norway was around 155,500, of which approximately 88,500 were smaller than 4.9 hectares and 134,000 kept livestock. By end of 2019, the total was reduced to about 39,000 farms, 5,300 of which were smaller than 4.9 hectares and 29,000 kept livestock. Within the same time frame, the average farm size increased from 6.2 hectares to 25.2 hectares (Statistics Norway, 2020b).

Dairy farming in Norway

Like the entire Norwegian agricultural sector, dairy farming in Norway is strictly regulated, as a consequence of the country's history and prevailing economic and physical circumstances. This, along with the geographical restrictions previously mentioned, has contributed to a smaller number of cattle per farm compared with the neighbouring countries Sweden and Denmark, and also lower milk yield per cow.

The development of dairy farming in Norway was also influenced by a strong co-operative ideology in its dairy tradition, with the establishment of the very first co-operative dairy in 1856. Those that followed were later combined into one national dairy co-operative, which today is owned by 9,567 farmers, with milk deliveries from 7,728 holdings (TINE SA, 2020). An important aspect of this farmer unionisation is the semi-public role of farmers' organisations as market price regulators, negotiating with the government on milk target prices and quota regulations in the annual agricultural agreement (Almås & Brobakk, 2012; Almås, 2002). Another important aspect was (and still is) the rigid principle of price equalisation, making it possible to maintain de-centralised and diverse dairy production even in remote and low-productivity regions of Norway.

The farmers' organisations also held a position as stock keepers, with animal breeding having a strong cooperative element. At the establishment of a national dairy breeding index, the initial goal was to develop a breed with high milk yield, good meat yield and fast growth, and also well-adapted to grazing. Reproductivity and health, traits then commonly ascribed low inheritability, were included in the breeding goals and selection criteria for the Norwegian Red and White (now Norwegian Red Cattle), currently the dominant breed in Norwegian dairy production. With the co-operative tradition already strongly implemented, the national dairy herd recording system (NDHRS) had a high participation rate already from its beginning in 1975 (TINE Produsentrådgiving, 2003). Currently, 97.5% of Norwegian dairy herds participate in the scheme (TINE Produsentrådgiving, 2020). Production subsidy policies caused the breeding goals to have a stronger focus on mastitis reduction than yield improvement in the 1980s, giving a cow with pleasingly high health indices, but somewhat lacking with regard to yield. However, in the past 20 years there has been a substantial genetic improvement also in milk yield.

In recent years, there has been an increased focus on animal welfare. In 1996, the Norwegian regulations on keeping cattle introduced a grazing requirement for all bovines older than six months and kept in tie-stalls (Forskrift om hold av storfe og svin, 1996). When the updated regulations on keeping cattle were passed in 2003, a ban on new tie-stalls entered into force (Forskrift om hold av storfe, 2004). A future general ban on tie-stall dairy barns was announced at the same time. With the impending ban on tie-stall housing, many farmers were compelled to make a choice between closing down their farm, reorganising production in a joint farming operation or different agricultural production system, or investing in a new-build or complete rebuild. The milk quota of farmers closing down or reorganising their production and the agricultural land of those closing down became available for sale or hire for those opting to remain dairy farmers, allowing for a considerable increase in mean herd size.

2.2 Automatic milking

The introduction of reliable electronic identification of animals in 1980, originally intended for automatic concentrate feeders in freestall houses, enabled development of new management practices and possibilities for new technology. The rapid development throughout the 1980s within robotics in general, and robotic arms in particular, permitted the first milking of a cow (more or less) without human involvement in 1986. This paved the way for installation of an experimental automatic milking system (AMS) unit on a Dutch experimental farm in 1990 (John *et al.*, 2016).

It was not until 1992 that the world saw the installation of the first commercial AMS. This was a huge step as regards farmers' health and safety in the workplace, by taking over the monotonous, repetitive and backbreaking work involved in conventional milking. The innovation also opened the way for a completely new system of farm management and a lifestyle change for both cow and farmer. It was also an important first step towards a precision livestock farming strategy, with individualised performance management aimed at optimisation for each individual cow in the herd.

One of the main characteristics of the AMS is that the animals eat, rest, socialise and visit the milking unit at their own leisure and that robots, rather than humans, control the milking process. With animals deciding for themselves when and how frequently to seek out the milking unit, milking is no longer performed in defined sessions, but rather spread out throughout a 24-hour period. This cow autonomy has led to greater milking frequency than the twice daily milking commonly practised in traditional milking systems, again followed by an increase in milk yield in most cases (Tse *et al.*, 2018; Svennersten-Sjaunja & Pettersson, 2008; Wagner-Storch & Palmer, 2003). For the farmer, time previously spent in a milking parlour or crouched down in cubicles is freed up for other farm tasks. Moreover, the absence of the strict milking schedule allows for greater flexibility in daily routines and schedule than with manual milking.

Investing in robotics comes at a cost, however, a major capital investment in a robotic unit(s) and barn refurbishment before installation, to be exact. In order to obtain returns on assets by increased production and reduced labour cost, the capacity of the system must be fully utilised, and both herd and machinery management may need optimisation.

Steady, well-functioning cow traffic is essential for succeeding with AMS. Well-functioning here means an optimal number of meals and milking events, minimal time spent standing/waiting and maximal time spent resting while ruminating and synthesising milk. Cow traffic optimisation has been a topic of great interest since the first commercial AMS was introduced, and generated a vast amount of peer-reviewed papers and PhD theses in the past few decades. In short, a cow needs sufficient motivation to seek out the milking unit, while the system requires an animal group of a manageable size and a level of production that is sufficiently large to flush milk through to the bulk-tank in a steady flow, but gently enough to maintain the hygienic and sensory quality of milk.

Udder engorgement alone does not seem to provide sufficient motivation for a cow to seek out the milking unit. Prescott *et al.* (1998) found that, when given the choice of consuming feed or being milked, cows will choose the feed. To mitigate this, either strategic use of concentrate supplementation in the milking unit in both free and guided traffic systems or feed bunk placement in guided traffic systems are used to drive the cow traffic. On average, AMS units have 20-22 hours per day available for milking, when time for washing the system, technical maintenance, milking failures and periods of non-attendance are taken into consideration. Actual capacity of a single AMS unit depends primarily on duration of each milking event, which is highly dependent on herd mean daily milk yield, and number of visits to the milking unit per cow and day, the latter greatly influenced by the cow traffic system. While most manufacturers promote a capacity of 70 cows, 60-65 cows/unit is generally recommended to keep waiting times down and milking frequency up in traditional systems where cows are primarily kept indoors. The last decade has seen rising interest in implementing robotic milking in pasture-based dairy systems, making the technology of increasing interest outside Europe.

A detailed review of strengths and weaknesses with AMS, prerequisites for succeeding with adapting the technology and the continuous course of development was outside the scope of this thesis. Excellent summaries and reviews may be found elsewhere (*e.g.* Vik *et al.*, 2019; Rodenburg, 2017; Vik *et al.*, 2017; Butler & Holloway, 2016; John *et al.*, 2016; Svennersten-Sjaunja & Pettersson, 2008).

2.2.1 Automatic milking in Norway

While outdoor mechanisation revolutionised how farming was practised in Norway, with a steady stream of new inventions and/or adaptation of foreign technology to better fit Norwegian geographical requirements, innovations inside animal houses remained static for a long time. The extensive electrification and installation of running water on farms paved the way for widespread introduction of milking machines, but uptake of newer indoor mechanisation innovations was marginal.

Norwegian farmers were relatively slow to embrace the emerging technology of automatic milking, unlike earlier innovations made available to them since the beginning of national recovery after World War II. With national mean herd size having increased by only one unit from 1992 till 1999, and with less than 14% of herds being larger than 19.9 cow equivalents (TINE Produsentrådgiving, 2003), such a considerable financial investment was not rational as utilisation factor would simply not provide an acceptable return on assets. Thus, the first AMS unit was not installed in Norway until 2000 (Figure 1). Further installations came at a slow rate in the following four years, primarily in larger joint farming operations.

As freestall housing became the only legal option for new-builds and rebuilds from 2004 onwards, the cost of building and refurbishing was already inflated. Some farmers staked on the continued existence of their business and made the choice of the investments required. For those farmers, the inducement of a more flexible working day compatible with family and social life, improved nature of work and positioning the farm for future generations justified the added investment in AMS, even where economic considerations alone could not (Vik *et al.*, 2019; Hansen, 2015). This, along with scarcity of hired help and high cost of wages, has since contributed considerably to making AMS a significant feature in Norwegian dairy production.

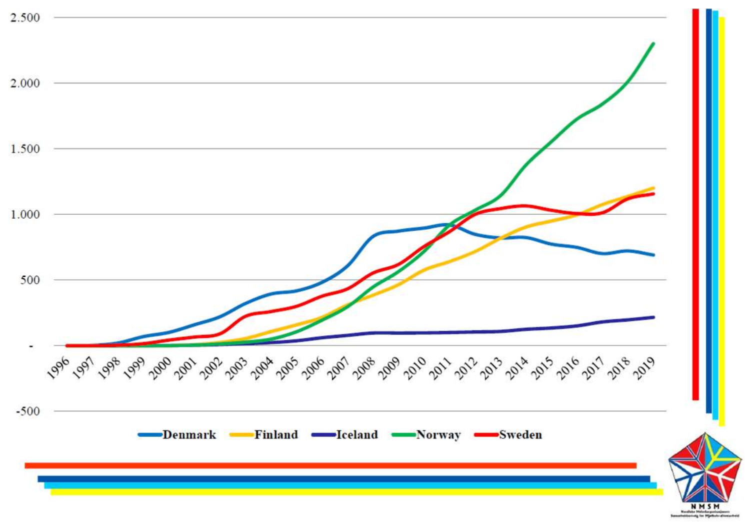


Figure 1. Number of dairy herds in the Nordic countries using automatic milking systems (AMS). Reproduced with permission from NMSM (NMSMt, 2020).

Of an estimated total of approximately 65,000 AMS farms around the globe at the end of 2019, 5,565 were in the Nordic countries. Despite the late start in embracing the new technology, Norway overtook the other countries in the region in terms of AMS farms already in 2011 (Figure 1). Number of AMS units has shown a relative steady increase of approximately 150 units per year since 2005, and in 2019 the total number of AMS units in Norway surpassed that in the heyday of AMS in Denmark, with a total of 2,558 registered (NMSMt, 2020).

In 2019, 31.7% of all Norwegian dairy farms were AMS farms, with 48.1% of all Norwegian dairy cows milked in AMS and 57.2% of all milk produced by AMS. Unlike most other countries with a high proportion of AMS farms, Norwegian AMS farms tend to have one unit (mean 1.1 AMS unit/AMS farm), and frequently allow for low utilisation of robot capacity. In 2019, overall mean herd size in Norway was 28 cows, while mean number of cows per AMS farm was 43 (NMSMt, 2020), or 39.1 cows/AMS unit, well below the maximum capacity recommendation. For comparison, the corresponding figure was 50, 50.1, 51.6 and 58.7 cows/AMS unit in Iceland, Finland, Sweden and Denmark, respectively. Average production per Norwegian AMS farm was 346 tons milk/year, compared with 982 tons/year on Swedish AMS farms and 1,907 tons/year on Danish AMS farms (NMSMt, 2020).

The total level of debt among Norwegian dairy farmers has almost doubled since 2010. The number of farmers with a debt burden less than 1 million NOK has decreased by 20%, while the number of farms with a debt burden greater than 4 million NOK has increased by almost 40% (Statistics Norway, 2020c). Investments in freestall housing and AMS have been a considerable contributor to this increase in debt-income ratio (Almås, 2016).

2.3 Grazing

Grazing is both a verb, describing the natural feeding behaviour of herbivores living on the grasses and forbs of grasslands, and a noun, describing a feeding management strategy in animal husbandry. The nounification is highly indicative of the importance that *graminivory* (the action of eating grasses) has held throughout the history of human civilisation.

Ruminants have the ability for converting grasses and other roughages (containing nutrients which are indigestible to man) into food, clothing and tools, while utilising land ill-suited for arable farming. Therefore keeping ruminants has made it possible for humans to settle even in the harshest conditions. Traditionally, pasture was considered a low-cost feed, as it did not need to be harvested or treated for storage. By transhumance grazing utilising remote and hard-to-reach resources, pasture also saved on near-settlement resources needed for winter feed and food.

In climates allowing for year-round grazing, or grazing for the greater parts of the year, pastoralism is still an important way of animal husbandry, both in the traditional sense of nomadic or transhumant rearing of domesticated animals and in the broader meaning of pasture-based enclosed farming/ranching. Pasture-based dairy production is still the dominant production method in important dairy producing countries, like New Zealand, Australia and Ireland. A feature in common to these pasture-based dairy industries is an orientation towards maximising milk yield per pasture unit, as opposed to the high-input/high-output system. The latter is typically adopted in regions where land is scarce and/or climate drives the cost of winter housing, and moves towards maximising annual milk yield per cow instead.

As a whole, following intensification and rationalisation of the industry, there is a decreasing trend in grazing of dairy cattle in Europe. In large parts of the continent, *e.g.* Central, Eastern and Southern Europe, and in countries like Denmark, grazing of dairy cows is a tradition lost or on its way out in non-organic management (Isselstein & Kayser, 2014). In some regions, *e.g.* The Netherlands, Germany, Portugal and Switzerland, economic remuneration through a pasture milk premium or payment for ecosystem services performed by grazing livestock has been introduced by private sector and government bodies to incentivise grazing. Other countries, *e.g.* Norway, Sweden and Finland, have chosen to make outdoor access for cattle mandatory, as part of animal welfare legislation. The nature and wording of the legislation differs, *e.g.* the Swedish legislation (Djurskyddsförordningen, Chap 2, §3) applies to all dairy holdings, while the Norwegian legislation (Forskrift om hold av storfe, §10) applies to all holdings with tie-stalls and freestall holdings brought into use after 2013 (the 2014 amendment has no retroactive effect for older freestall holdings), and the Finnish legislation (Valtioneuvoston asetus nautojen suojelusta, §17) applies to tie-stalls only.

However, the intention of the legislation is similar in all three cases; to ensure that cattle have free access to exercise and expression of natural behaviour.

The grazing legislation in Norway, Sweden and Finland is not universally popular. A Swedish farmer-initiated lobbying group is working to repeal the legislation, arguing that it is obsolete and puts Swedish dairy farmers at a disadvantage, as they sell their produce on the same open market as dairy producers from regions where grazing is optional. In a 2014 report, the Swedish Board of Agriculture concluded that dairy farmers make a loss by keeping lactating cows on pasture (Swedish Board of Agriculture, 2014), based on calculations assuming a milk yield drop from grazing. In contrast, a study in Norway comparing part-time production pasture with exercise pasture found that, although the change in revenue from raw milk sales was the grazing-related factor contributing most to changes in farm economics, production pasture would in most cases be more profitable than exercise pasture in both Norway and Sweden (Overrein *et al.*, 2018).

In Norway, legislation amendments and policy changes are in general criticised for causing an unpredictable and unstable sector framework, resulting in increased shutdown of farm operations, in particular in more remote and harsh regions where profit margins are already under pressure. Other pressure groups criticise the text of the law as inefficacious, by being too non-comprehensive and too vaguely worded and ill-defined to contain any merit.

2.3.1 Grazing in Norway

A hundred years ago, rough grazing was by any measure the greatest feed source in Norwegian agriculture. Prior to the world wars, transhumance was the norm for providing summer feed for livestock, utilising land otherwise difficult to access and utilise. Milkmaids went with the animals to mountain, forest or island pastures and stayed there for the summer, tending the cows and converting the milk into butter and cheese for winter food and sale to market.

With the post-war entry of tractors and artificial fertilisers, the exploitation of farm-near areas increased and winter feed for the animals was harvested closer to home. With the decasualisation of agriculture and fewer hired milkmaids and farmhands, the nucleus family was needed at home for the spring and summer work, and the traditional summer farming was no longer expedient. The traditional transhumance dwindled and by the 1970s it was close to being merely a tourist set-piece. To reach national goals of an annual increase in arable land of 8,000 hectares (Almås, 2002), farm-close areas were needed for roughage production and new solutions were required for rationalisation of grazing. Initiatives like cooperative pastures and mountain farm cooperatives were introduced. The participating farmers took turns caring for the animals, freeing both farm-close land and time for the farmers currently not on duty. Unlike the traditional mountain farming, these were frequently established on lowlands rather than mountains, close to roads for milk tanker access, and, rather than free ranging on rough grazing and natural grasslands, cultivated enclosed pastures were established.

As the traditional mountain farms fell out of use, the land cover and ecosystem of these swiftly changed and reforestation caused the treeline to climb (Wehn *et al.*, 2012). In order not to lose the tradition of mountain farming and to maintain cultural landscapes and a feed resource, a mountain farming subsidy was introduced in Norway in 1989 (Nordtømme *et al.*, 2007).

As the proportion of cows in lactation given access to pastures continued to dwindle, a revision of the Animal Welfare Act of 1996 introduced a statutory right of all bovines older than six months and kept in tie-stalls to free movement and exercise for a minimum of eight weeks during the summer months. A recapitulation from 1996 summarising reports on occurrence of grazing from regional veterinary officers (as cited in Blytt, 1997), conducted prior to the initial introduction of a grazing requirement in national animal welfare legislation, found that 10% of herds with tie-stalls and 20% of herds with loose houses kept their dairy cows indoors all year round.

From 2014 onwards, the right to outdoor access and exercise came into force also for cows in freestall housing. According to the current Norwegian legislation on the welfare of cattle, all cattle should have access to free movement and exercise on pasture for at least eight weeks (or 16 weeks for cattle kept in tie-stalls) during the summer months. However, there are several exemptions from the legislation, including a possibility to provide a bedded pack or exercise paddock rather than pasture to cattle kept in freestall housing completed prior to 2014.

2.3.2 Why grazing?

Although the growth rate is slowing, the world's population is projected to continue to increase throughout the 21st century, with worst-case projections predicting a human population two-thirds greater than today (UN, 2019). Food production is essential for sustaining the global population, and the modernisation of agriculture has proven successful in terms of producing larger amounts of food per land or animal unit. However, intensive food production and agriculture are also major contributing factors to destabilising the Earth system and pushing it outside its safe operating space as regards water pollution, land degradation, loss of biodiversity and climate change (Gerber *et al.*, 2013).

In parallel with population growth, an increase in material wealth and consumption is occurring in all regions of the world. Increased material wealth is generally accompanied by an increased percentage of food budget spent on animal protein (Sans & Combris, 2015). Animal-based food production, in particular production of red meat and milk of ruminant origin, has come under fire in recent years for its contribution of greenhouse gases and role in climate change, but arguing for a cessation of production is neither rational nor feasible. In the world as a whole, a protein shortage already exists, and further increases in demand for animal products like meat and milk can be expected as more people come out of poverty and hunger. An FAO report in 2013 estimated that demand for milk and meat would increase by 58% and 73%, respectively, by 2050 compared with 2010 levels (Gerber *et al.*, 2013).

In order to accommodate this increasing global population and its increasing requirements for food, water and living space, and at the same time work towards a sustainable development by ending world poverty, hunger and other deprivations (UN, 2015), smarter and more responsible food production is needed, exploiting the resources available in a sustainable manner.

Utilising local feed resources unfit for human consumption (*e.g.* grasses and by-products from industry) contributes to human food security by improving *net food production* (gross human-edibles output of animal origin after deduction of potentially human-edible feedstuffs used in production), by exploiting the evolutionary advantages of ruminant digestion (Wilkinson, 2011). In a year-round indoor feeding system for high-yielding dairy cows, most diets include high proportions of cereal grains, pulses or other nutrient-dense human-edible crops, causing dairy production to result in negative net food production. A considerable part of the human-edibles used are imported, adding carbon footprint from transport to the ration and, for some feedstuffs, deforestation to meet production requirements.

As previously mentioned, Norway's territory comprises only 3% arable land and 95% uncultivated land, of which almost 50% is classified as natural and semi-natural pasture of high nutritive quality. By replacing parts of the human-edible inputs in cattle feed with roughage, in particular roughages from non-arable land, grazing is key to increasing the proportion of national feed resources, thus increasing national self-sufficiency.

Animal welfare is a major concern for consumers (*e.g.* Beaver *et al.*, 2020; Hötzel *et al.*, 2017; Cardoso *et al.*, 2016; Spooner *et al.*, 2014; Miele *et al.*, 2011; Prickett *et al.*, 2010). In a 2016 survey, 94% of EU citizens stated that they "[..]believe it is important to protect the welfare of farmed animals[…]" (Directorate-General for Health and Food Safety *et al.*, 2016). For 46% of respondents, animal welfare was seen as 'a duty to respect all animals', and 40% of respondents understood animal welfare as 'concerns about the way farmed animals are treated, providing them with a better quality of life'. Dairy farming is perceived with greater positivity than other livestock farming as regards animal welfare (Weinrich *et al.*, 2014), and this positive perception is mainly due to a strong association of dairy farming with pasture access (Armbrecht *et al.*, 2019). Good quality of life is frequently associated by consumers with access to natural environments and the ability to engage in natural behaviour (Beaver *et al.*, 2020; Cardoso *et al.*, 2019; Hötzel *et al.*, 2017; Schuppli *et al.*, 2014; Spooner *et al.*, 2014; Weiss, 2014; Prickett *et al.*, 2010). Grazing and pasture access are frequently used to exemplify this, as its value is perceived to go beyond that of eating grass. Respondents in the USA and Canada, both affiliated and non-affiliated with the dairy industry, perceived free movement, fresh air, socialising and improved animal and consumer health as benefits of having dairy cows on pasture (Schuppli *et al.*, 2014).

Willingness to pay is an established method to evaluate consumer demands and preferences. In the 2016 EU survey, 59% of respondents stated that they were prepared to pay more for products from animal-welfare friendly animal production. This is in line with findings in other studies (*e.g.* Bir *et al.*, 2020; Jackson *et al.*, 2020; Olynk *et al.*, 2010; Prickett *et al.*, 2010). In surveys in the USA on cheese (Bir *et al.*, 2020) and liquid milk (Olynk *et* *al.*, 2010), pasture access was regarded as a crucial attribute by consumers for increased willingness to pay. In a UK survey, consumers ranked access to grazing, cow health and welfare highly, and ranked cow comfort as an equally important feature for animal welfare in dairy cow management and milk production (Jackson *et al.*, 2020).

The positive health and welfare effects of pasture access are not only in the perception of consumers, but are well documented in the literature. Several studies on mortality risk indicate a positive effect of grazing on dairy cows (Alvasen *et al.*, 2012; Burow *et al.*, 2011; Thomsen *et al.*, 2006). Grazing has been linked to overall improved health (Alban & Agger, 1996), a reduced risk of mastitis (Washburn *et al.*, 2002; Barkema *et al.*, 1999; Schukken *et al.*, 1991), lower incidence of lameness, hoof and leg disease (Armbrecht *et al.*, 2019; Armbrecht *et al.*, 2018; Olmos *et al.*, 2009; Hernandez-Mendo *et al.*, 2007; Haskell *et al.*, 2006; Loberg *et al.*, 2004; Bergsten, 2001), calving difficulties and calf mortality (Washburn *et al.*, 2002) and metritis (Bruun *et al.*, 2002), and improved reproductive performance (Dhakal *et al.*, 2013; Washburn *et al.*, 2002). Healthier animals have the opportunity to perform closer to their genetic potential with less input factors, as they do not need to spend energy on healing. Furthermore, disease prevention through measures like improving animal welfare, rather than prophylactic or therapeutic use of antibiotics, is an important contribution to the one health sustainability measure of reducing the build-up of antimicrobial resistance.

While improved health can bring an improvement in animal welfare in itself, summer grazing has also been shown to have a general positive effect on dairy cow welfare (Armbrecht *et al.*, 2019; Crump *et al.*, 2019; Arnott *et al.*, 2017; Wagner *et al.*, 2017; Burow *et al.*, 2013), with lowered blood and urinary cortisol levels (Higashiyama *et al.*, 2007). Occurrence of abnormal behaviour decreases, while normal social-, self-grooming-, and investigative behaviour increases (Loberg *et al.*, 2004; Krohn, 1994). Cows on pasture have even been shown to rest in a more free-sprawled manner, and rise and lie down faster and with greater ease (Krohn & Munksgaard, 1993). Several studies have shown that cows have a preference for pasture access (Arnott *et al.*, 2017; von Keyserlingk *et al.*, 2017; Jørgensen *et al.*, 2015; Motupalli *et al.*, 2014; Charlton *et al.*, 2013; Falk *et al.*, 2012; Charlton *et al.*, 2011a; Loberg *et al.*, 2004). However, some studies have found that when offered a free choice, cows prefer to be indoors under certain weather conditions, *e.g.*

heavy rain (Jørgensen *et al.*, 2015; Charlton *et al.*, 2013) or high heat and humidity during the day (Smid *et al.*, 2019; Falk *et al.*, 2012; Legrand *et al.*, 2009), indicating that having the opportunity to choose might also improve animal welfare.

In addition to the nutritive and production aspects and values of grazing, pastures and grazing bring further values. The importance of grazing as part of cultural heritage, traditions and providing a feeling of roots and belonging has been highlighted by several interest groups (farmers, decision-makers and general population) in different European regions. Maintenance of cultural landscapes and continued beautification of landscapes are also important factors in the maintenance of rural populations, both by providing employment through the tourist industry and knock-on effects from this (Vinge & Flø, 2015), and by increasing quality of life for the resident population through maintaining areas for recreation, inspiration and aesthetic values (Bergslid & Støbet Lande, 2013; Bryn *et al.*, 2013).

Maintenance of open landscapes also provides important ecosystem services. Grazing land, in particular semi-natural and natural pastures, is often rich in species and a key habitat for numerous endangered and critically endangered plants, fungi, birds and insects (Henriksen & Hilmo, 2015). When managed and incorporated in a sustainable manner, grazing livestock in agroecosystems provide important ecosystem services by preventing reforestation and loss of key habitats (Pelve *et al.*, 2020; Aune *et al.*, 2018) and enabling seed dispersal (Czortek *et al.*, 2018). However, it is worth noting that intensification of grazing systems, *e.g.* by artificial fertilisation or tillage and re-seeding, may cause biodiversity to decrease (Aune *et al.*, 2018). Nutrient enrichment of semi-natural and naturalised pastures and nutrient transport between different vegetation types by fouling by grazing livestock does not seem to pose a major threat to biodiversity in grasslands (Pelve *et al.*, 2020).

Compared with annual grain and vegetable crops and slow-growing perennials like trees and shrubs, perennial herbaceous plants provide a considerably greater ground cover. Their root systems are also much more voluminous in permanent and semi-permanent grasslands than in other types of farmland and natural landscapes. The water retention ability provided by these landscapes, which is important for water supply and flow control, as well as erosion control and run-off prevention, is thus considerable (Bengtsson *et al.*, 2019; Isselstein & Kayser, 2014).

This vast root system can also perform an important carbon sink function. Young plant leaves have a higher photosynthetic rate than older leaves, and when animals remove foliage continuously by grazing they stimulate new growth while at the same time removing less effective older leaves prior to on-site decomposition. While green foliage can transform atmospheric carbon into organic matter, carbon stored aboveground is rapidly decomposed and re-released as carbon dioxide and methane as the foliage wilts or is digested. However, vast amounts of the carbon that plants use as nutrient reserves are stored in their roots and large amounts of plant-origin carbon are also bound in the surrounding soil (Bengtsson *et al.*, 2019). The soil carbon content of permanent grasslands is much greater than that of croplands and sometimes as great as that of forest soil (Bengtsson *et al.*, 2019), as long as the soil is left undisturbed. Tilling and re-seeding release soil-bound carbon to the atmosphere. Carbon sequestration has been shown to increase when grassland management is intensified by increased nutrient input (Kätterer *et al.*, 2012), but many indigenous grassland species are sensitive to over-fertilisation.

Taking the full picture into consideration, several studies suggest that the positive climate effects of grazed grasslands may balance out the negative effect of greenhouse gas emissions from livestock production or even have an overall positive climatic impact (Batalla *et al.*, 2015; Bellarby *et al.*, 2013). On a cautionary note, however, it is easier and faster for soils to lose than to gain carbon, so any positive climate effects of grazing ruminants can be greatly reduced by any intensive pasture maintenance practices, such as use of artificial fertilisers, frequent tilling and re-seeding, or overgrazing (Röös *et al.*, 2017; Smith, 2014; Garnett *et al.*, 2013).

2.3.3 Constraints to grazing

Despite the numerous benefits of grazing listed above, there are also several constraints that explain the decrease in grazing. These constraints need to be understood and addressed if grass-based production systems are to be stimulated. While some constraints are universal, others are more dependent on climate, geographical, political and/or socio-economic aspects, while yet others are specific to year-round pasture-based dairy farming (for a more exhaustive overview, see *e.g.* van den Pol-van Dasselaar *et al.*, 2020; van den Pol-van Dasselaar *et al.*, 2016; Hennessy *et al.*, 2015; van den Pol-van Dasselaar *et al.*, 2008).

This thesis primarily examined resource-related and climate constraints to grazing in northern European systems traditionally practicing seasonal grazing. Structural changes, intensification and specialisation of dairy farming have brought a high input/high output production model in the northern Europe region, meaning larger herds (*larger* relative to country and region) aiming at maximising milk yield per cow. This is in contrast to the pasture-based dairy production pursued in *e.g.* New Zealand, Australia and Ireland, which aims at maximising milk yield per unit pasture.

Important constraints for the Nordic region are the short summers and long, cold winters, requiring sturdy and weather-proof animal housing capable of carrying heavy snow-loads. Where available area, outdoor season length or both are restricted, keeping fewer animals per tonnage of produce has been a rational strategy. This saves on the area required for spreading slurry, while keeping within effluent standards, and/or reduces the number of cubicles needed in housing units, while maintaining total production. However, it also requires compromises, such as increasing fraction of concentrate feed in the ration and reduced grazing. This strategy has led to high average milk yield in the Nordic countries, ranging from 8,120 kg per cow in Norway (TINE Produsentrådgiving, 2020) to 10,400 kg per cow in Denmark, with Finland and Sweden intermediate (NMSMt, 2020).

In high-yielding seasonal grazing systems, diet formulation during the grazing season is the first main obstacle. In a review by van Vuuren and van den Pol-van Dasselaar (2006), potential maximum milk yield sustained by a grass-diet alone was calculated to be 22-28 kg milk/day, restricted by maximum dry matter intake (DMI) capacity. Those authors concluded that cows with daily yield greater than ~28 kg milk/day need supplementary feeding to meet their energy and protein requirements. Feeding on grazed grass, rather than being fed grass silage, is a slower process, as the animal needs to bite off and chop the forage itself prior to chewing cud. Thus even if a high-yielding cow had the rumen capacity for sufficient roughage DMI for greater yield, the time spent foraging would have to increase to such a degree that rumination and milk synthesis time would be impaired. Relying on grazing alone can thus negatively affect the energy balance of high-yielding dairy cows (Melin *et al.*, 2005; Chilibroste *et al.*, 1997).

Another complication with relying on pasture DMI in a system with supplementary feeding is determining daily nutrient intake from pasture, and thus supplementary feed requirements. Estimation of DMI is difficult even in laboratory conditions. To my knowledge, good cow-side decision tools for real-time intake estimation are currently not yet available to farmers (various strategies have emerged and are currently being tested since the onset of my enrolment, *e.g.* Schils *et al.*, 2019; Giovanetti *et al.*, 2020). Sward height to dry matter ratio can vary considerably between different seed mixes and with incidence of dicot weeds, both from year to year and within the grazing season. Even when an updated regression between sward height and DM yield is available, estimates of DM removed from pasture can be grossly overestimated due to *e.g.* trampling and fouling. The nutrient content per kg DM also varies considerably (Peyraud & Delagarde, 2013). For example, the sugar content differs considerably between evening grass and morning grass; foliage after a sunny summer day has a high content of freshly synthesised sugars, but after a night with no photosynthesis the majority of these will have been consumed by the plant (John *et al.*, 2019). Nutrient content also varies greatly throughout the summer season, with neutral detergent fibre (NDF) content increasing, and metabolisable energy and crude protein (CP) content decreasing, with pasture maturity (*e.g.* Marshall *et al.*, 1998). Further confounding intake estimations and efforts at ration optimisation, there is a substitution effect whereby supplementary feeding negatively affects time spent grazing and DMI obtained from pasture, increasing the need for supplementary feeding.

Some studies evaluating animal welfare in pasture-based dairy production highlight the risk of body condition loss or even hunger as a risk to welfare on pasture (Mee & Boyle, 2020; Beggs *et al.*, 2019; Arnott *et al.*, 2017; Hernandez-Mendo *et al.*, 2007). A solution often employed by Swedish and Norwegian farmers in order to comply with grazing legislation, and at the same time not risk production losses due to insufficient nutrient coverage, is to continue feeding a full indoor ration of grass silage or total-mixed ration while also offering pasture. While this meets the nutrient requirements of the animals, providing both can be a costly solution.

Increasing herd size increases the need for land for feed production. In farm operations with restricted grass production, this can increase competition between area used for grazing and area used for feed production to a level where grazing is not viable, as so much of the grass produced is lost to trampling or soiling. For many farmers, the existing land base of farm has not been sufficient to sustain feed production with growing herd size, increasing their need to lease or acquire additional land (Statistics Norway, 2020b) or rely on purchasing roughage feed on the open market. Either option significantly increases the alternative cost of pasture land. Land acquisition and leasing also increase land fragmentation, increasing time expenditure and input factors in the form of time, tyres and diesel, further adding to the cost.

Increasing herd size also make grazing more difficult even when total available land is not a challenge. In general, area of available land just outside the barn doors does not increase with increasing farm size and herd size. This complicates provision of adequate pasture area close to the milking unit. The solution is often either increased grazing pressure by increased stocking rate on same area of pasture land as before, or incorporation of additional land into the grazing area, which increases walking distance to the milking unit (Burow *et al.*, 2014) and increases the need for grazing infrastructure, such as permanent cow tracks.

Depending on soil type and precipitation levels in a region, the groundwork required and maintenance of permanent cow tracks can be quite costly. Lanes and swards with low trample resistance may also increase the risk of hoof damage, both by prolonged exposure to mud and by uncovering sharp stones and other foreign objects. Muddy and trampled pasture also reduces cow cleanliness and potentially raises the insect load, increasing the risk of cows developing mastitis and integument lesions and reducing cow welfare.

To allow for control of feed supply, indoor housing in modern buildings also permits control of environmental factors. Heat stress is known to negatively affect cow performance, primarily through reduced feed intake and milk yield. The thermoneutral zone of dairy cattle varies depending, among other things, on adaptation to where the individual was raised and relative humidity (RH). Kibler (1964) concluded that a temperature-humidity index (THI; an indicator of combined heating-effect of ambient temperature and RH) value greater than 72 increases the risk of heat stress considerably. With the changes in body size and milk yield of modern dairy cattle, and consequently in their metabolic rate and intrinsic heat generation, since Kibler's initial studies in the 1950s, the threshold THI value is presumably much lower now. Thus, it stands to reason that cows may experience heat stress out on pasture even in temperate regions. The rule of thumb for cattle housed in Norway is a thermoneutral zone ranging from -15 to 20°C, meaning that heat stress may occur already from temperatures of 20°C when assuming RH of around 80%, which by Kibler's equation would give a THI value of 67. Several previous studies on animal welfare in pasture-based solutions have identified increased heat load as a potential disadvantage to animal welfare on pasture (*e.g.* Mee & Boyle, 2020; Arnott *et al.*, 2017; Polsky & von Keyserlingk, 2017). Behaviour studies have shown that cows show a preference for remaining indoors or seek shade rather than grazing during the warmer hours of the day (Spörndly *et al.*, 2015; Falk *et al.*, 2012; Schütz *et al.*, 2009; Schütz *et al.*, 2008). Cows have also been found to show a stronger preference for being on pasture in the cooler hours at night (Smid *et al.*, 2018; Charlton *et al.*, 2013; Falk *et al.*, 2012; Legrand *et al.*, 2009).

Further complications come with instalment of an AMS unit. As mentioned, steady, well-functioning cow traffic is critical for success with AMS. Workarounds utilising the food motivation of cows function well under total confinement. However, including grazing in the system adds another element of complexity when targeting optimised robot utilisation. For example, cows need continuous access to move between pasture and milking unit, further increasing the already challenging requirement of a large land base in the immediate vicinity of the milking unit. Moreover, it is conceivable that free availability of lush and rich grasses, particularly when considering the novelty of outdoor access for animals kept indoors for the majority of the year, could reduce cows' motivation to visit to the milking unit, which is normally incentivised by offering concentrates.

Milking frequency is positively associated with milk yield (Stelwagen *et al.*, 2013; Svennersten-Sjaunja & Pettersson, 2008; Wagner-Storch & Palmer, 2003; Hogeveen *et al.*, 2001; Lacy-Hulbert *et al.*, 1999; Stelwagen & Lacy-Hulbert, 1996). Pasture-based AM systems tend to have a lower milking frequency than can be achieved in indoor systems (Lessire *et al.*, 2020; Scott *et al.*, 2015; Lyons *et al.*, 2013a; Lyons *et al.*, 2013b; Lyons *et al.*, 2013c). A similar tendency has been reported during the grazing season for primarily indoor-based AMS systems with seasonal grazing (Spörndly & Karlsson, 2015). One proposed explanation for this decrease in milking frequency is the increased walking distance from pasture to milking unit (Motupalli *et al.*, 2014; Charlton *et al.*, 2013; Lyons *et al.*, 2013a; Spörndly & Wredle, 2004), although not all studies have found distance to be important (Dufrasne *et al.*, 2012; Jago *et al.*, 2002; Ketelaar-de Lauwere *et al.*, 2000). Reviews by Lyons *et al.* (2014) and John *et al.* (2016) suggest that a distinction should be made between grazing experiments carried out in pasture-based systems and those carried out in systems where animals are kept indoors during winter. Lyons *et al.* (2014) concluded that there is an upper maximum to how far cows are prepared to walk for voluntary milking, but that this is greater for cows kept in pasture-based AMS systems. In a recent meta-analysis of factors influencing milking frequency of cows milked in AMS combined with grazing, Lessire *et al.* (2020) found that, among factors that can be modified, *e.g.* maximum distance from pasture to milking unit, concentrate supply level in milking unit, minimum milking interval and increased concentrate supply at longer minimum milking interval, only the latter induced a significant increase in milking frequency.

Considering the challenges of estimating pasture DMI and thus optimising the diet, the increased energy expenditure associated with increased exercise and prolonged eating time, and the decrease in milking frequency for cows on pasture, many farmers believe that high-yielding dairy cows, in particular those milked in AMS, will fail to maintain high milk yield when on pasture (Becker *et al.*, 2018; Kristensen *et al.*, 2010). However, there is no documented evidence of an unambiguous relationship between milking system and any objective measure of response to grazing.

The abolition of milk quotas in the European Union (EU) made maximising production more desirable and caused milk prices to fluctuate more. In combination with the debt burden from investments in AMS and new-build or refurbishment of animal houses, and generally narrower margins overall, farm finances have become more vulnerable. Since farmers have poor expectations for a combination of grazing and AMS, the introduction of AMS has generally been associated with a decrease or even cessation of grazing (van den Pol-van Dasselaar *et al.*, 2020; Hennessy *et al.*, 2015; Bühlen *et al.*, 2014). Less than 3% of dairy cows in the USA are provided with access to pasture (USDA, 2007). From 2008 to 2012, the average proportion of dairy cows with pasture access in Europe declined from 52% to 35% (Reijs *et al.*, 2013). Although not monitored explicitly, it is safe to say that, together with abandonment and urbanisation, the changes to agricultural production in recent decades have run counter to consumer and political desires.

“She looked like the kind of person who asked questions. And her hair was too red and her nose was too long. And she wore a long black dress with black lace fringing. No good comes of that sort of thing.”

– Terry Pratchett

3. Aims

The overall aim of the work described in this thesis was to identify feasible solutions for optimisation of a system combining grazing with automatic milking in a Nordic setting, maintaining daily milk production when offering high-yielding AMS cows a diet with a substantial proportion of grazed grass in the roughage ration.

Specific objectives of the work reported in Papers I-IV were:

- To compare production of AMS cows offered time-restricted access to either production pasture or an outdoors exercise paddock (Papers I and II)
- To study behaviour and time budgeting of time spent outdoors of AMS cows offered time-restricted access to either production pasture or an outdoors exercise paddock (Papers I and II)
- To investigate if the decreasing daylength characteristic of a progressing Scandinavian summer influenced time spent outdoors of AMS cows offered time-restricted access to either production pasture or an outdoors exercise paddock (Paper II)
- To investigate the relationship between milking system and changes in milk production parameters at pasture turnout, comparing cows milked in AMS to cows milked in a conventional system (Paper IV)
- To investigate the relationship between grazing strategy, in terms of level of expected roughage intake from pasture, and change in milk production parameters at pasture turnout (Paper IV)
- To evaluate the suitability of using recorded drinking water intake to predict pasture dry matter intake (Paper III)

“I seem to have spent a good part of my life - probably too much – in just standing and staring”
– James Herriot

4. Summary of the studies

The materials and methods used in the studies on which this thesis is based and the main results from these studies are summarised below. Detailed descriptions can be found in Papers I-IV.

4.1 Materials and methods

4.1.1 Study design

Experimental studies (Papers I-III)

The three experimental studies (Papers I-III) were highly similar in study design and animal management. Their common attributes are described in general terms below, followed by subsections describing the individual studies. All animal trials were conducted during the grazing season of 2015 and 2016. The animal trials were approved by Uppsala Ethics Committee for Animal Research (Uppsala, Sweden; registration number C20/15).

<u>Experimental site and animals</u>

The experimental studies described in Papers I, II and III were conducted on cows in the university herd of the Swedish University of Agricultural Sciences, which is kept at the Swedish Livestock Research Centre (59°50′N, 17°46′E; Uppsala, Sweden).

Primi- and multiparous cows of the Swedish Red Breed (SRB) and Swedish Holsteins (SH) were recruited from the university herd based upon days in milk (DIM), milk yield and somatic cell count (SCC). The cows were blocked according to parity, pre-experimental milk yield and breed, and then randomly assigned to one of two treatment groups: exercise paddock (EX) or production pasture (PROD). The two groups were checked for balance with respect to mean pre-experimental DIM, milk yield, milking frequency and body weight, by simple *t*-test.

Fluctuating numbers of non-experimental cows were included in the experimental herd to match milking unit capacity, and subjected to the same treatments as their experimental counterparts.

<u>Treatments and management</u>

The two treatments ran in parallel, with both treatment groups cared for by same personnel, kept in same feeding and resting area indoors, milked in the same AMS unit, given access to respective outdoor areas (treatment PROD or EX) during the same hours of the day, and fed the same grass silage and concentrates indoors.

Group PROD cows were allocated a new strip of pasture daily, with a minimum of 15 kg DM herbage available per cow (plus back-grazing), in addition to a restricted grass silage ration of 6 kg DM/cow and day available to them only during the hours when restricted to staying indoors. Group EX cows had access to the same grass-covered paddock (<1kg DM pasture/cow) throughout the experiment, and *ad libitum* grass silage indoors for 24 h. The two grazing systems are illustrated in Figure 2.

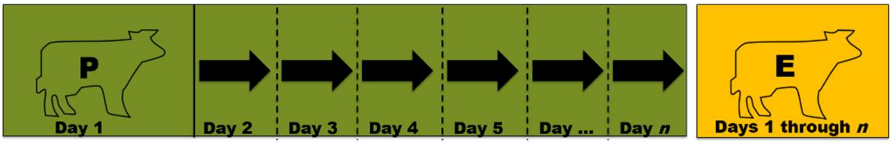


Figure 2. Illustration of the two pasture treatments used in Papers I-III. Letters correspond to treatment; production pasture (P) and exercise paddock (E). Production pasture cows had a daily allocation of a new pasture strip of minimum 15 kg dry matter (DM) grass per cow in group, with back grazing. Exercise pasture cows were given access to the same grass-covered paddock throughout the study, maintained at <1 kg DM pasture available per cow in group.

In addition to roughage, both treatment groups were offered a restricted concentrate ration. This ration was calculated individually, based on milk recording made the day before start of the transition period to pasture and an assumed daily roughage intake of 12 kg DM (10.5 MJ of ME/kg of DM). The concentrate ration was adjusted fortnightly to cover daily requirements according to a standardised lactation curve. Individuals with pre-trial yield >40 kg energy-corrected milk (ECM) per day also received an additional protein supplement according to milk yield.

The exercise pasture was mown on a regular basis to ensure a sward height offering negligible herbage access (<1 kg DM pasture/cow). Production pastures were mown when the group moved to the next field in the rotation.

After a selection gate outside the barn door, diverting cows to their correct lane according to treatment, two parallel lanes led to the entrance of the exercise paddock and the production pasture currently in rotation (Figure 3).

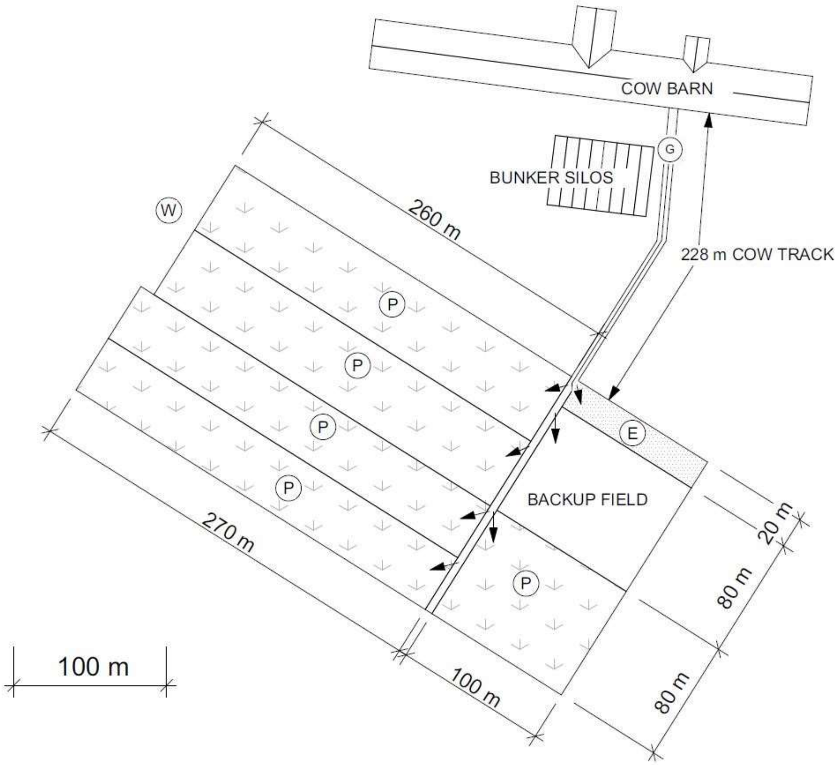


Figure 3. Schematic to-scale illustration of the outdoor layout of experimental pastures. Positioning of selection gate (G), cow track, exercise paddock (E), production pastures (P) and weather station (W) in relation to the cow barn. (Reproduced with permission from Journal of Dairy Science).

Recording and sampling

Milking events, kg silage intake (per feed trough visit), kg concentrate intake (concentrate feeder visits), body weight and passes through selection gates were recorded automatically at each occurrence. Milk yield was recorded automatically at every milking. Individual composite milk was sampled for analysis fortnightly during a 24-h period.

Pasture (grab samples) and grass silage (from feed troughs) were sampled daily and pooled weekly for chemical analysis. Pasture samples were dried and stored at room temperature, whereas silage samples were stored at -20 °C until analysis. Batch samples of the concentrates fed were taken upon delivery to the farm.

Pre- and post-grazing sward height were measured daily on PROD pasture as the basis for pasture allocation and pasture utilisation estimation, and three times per week on EX pasture to monitor and ensure minimal herbage access. Sward height was related to herbage DM mass by regression analysis for sward mass estimation. The regression, which was updated fortnightly, was determined by measuring compressed sward height and clipping 20 random 0.25 m^2 squares at 3 cm stubble height.

Botanical composition and development stage of the pastures were determined throughout the experimental periods by randomly selecting 10 of the regression clippings for hand separation into grass leaf laminae, grass stems including inflorescence, clover laminae, clover inflorescence including petioles, dicot weeds and dead matter fractions.

Outdoor behaviour observations were performed on all individuals in both treatment groups. Scan recordings of location (cow lane or pasture) and activity (lying down, grazing, idling) at 15-minute intervals of each individual cow outdoors were made once for obtaining a pre-experimental covariate value, and later fortnightly throughout the experimental period.

A weather station situated directly adjacent to the grazing area recorded hourly outdoor temperature, precipitation and RH.

Laboratory analysis

Composite milk samples were analysed for fat, protein and lactose content, and SCC.

The daily silage samples taken from feed troughs and hand-plucked pasture samples were dried, milled and pooled to weekly samples, prior to laboratory analysis of DM, ash, Kjeldahl nitrogen (N), ash-free NDF, and 96 h in vitro digestibility for metabolisable energy (ME) estimation.

Fortnightly pooled silage samples directly from the bunker silo were used for obtaining silage juice for pH determination, content of acids and alcohols, and ammonia concentration.

Concentrate samples were analysed for DM, ash, crude protein and ash-free NDF. Metabolisable energy value was taken from the product declaration provided by the manufacturer.

Specific methods in the morning/evening part-time grazing study (Paper I)

The experiment described in Paper I ran from 8 June to 27 July 2015, preceded by a three-week adaptation period. At the start of the adaptation period (18 May), the sun rose at 0407 h and set at 2126 h. On the shortest day of the experimental period (26 July), sunrise was at 0418 h and sunset at 2121 h.

Both treatment groups had access to their respective outdoor areas during a 4.5-h morning period and a 4-h evening period (Figure 4). Group PROD cows had access to their silage ration between 1800 and 0600 h.

An initial 40 cows (23 SRB, of which five primiparous, and 17 SH, of which four primiparous) entered the experiment. One cow in group EX (primiparous SRB) died halfway through the experiment (diagnosed post-mortem with exsanguination by acute hardware disease unrelated to the experiment), and her recordings up to that point were removed from analysis. Mean pre-experimental body weight, DIM, milk yield and milking frequency of the two treatment groups were comparable.

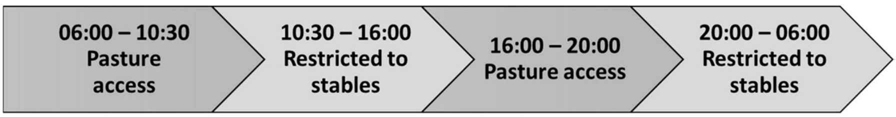


Figure 4. Daily schedule used for cows in Paper I and III. Times of the day with and without outdoor access for the two treatment groups.

Specific methods in the overnight part-time grazing study (Paper II)

The experiment described in Paper II ran from 23 June (summer solstice) to 11 September 2016, preceded by a one-week adaptation period. The first (and longest) day of the experimental period saw sunrise at 0329 h and sunset at 2214 h. There was no complete darkness during the first night. Sunrise on the last (and shortest) day was at 0609 h and sunset at 1920 h, and there were 5.6 h of true darkness (sun 18° or more below the horizon).

Both treatment groups had access to their respective outdoor areas during a 12-h evening and night-period (1800 to 0600 h) (Figure 5).

Forty-six cows entered the experiment. Five cows (two from EX, three from PROD) were removed due to mastitis (3), leg/claw problems (1) and incorrect automatic recordings (1). Their recordings up to the point where they left the experiment were removed from analysis, leaving 41 cows (26 SRB, of which 14 primiparous, and 15 SH, of which seven primiparous). The initial group means were found to be similar for body weight, DIM, milk yield and milking frequency, but correction of group means after removal of these five cows found revealed that pre-trial milk yield differed significantly ($P < 0.05$) between the two groups, being 3.5 kg higher for the PROD group than the EX group.

In addition to outdoor weather and climate, hourly recordings of indoor temperature and RH were also made.

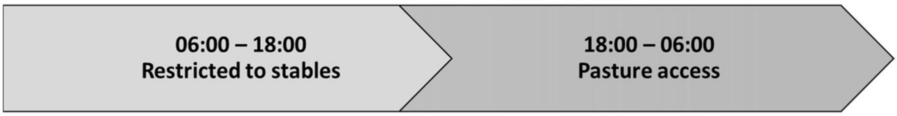


Figure 5. Daily schedule used for cows in Paper II. Times of the day with and without outdoor access for the two treatment groups.

<u>Specific methods in the dry matter intake estimation study (Paper III)</u>

The DMI estimation study (Paper III) was conducted during three five-day periods within the morning/evening grazing experiment in Paper I. Sampling method used in the DMI estimation study was tested and validated during the preceding indoor feeding season.

Treatment PROD in the grazing experiment was deemed the experimental group and treatment EX the control group. Silage intake rate was measured on individual level for the participating cows over the duration of the experiment in Paper I and post-experimentally, when all cows had access to an *ad libitum* 24-h silage ration.

Spot samples of voluntary urinations, minimum one per cow and day, were preserved by 0.1 M HCl and stored at -30°C until analysis of urea and creatinine (Autoanalyser III, SEAL Analytical GmbH, Norstedt, Germany).

Water consumption was recorded on individual cow basis. Accuracy of each flow meter was checked and an water bowl-specific calibration coefficient applied. Mineral and salt-mix supplementation of grass silage was interrupted throughout the three periods. Sampling frequency of pasture samples during the study was increased to four a day. Milk recording composite samples were collected over 72 h in each sampling period.

Weekly pooled silage samples from feed troughs and concentrate samples were digested with nitric acid and analysed for mineral content by inductively coupled plasma atomic emission spectroscopy (Spectroflame, Spectro GmbH, Kleve, Germany). The urine samples were analysed for potassium (K) concentration by the same method, omitting the digestion step.

Observational study – Paper IV

The observational study presented in Paper IV was a cross-sectional survey with retrospective elements. The reference population was the entire population of dairy cow farmers in Norway. The study was approved by the Norwegian Centre for Research Data (nsd.no, diary number 55137). All participants provided written informed consent. Anonymity of respondents was safeguarded by replacement of email address and identification number with an anonymous code in the dataset prior to data analysis.

<u>Questionnaire</u>

A comprehensive questionnaire about farm management, milking system and grazing strategy was developed. It was based on input from a workshop with interested farmers, advisors within nutrition and agricultural engineering, researchers within roughage production, grassland management, and animal welfare and ethology, educators, representatives of AMS manufacturers and farm equipment vendors.

The survey questions were tested for clarity and unambiguity on recently retired farmers (3) and extension specialists (2), and the survey mechanics of branching and logic were tested repeatedly prior to distribution. Appropriate revisions were made on feedback.

Using an online survey management system (Qualtrics, Provo, UT, USA), an email was sent to all Norwegian dairy farmers with a valid email address registered. This contained an invitation to participate, an individualised access link to the survey, a brief description of the project, a detailed description of registry data to which access was requested, information about time frames for depersonalisation of data and opt-out options in accordance with European General Data Protection Regulation (GDPR), and contact information on the project manager. The questionnaire consisted of two parts sent out separately. Only sections of part one were included in Paper IV.

Part one consisted of factual questions: a mandatory request for active consent, structural aspects of the farm, fulfilment of grazing/exercise legislation, farm economics and demographic background of respondent. The questions used in Paper IV related to structural aspects of the farm (milking system), grazing management of lactating cows (turnout month, how the exercise legislation is fulfilled for this animal category), and demographics of respondent (sex, age, marital status, years of experience as dairy farmer). Fulfilment of exercise legislation was categorised into three strategies: production pasture (DMI from grazed grass comprising a substantial part of daily roughage ration), exercise pasture (access to grass-clad outdoor area, but negligible DMI from grazed grass), and zero grazing (access to an outdoor area/hard bedded paddock in close proximity to barn with a surface other than grass cover).

Apart from consent, none of the questions were mandatory. All questions were close-ended, with an open-ended option for “other”-responses. It was distributed on 14 February 2018. Non-responders received up to two reminders by email, and data collection closed on 1 March. As motivational compensation, surveys completed to at least 90% were entered into a sweepstake.

Collection of registry data

Respondent contact information was purchased from the cooperative-owned agricultural register (Produsentregisteret SA, Oslo, Norway). The address list contained a holding identification number and email address of each holding registered as a dairy unit (specialist units and units with mixed farming, TINE and non-TINE members).

Data were retrieved from the NDHRS, managed by TINE Extension Services, for participating herds that had provided informed consent for this data retrieval.

Herd data for 2017 contained: annual benchmarking statistics (herd size in cow equivalents, 305-d milk yield, concentrate supplementation level in terms of kg concentrates/100 kg ECM, dairy delivery percentage, culling rate of primi- and multiparous cows, heifer recruitment percentage) and monthly mean quality of delivered bulk-milk (arithmetic mean milk composition, freezing point and hygiene indicators, geometric mean SCC).

Individual cow data contained basic data with birth, breed and owner history, and monthly milk recordings with recording date, milk yield, composite sample analysis (milk composition, SCC) and reported concentrate supplementation level (in kg concentrates). Records of disease from 2017 and dates of artificial insemination, calving, drying off and culling from 2016-2018 were also included in the dataset for individual cows.

Dairy delivery data from 2017 were retrieved from the dairy delivery database (LDB) managed by the raw milk market regulator TINE Råvare. These contained: delivery date, kg conventional milk delivered and kg organic milk delivered for each bulk-tank delivery through the year, and results of weekly quality analysis (milk composition, SCC, freezing point, hygiene indicators) of delivered bulk milk.

The address list, herd level NDHRS data and LDB data were linked using the holding number, while holding number of current owner and life number were used for individual cow data, and email address for questionnaire survey responses.

Model outcome variables

The registry data were used for creating the model outcome variables. Four variables considered of economic interest to farmers were used to assess responses to pasture turnout: change in milk yield, change in kg milk fat, change in kg milk protein and change in SCC.

On herd level, the difference was expressed as daily change per cow contributing to the bulk-tank milk. On individual cow level, the difference was expressed as change per 30 days. Change was found by difference, subtracting the month prior to pasture turnout from the month after pasture turnout. A drop in milk yield after turnout would thus give a negative difference value. Outputs were created using herd as its own control on herd level (meaning that observed difference is difference in herd mean yield) and by using individual cow as its own control.

4.1.2 Statistical methods

Grazing strategy

In Papers I-II, statistical analysis of variance (ANOVA) was performed on milk variables, body weight change and behaviour data, using the SAS software (ver. 9.4, SAS Institute Inc., Cary, NC). The analyses were made with a mixed regression model. The following general model was used for all response variables:

$$\text{Response variable} = \text{covariate} + \text{Treatment} + \text{Parity} + \text{Breed} + \text{StartDIM} + \text{Week} + (\text{two} - \text{way interaction when significant})$$

where class variables were treatment (EX or PROD), parity (primi- or multiparous), and breed (SH or SRB), and continuous variables were StartDIM (*i.e.* DIM at experiment start) and week of observation (week). Cow was the repeated subject, and corresponding pre-experimental recordings of response variables were included as covariates.

Interactions between the variables treatment, parity, breed, StartDIM and week were tested by backward elimination, and included in the model if significant. Least-square means (LSM) were calculated for the fixed effects, and the differences between LSM were tested for significance using *t*-tests. Normality of the residuals was visually assessed by Pearson residuals panel for all analyses. All results presented are LSM ± standard error of the mean. Significance was set at $p<0.05$.

Dry matter intake estimation

Data in Paper III were analysed with SAS. Initial calculations were made using data for the control group (group EX) only, for calculation of correlations between different factors. The total DMI in the control group was then regressed against daily drinking water intake and daily urine excretion. Daily CP intake was regressed against urinary urea N excretion whereas daily K intake was regressed against daily urine excretion, urinary K excretion and urinary K excretion corrected for milk K.

Regressions were first performed by a mixed model with random intercept for the individual cow (St-Pierre, 2001). However, since the mixed model resulted in little improvement compared to a GLM model on experiment-wise means for each cow, this simpler model was chosen.

The regressions obtained for the control group were directly applied separately on water intake and urinary excretion for the experimental group (group PROD), calculating total intake estimate for DM, K and CP for each cow in each period. Pasture intake was then calculated by deducting silage and concentrate intakes of DM, K and CP. The intake estimates were then tested for their correlation to individual pasture eating time from behaviour observations, with or without taking into account each cow's eating rate of silage.

Observational study

In Paper IV, occurrence of grazing was visualised by frequency distribution. Package lme4 (Bates *et al.*, 2015) in statistical software R (2020) was used to assess differences between AMS and manual milking, and between zero grazing, exercise pasture and production pasture, in response to pasture turnout. Multivariate models were fitted on both herd level and individual cow level, using a multiple linear regressions (MLR) approach on herd level and, due to lack of independence between cows in the same herd, linear mixed models (LMM) with herd as random intercept on cow level.

Explanatory variables and first-order interactions were determined *a priori* for a global model for the two levels and the four response variables. Prior to model selection and fitting, the dataset was checked for apparent faulty data entries and assessed for dependencies and the need for data transformation. The variables of the global models were checked for collinearity and the slope for each combination of milking system and grazing strategy, and each combination of DIM and parity, was inspected visually. Adjustments were made accordingly and left a null-model to select from for each response variable and level.

Model selection for herd-level MLR was performed by backward stepwise elimination of first-order interactions and main effects, with lower Akaike information criterion (AIC) as exclusion and re-entering criterion. Model selection for cow level LMM was done by backward selection by a likelihood ratio test with maximum likelihood estimation. A series of embedded models were tested and ranked by AIC, as described in Zuur *et al.* (2013). Confounding was controlled for in both MLR and LMM by subsequent forward stepwise inclusion.

The fitted models were verified by testing their fulfilment of model assumptions, *i.e.* by plotting residuals versus fitted values, versus each covariate in the model and versus each covariate not in the model, as described in Zuur *et al.* (2009) and Zuur & Ieno (2016).

A standard method has not been established for describing proportion of variance explained in LMM. Using package performance (2020), marginal and conditional R^2, quantifying variance explained by fixed effects and by fixed and random effects combined, respectively, was calculated, as proposed by Nakagawa & Schielzeth (2013) and Johnson (2014).

4.2 Main findings

4.2.1 Morning/evening part-time grazing study (Paper I)

Group EX and group PROD did not differ significantly with respect to milk yield, milk solid yields or SCC, with the exception of daily milk protein yield, which was greater in group PROD.

Overall, milking frequency was significantly higher in group EX. There was a significant interaction between effects of StartDIM (DIM day 1 of experiment) and treatment on milking frequency. In early lactation (StartDIM = 100), there was little difference between the two groups, but in mid-lactation cows (StartDIM = 190), milking frequency was significantly greater for group EX than for group PROD. Milking frequency also changed as the summer progressed, with an increase of 0.03 milkings/d for each week the experiment advanced.

Group PROD spent more time with outdoor access than did group EX, both in total and in time spent resting outdoors in addition to time spent grazing. There was also a significant interaction between treatment and experimental week with respect to time spent resting outdoors. Thus, while group PROD spent more time than group EX resting outdoors in the first experimental week, the two groups spent the same amount of time resting outdoors in the last experimental week.

Behaviour differed between the morning and afternoon outdoor access allocation sessions, both within and between treatments. Compared with group PROD, fewer cows from group EX ventured outdoors in the morning. In the afternoon, most cows of both groups took the opportunity to go outside. Group PROD cows spent most of the available time outdoors in both morning and evening, but they spent more of the time idling in the morning and showed more pronounced grazing activity in the afternoon.

4.2.2 Overnight part-time grazing study (Paper II)

Group EX had significantly higher milk yield than group PROD in terms of kg milk (daily recordings from AMS). However, there was no significant difference between the two groups in terms of kg ECM (fortnightly milk recordings with composite samples analysis).

Utilisation of available outdoor time was low for both groups. The EX cows began to move indoors somewhat earlier and at a faster speed and in a more synchronous manner than the PROD cows (on average at approximately 2000 h and 2100 h for group EX and PROD, respectively). However, 10-20% of PROD cows lingered outdoors grazing (until 2300 h). After returning indoors, neither group ventured out on pasture again during the remaining outdoor access time, for grazing or for resting. However, while group PROD spent a longer time outdoors and on pasture than group EX, the animals in group PROD allocated little of the time spent outdoors to activities other than grazing. Thus, time spent lying down outdoors was shorter for cows in PROD than for cows in EX.

Group PROD spent approximately the same time on pasture and actively grazing throughout the experimental period, while group EX decreased both time spent on pasture and time spent exhibiting grazing behaviour as the experiment progressed. However, total outdoor time (time on pasture + in cow lane) increased by approximately 1 h for both groups during the course of the experiment.

Group EX silage intake was quite evenly distributed over the 24 h, whereas silage intake in PROD group peaked twice. The first peak occurred in the morning, as soon as silage access was granted after termination of the outdoor access period at 0600 h. The second peak occurred at noon, when access to the remainder of the daily silage ration was given.

4.2.3 Dry matter intake estimation study (Paper III)

The predictor most correlated to total DMI for group EX cows was K intake corrected for milk K and regressed on urinary K excretion, which demonstrated the lowest root mean square error (RMSE). When used for estimating pasture DMI in PROD cows, it was also most correlated with the product of observed grazing time and silage intake rate.

Drinking water intake was well correlated with total DMI in group EX, but the pasture DMI estimates for PROD were not well correlated with grazing time and intake rate, although the estimated average was reasonable.

For urine volume, the outcome was the opposite to that seen for drinking water. It was less strongly correlated with DMI in group EX, but when the regression obtained was applied on group PROD, the correlation with the product of observed grazing time and silage intake rate was larger for urine volume estimates than for drinking water estimates.

All group PROD pasture DMI estimates were more strongly correlated with the silage intake rates recorded post-experimentally, when silage was once again allowed *ad libitum*, than with the intake rates recorded during the experiment, when allowance was restricted.

4.2.4 Observational study (Paper IV)

Occurrence of grazing

The results from the observational study showed that grazing is still a widespread practice in Norwegian dairy herds, with production pasture being by far the most common grazing strategy. However, choice of grazing strategy varied between milking systems. Notably, the use of exercise pasture and other outdoor access solutions such as bedded pack was more common among herds with AMS than herds with manual milking (Table 1).

Table 1. Strategy used by Norwegian dairy farmers to meet grazing legislation, as percentages of all survey respondents and specifically by respondents milking with automatic milking systems (AMS) during the grazing season.

	Overall $n = 2402$	**AMS** $n = 608$
Production pasture	66.7	58.3
Exercise pasture	11.4	29.4
Other outdoor solution	4.0	8.0
Dry off herd	2.3	2.3
Exemption decision	0.4	1.3
Does not graze, other	0.4	0.1
Non-response or not classifiable	14.8	0.6

Very few farmers reported not offering their lactating cows access to pasture or an outdoor environment. Approximately half of these farmers reported drying off the entire herd prior to turnout for synchronous autumn calving, and thus not having any cows in lactation during the grazing season. This drying-off strategy was also used extensively among the respondents with AMS who did not offer lactating cows outdoor access. However, there were some cases of farmers not complying with grazing legislation and the rate of non-compliance was greater among AMS farmers than among all farmers.

Response to pasture turnout

Overall, when modelling for objective measures of response to pasture turnout, the multilevel models for individual cow with herd as random intercept consistently explained more of the variation in the data than the unilevel models for herd means.

Milk (kg ECM), milk fat and milk protein yields showed an overall negative trend, and SCC an overall positive trend, from the month preceding pasture turnout to the month following it. The average decline in individual cow ECM was greater than expected based on progressing stage of lactation alone, assuming standardised lactation curves (Volden, 2011).

Milking system

Milking system did not show a relationship with any of the variables (*i.e.* kg ECM, kg milk fat, kg milk protein, SCC in bulk milk deliveries and individual test-day samples) used to measure response to pasture turnout, either on cow level or for bulk milk deliveries to a dairy. When milking system was forced upon the models, the effect was marginal.

Grazing strategy

In most cases, grazing strategy did not show a relationship with the response measures to pasture turnout, either on cow level or for bulk milk deliveries. Exceptions were bulk milk protein and cow level milk fat, for which production pasture and exercise pasture had the most positive estimates, respectively. When grazing strategy was forced upon the remaining models, the effect was marginal.

Other findings

Cows kept in organic management showed a smaller decrease in ECM around pasture turnout than cows kept in conventional management.
The changes in response variables were generally more favourable for primiparous cows than for multiparous cows.

5. General discussion

5.1 Milk production and milking frequency

The old dogma that grazed grass is a cheap feed and a profitable form of ruminant production has come under question regarding its viability for high-output production (Spörndly *et al.*, 2015; Swedish Board of Agriculture, 2014; Spörndly & Kumm, 2010). A grazing system is no longer automatically preferable to dairy farmers, as indicated by declining occurrence of grazing (van den Pol-van Dasselaar *et al.*, 2020). This is to a great degree due to structural and production-related changes in modern agriculture. The single factor contributing most to dairy farm profitability is kg milk sold either to a dairy plant or directly to consumers (Overrein *et al.*, 2018). Thus, it is reasonable to assume that farmers' choice (not) to graze is affected by the widespread belief among farmers that high-yielding dairy cows, in particular those milked in AMS, will fail to maintain high milk yield on pasture, unless provided with a full indoor feed ration in addition to pasture (Becker *et al.*, 2018; Kristensen *et al.*, 2010). For farmers choosing to graze, this belief affects the degree to which they rely on grazed grass as part of the ration for high-yielding dairy cows.

Analysis of registry data for 449 active Norwegian farms in Paper IV revealed no evidence supporting the notion that cows milked in AMS respond any differently to pasture turnout than cows milked in manual milking systems, either with regard to kg milk or any other of the traits examined. The analysis also provided no support for the claim that response to pasture turnout was influenced by the type of outdoor access offered for lactating cows (Table 2).

Table 2. Production data (least square means) for cows on production pasture (PROD) or exercise pasture (EX) in four separate part-time pasture access studies: 9.5 & 12-h day time pasture access pilot study (Spörndly *et al.*, 2015, Exp 1 & 2), 8.5-h morning/evening pasture access (Paper I), and 12-h night time pasture access (Paper II), and mean difference (cow-level) in change in production from month before to after pasture turnout (Paper IV), grouped according to farmer-reported grazing strategy of PROD, EX, or zero-grazing on outdoor bedded pack (BP), with EX as reference level and PROD and BP relative to this.

	Daytime, exp. 1[1]		**Daytime, exp. 2**[2]		**Morning-evening**[3]		**Overnight**[4]		**Questionnaire survey**		
	PROD	EX	PROD	EX	PROD	EX	PROD	EX	PROD	EX	BP
Milk, kg/d	35.6^{a}	33.3^{b}	32.2^{a}	32.6^{a}	36.3^{a}	35.1^{a}	31.7^{a}	33.1^{b}			
ECM[6], kg/d	35.8^{a}	34.2^{b}	32.5^{a}	32.1^{a}	34.0^{a}	32.5^{a}	32.3^{a}	31.5^{a}	-0.04^{a}	0^{a}	-0.75^{a}
Milk fat[7]	4.03^{a}	4.25^{b}	4.04^{a}	3.91^{a}	1.29^{a}	1.31^{a}	1.30^{a}	1.27^{a}	-0.015^{a}	0^{b}	-0.053^{b}
Milk protein[7]	3.36^{a}	3.37^{a}	3.37^{a}	3.32^{a}	1.19^{a}	1.08^{b}	1.07^{a}	1.05^{a}	0.006^{a}	0^{a}	-0.006^{a}
SCC[8]					1.73^{a}	1.80^{a}	1.48^{a}	1.46^{a}	3.82^{a}	0^{a}	1.52^{a}
Milking frequency	2.83^{a}	2.72^{a}	2.65[9]	P:2.75[8] M: 2.51[9]	2.46^{a}	2.76^{b}	2.27^{a}	2.31^{a}			

a, b Means within experiment with different subscripts differ significantly ($p<0.05$).

[1]Pasture access 06.00-15.30 h, group PROD >20 kg DM pasture + *ad libitum* silage, group EX <3 kg DM pasture + *ad libitum* silage.

[2]Pasture access 06.00-18.00 h, group PROD 15 kg DM pasture + 6 kg DM silage, group EX <3 kg DM pasture + 16 kg DM silage.

[3]Pasture access 06.00-10.30+16.00-20.00 h, group PROD 15 kg DM pasture + 6 kg DM silage, group EX <3 kg DM pasture + *ad libitum* silage.

[4]Pasture access 18.00-06.00 h, group PROD 15 kg DM pasture + 6 kg DM silage, group EX <3 kg DM pasture + *ad libitum* silage.

[5] Based on analysis of registry data for 449 Norwegian active dairy farms.

[6]Energy-corrected milk, calculated according to Sjaunja *et al.* (1990).

[7]Given in % in Daytime Exp.1 & 2, in kg/d in Morning/Evening and Overnight, and in difference in kg on test-day milking in survey study.

[8]Given in log10 in Morning/Evening and Overnight, and in difference in thousands on test-day milking in survey study.

[9]Interaction Treatment X Parity in Day time Exp. 2: Milking Frequency in group EX 2.75 and 2.51 for primi- and multiparous cows, respectively, similar frequencies for both ages in group PROD.

The only exceptions were change in kg milk fat on individual cow level, for which cows in herds using exercise pasture showed a less negative change than cows in herds using production pasture, and change in kg milk protein on herd level, for which herds using production pasture showed a less negative change than herds using exercise pasture (Table 2). However, there was a difference in how parity and production method influenced the reaction of individual cows to being turned out to pasture. Observed changes in kg ECM, kg milk fat and kg milk protein yield around pasture turnout were more negative for multi- than primiparous cows, and less negative for cows kept in organic management than for cows kept in conventional management. It is worth noting that the AMS herds included in this study, like the average Norwegian AMS farm, had on average quite a generous robot capacity in regard to herd size.

Prior to the morning/evening study (0600-1030 h + 1600-2000 h; Paper I) and the overnight study (1800-0600 h; Paper II), a pilot (daytime) study with two 12-h daytime pasture trials, Experiment 1 (0600-1530 h) and Experiment 2 (0600-1800), was performed with a similar study set-up and protocol as that used in Papers I and II (Spörndly *et al.*, 2015). These two experiments (see Table 2 footnotes) demonstrated potential for production pasture to either support significantly greater milk yield when provided on top of an indoor silage intake comparable to that of cows on exercise pasture; or to sustain a milk yield similar to that produced on a full indoor grass silage ration when provided as a substitute for part of the silage ration (Spörndly *et al.*, 2015). The findings in Paper I were similar to those in Experiment 2 of the daytime study, with similar yield of kg milk, kg ECM and kg milk fat displayed by the two experimental groups when indoor silage was restricted to 6 kg per cow and day in group PROD. The results in Paper I also showed significantly greater yield in kg milk protein in group PROD compared with group EX. In Paper II (overnight study), group PROD did not manage to maintain daily milk yield (kg/d) at a level comparable to that in group EX. This decline in comparison with the morning/evening study (Paper I) could be attributable to the warmer weather (Figure 6), the lower nutritive quality of the pasture (Figure 7) and the considerably shorter grazing time (Table 3) negatively affecting energy intake in the overnight trial (Paper II).

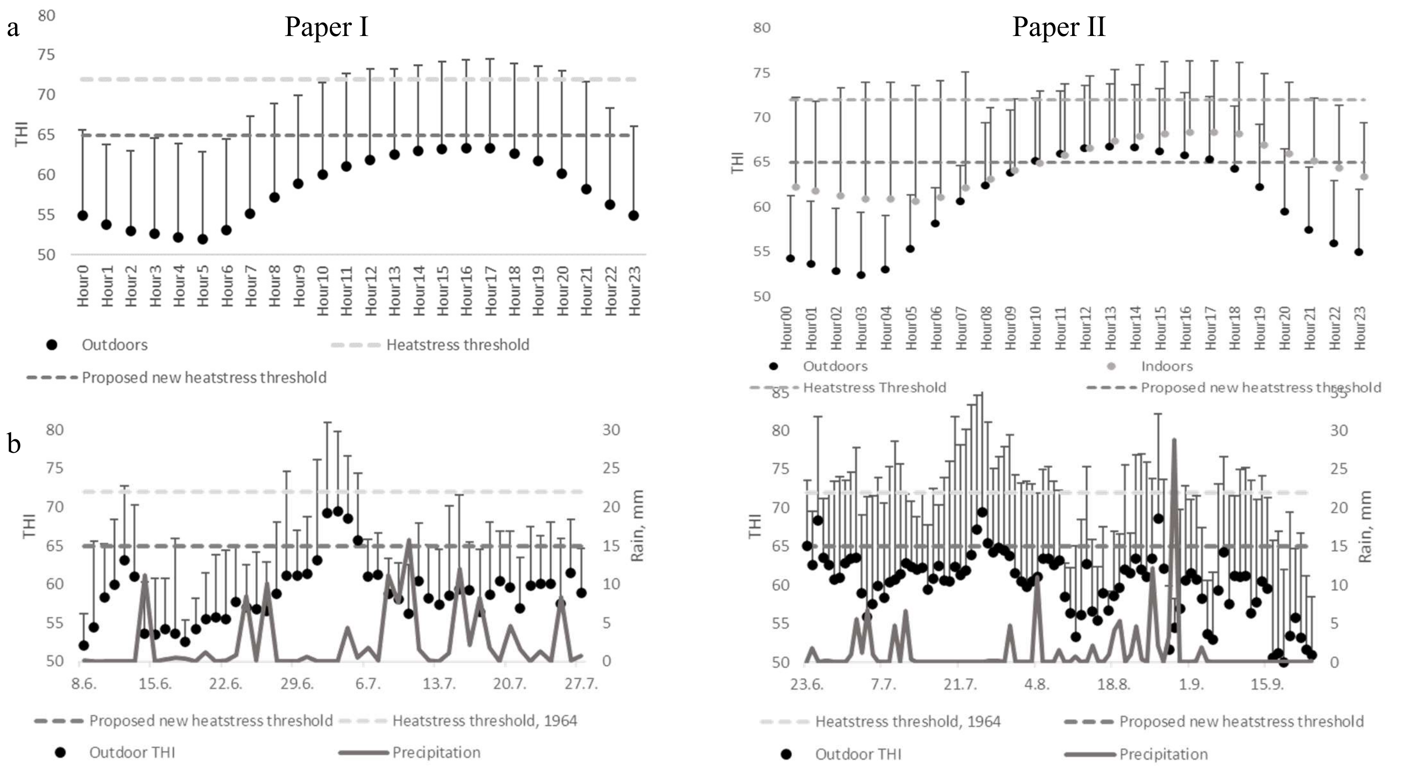


Figure 6. a) Diurnal temperature humidity index (THI) in Papers I & II, with hourly means (dots) and hourly maximum (error bars), b) Daily precipitation in mm and THI throughout the experimental period (dd.mm) in Papers I & II, with daily means (dots) and daily maximum (error bars). Kibler's (1964) heat stress threshold (THI 72) is indicated in both (a) and (b), as is a tentative threshold (THI 65) provided for discussion.

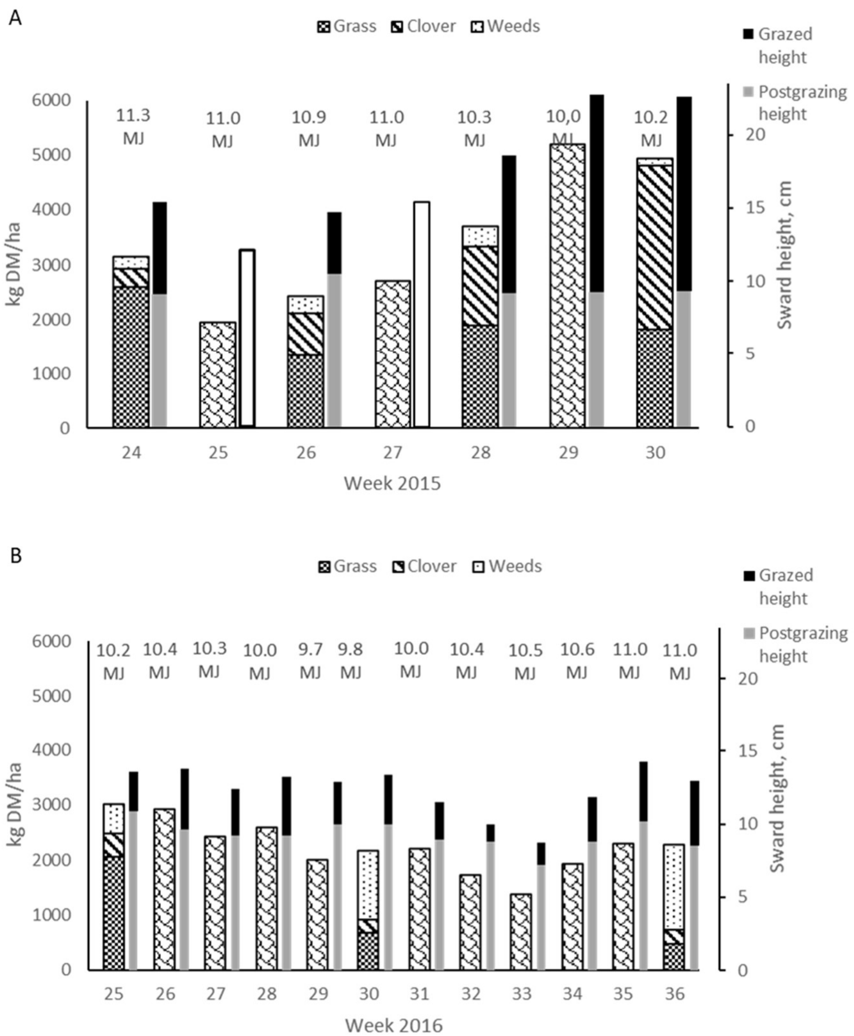


Figure 7. Mean available pasture herbage mass (wide bars; divided into botanical fractions of grass, clover and weeds for the weeks where botanical sorting was performed), metabolisable energy content of weekly pooled pasture grab samples, and mean weekly sward height (narrow bars) per experimental week in a) Paper I+III and b) Paper II. Grazed height + post-grazing height = pre-grazing height. As data on post-grazing heights, and thus grazed height, were missing for weeks 25 and 27 in a), pre-grazing heights are given.

The thermal environment is a major factor that can negatively affect dairy cows, especially animals of high genetic merit. Discomfort and stress from high outdoor temperatures can prevent cows from leaving the barn (Falk *et al.*, 2012; Schütz *et al.*, 2009; Schütz *et al.*, 2008). If avoidance of heat and direct solar radiation fails to prevent heat gain to exceed heat dissipation, a reduction in activity, appetite and feed intake to reduce innate heat generation through metabolic processes is an early thermoregulatory mechanism for maintaining physiological homeostasis. This results in decreased milk synthesis, which further decrease heat production (Kadzere *et al.*, 2002).

In summer 2015 (Paper I+III), temperatures were similar to the 30-year mean temperature in the Uppsala region and precipitation levels were almost twice the reference value during the experimental weeks (SMHI, 2017). The summer of 2016 (Paper II) experienced lower than average rainfall and higher than average temperatures. A particularly warm and dry period occurred midway through the experiment. The general shape of the circadian curves of mean hourly outdoor THI were quite similar for the two summers, but the magnitude differed, with greater THI for 2016 (Figure 6a). At first glance, the elevated THI around the clock throughout the experimental period could be suspected to have affected feed intake, behaviour and production in the cows, thus explaining the failure of group PROD in Paper II to maintain yield. However, the THI levels experienced were quite similar for animals in both treatments, as there was only a difference of approximately one hour between when group EX and group PROD withdrew from pasture and went indoors (Figure 9). Furthermore, estimated energy requirements, silage and concentrate intakes were comparable between groups PROD and EX across the two studies (Table 3). It would therefore be reasonable to assume that any negative impact of weather on production was similar for the two groups.

Nutritive quality of pasture can often be superior to that of silage used during summer months, in particular at the beginning of the grazing season when NDF content is still low and protein content high in pasture. This could be an advantage for a pasture-based system compared with feeding silage. Thus, efforts were made in Papers I-III to offer the best possible silage, in order to ensure that cows in group PROD were not favoured by experimental design or that performance of group EX was held back in any way by a sub-optimal indoor feeding regime. Efforts were also made to maintain pasture

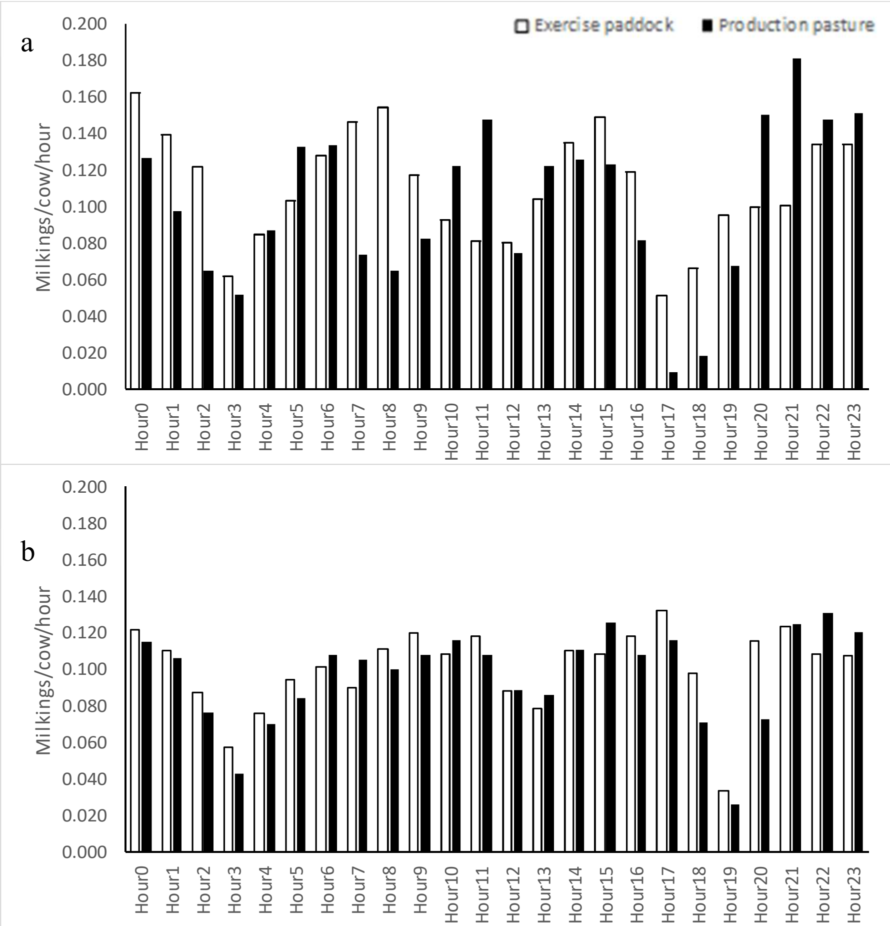
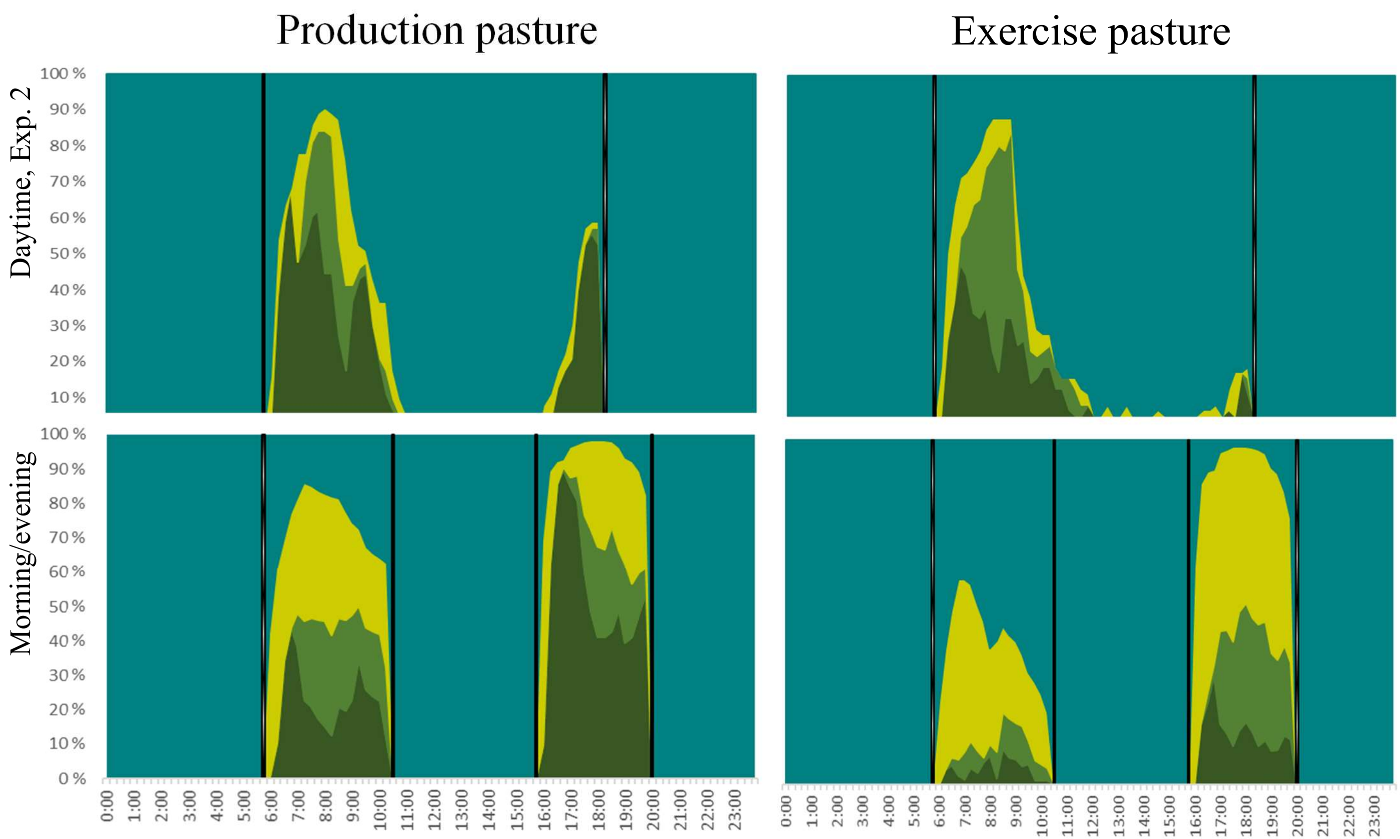


Figure 8. Average group milking frequency as milkings per cow by hour over 24 h and across the trial period for the exercise and production pasture groups in a) Paper I and b) Paper II.

quality, but these had to be within reasonable limits of labour and other input factors, comparable to conditions on a working farm. This representation of real-life mimicry was intended to improve the applicability of the findings, rather than describing best-case scenarios from an experimental situation that are impossible to achieve in real life. With the weather and precipitation described in Figure 6b, conditions seemed quite optimal for pasture growth in summer 2015 (Paper I+III) (Figure 7a). Available herbage mass remained well above 2,500 kg DM/ha throughout the study. Metabolisable energy content, CP and NDF remained at similar values throughout the experiment, as did grass to clover ratio and the level of maturation of the pasture. During the dry spell in summer 2016 (Figure 6b), temporary restriction of grass growth and a subsequent reduction in pasture ME content of pasture was seen, while NDF and protein content remained relatively stable (Figure 7b). However, herbage mass was not affected (Figure 7b). Apart from a sub-period in early August, both pre- and post-grazing herbage mass remained above 2,000 kg DM/ha, and provision of a pasture herbage allowance of at least 15 kg DM/cow and day could be maintained without difficulties. Furthermore, pasture intake estimates were comparable between the PROD groups in Papers I and II. However, the dry spell probably disadvantaged the cows in group PROD in Paper II, and could perhaps partly explain their failure to maintain yield.

The lower milk yield in group PROD, compared with group EX, suggested in Paper II was explained by the prolonged period that passed without any roughage intake between cessation of the intensive grazing session in the evening and the large silage meal as pasture doors closed in the morning (Figures 9 and 10). However, this contradicts results reported by Kennedy *et al.* (2011), who found no added effect of providing grass silage overnight, compared with offering no supplemental silage during overnight indoor confinement, when providing twice-daily pasture access for a period of either 3 or 4.5 h. There were some differences in experimental premises between the overnight study in Paper II and that by Kennedy *et al.* that could prevent direct comparisons. These included a difference in lactation stage of experimental cows (mid- vs. peak lactation), a difference in mean daily milk yield (31.7 vs. 28.3 kg/cow and day) and a difference in concentrate feed supplementation (9.9 vs. 3.0 kg/cow and day) of group PROD in Paper II and the silage treatment in Kennedy *et al.* (2011), respectively.

Furthermore, the silage and pasture in the study by Kennedy *et al.* were of more similar nutritive value than those in Paper II. Ferris *et al.* (2008) obtained conflicting results from two consecutive summers in a comparison of two grazing treatments (part-time grazing with silage supplementation during indoor confinement hours at night *vs.* a control with 24-h continuous grazing). In their first experiment, milk yield was significantly reduced in the silage-supplemented group, while in their second experiment it was significantly higher for the same group. This led Ferris *et al.* (2008) to conclude that milk yield response is determined by grazing conditions and



Production pasture
Exercise pasture
Daytime, Exp. 2
Morning/evening
100 %
90 %
80 %
70 %
60 %
50 %
40 %
30 %
20 %
10 %
0 %
0:00
1:00
2:00
3:00
4:00
5:00
6:00
7:00
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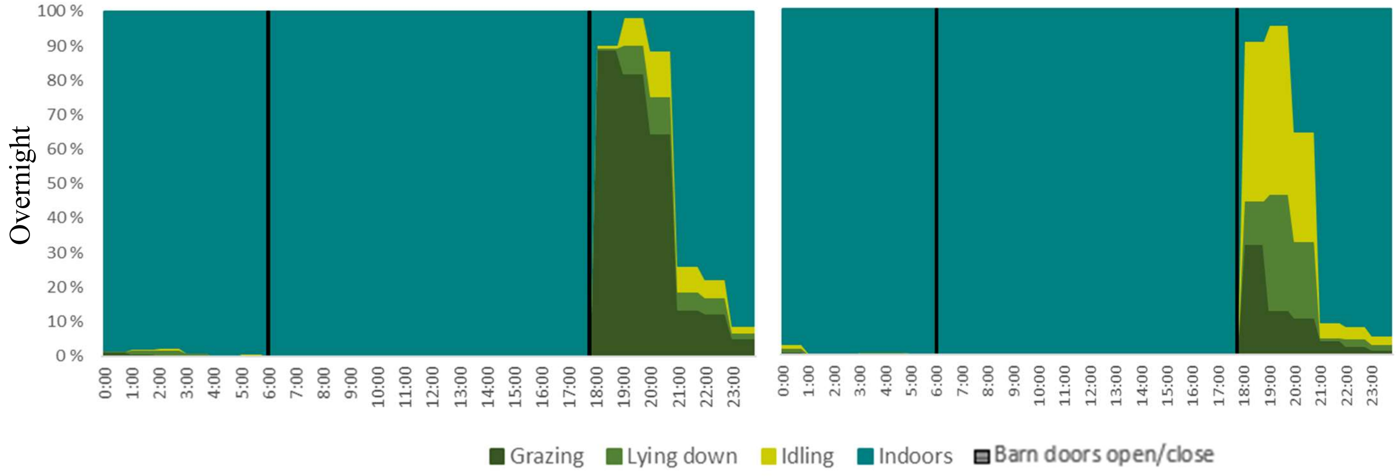

Figure 9. Daily outdoor activity of the groups with production pasture (group PROD) and exercise pasture (group EX) during pasture access hours; percentage of the group engaged in grazing, resting outdoors (i.e. recumbent, or in the process of lying down or rising), idling (i.e. any upright activities other than grazing), and remaining indoors, in three consecutive studies: (Top panels) A daytime pilot study (Spörndly *et al.*, 2015, Exp 2) with 12-h day time pasture access; (centre panels) studies with 4.5+4-h morning-evening pasture access (Paper I+III); and (bottom panels) a study with 12-h overnight pasture access (Paper II).

Table 3. Effect of access to production (PROD) and exercise (EX) pasture part-time on outdoor behaviour in two daytime experiments (Spörndly *et al.*, 2015), the morning/evening study (Paper I+III) and the overnight study (Paper II). Least square means of experimental period in hours (exploitation percentage of available pasture access period in brackets)

	Day time, exp. 1[1]		Day time, exp. 2[2]		Morning-Evening[3]		Overnight[4]	
	PROD	EX	PROD	EX	PROD	EX	PROD	EX
Outdoor time, hrs[5], (percentage of total outdoor access time)	3.1 (25.8)[a]	1.9 (15.8)[b]	4.5 (47.4)[a]	3.5 (36.8)[b]	6.9 (81.2)[a]	4.0 (47.1)[b]	3.9 (32.5)[a, e]	3.1 (25.8)[b, e]
Grazing time, hrs[5]	2.0[a]	1.1[b]	2.3[a]	1.1[b]	3.8[a, c]	0.6[b, c]	2.5[a, f]	0.7[b, f]
Resting time, hrs[5]					1.7[a, d]	1.3[b, d]	0.3[a, g]	1.0[b, g]
Pasture time, hrs[5]					5.6[a]	2.6[b]	2.8[a, h]	2.2[b, h]

[1]Pasture access 0600-1530 h (Spörndly *et al.*, 2015). [2]Pasture access 0600-1800 (Spörndly *et al.*, 2015). [3]Pasture access 0600-1030+1600-2000 h (Paper I+III). [4]Pasture access 1800-0600 h (Paper II). [5]Outdoor time = total time spent outdoors (incl. time in walkway), Grazing time = time spent with nose to ground biting off foliage (incl. grazing expressed on walkway), Resting time = time spent recumbent, lying down or standing up (incl. resting expressed on walkway), Pasture time = time spent on pasture area (grazing + resting + idling).

[a, b]Means within experiment with different subscript differ significantly (p<0.05).

[c]Interaction Treatment x DIM (P<0.0001); Grazing time cows with DIM = 100 at beginning of experiment: 3.4 and 0.7 h for PROD and EX, respectively (p<0.0001);
Grazing time cows with DIM = 190 at beginning of experiment: 4.3 and 0.6 h for PROD and EX, respectively (p<0.0001).

[d]Interaction Treatment x Week;
First experimental week outdoor resting time: 2.9 and 1.1 h for PROD and EX (p = 0.014), respectively; Last experimental week outdoor resting time 1.5 h for both groups (p = 0.71).

[e]Effect of week: Outdoor time increases overall with 0.09 h/week (p<0.0001).

[f]Grazing time increases overall with 0.02 h/wk. Interaction treatment x week (p<0.0001):
First experimental week grazing time 2.4 and 1.0 h for PROD and EX, respectively (p<0.0001);
Last experimental week grazing time 2.6 h and 0.3 h for PROD and EX, respectively (p<0.0001).

[g]Effect of week: Outdoor resting time increases overall with 0.036 h/week (p = 0.0053).

[h]Interaction Treatment x week: First experimental week pasture time 2.62 h and 2.53 h for PROD and EX, respectively (p = 0.62);
Last experimental week 3.01 and 1.93 h for PROD and EX, respectively (p<0.0001).

nutritive quality of the silage offered, rather than a universally applicable response prediction. Against this background and also considering the difference in nutritive quality of the pasture and silage available in the overnight study, the suggested explanation offered in Paper II that the prolonged period for group PROD without roughage intake reduced milk yield seems to be reasonable, at least for part of the difference seen between groups PROD and EX.

Despite similar milk yield in the two treatment groups in Paper I+III, group PROD had significantly lower milking frequency than group EX (Table 2). This difference in frequency most likely derived from the difference in location of feed source (feed bunker versus pasture) in relation to the milking unit. Cow motivation for being milked is lower than motivation to eat (Prescott *et al.*, 1998). The pattern of visits to the milking unit (Figure 8a) was recognisable as the time-frames of the experimental set-up when including the window for personnel to fetch late cows at 0500 h and 1500 h to the holding pen. However, the lack of decrease in milk yield, or even numerically greater milk yield, for group PROD in Paper I is in contradiction to most findings in the literature (*e.g.* Lessire *et al.*, 2020; Svennersten-Sjaunja & Pettersson, 2008). The observed difference in milking frequency (0.3 milkings/cow and day) was not nearly as extreme as that in experiments on milking two or three times a day frequently cited to highlight the importance of milking frequency. It would translate to a mean difference in milking interval of approximately 1.05 h between the two treatments in Paper I+III. In a study assessing effects of milking interval, Penry *et al.* (2018) found that milking interval would have to be prolonged either at very early onset in lactation or by more than 2 h to have an effect on milk production rates. In contrast, on comparing twice-daily manual milking with AMS, giving a difference of 0.4 milkings/cow and day, Wagner-Storch and Palmer (2003) observed significantly greater milk yield with the greater AMS milking frequency.

5.2 Animal behaviour

5.2.1 Diurnal behaviour pattern

Making feed available when cows wish to eat, and thus utilising animal behaviour and preference as a management tool, can improve animal welfare and increase yield.

In the series of controlled trials comparing groups with restricted access to PROD pasture with groups with restricted EX pasture access (Spörndly *et al.*, 2015; Papers I-III), cows in group PROD always spent more time outdoors than those in group EX (Table 3). Unsurprisingly, group PROD spent more of this time grazing, as the grass silage ration on offer indoors was insufficient to sustain their production.

However, in both the daytime study and morning/evening study, group PROD also spent more time resting outdoors than group EX. The distribution of outdoor activities and time spent indoors during outdoor access periods for groups PROD and EX in the three experiments is shown in Figure 9. In the daytime study (Spörndly *et al.*, 2015, Expt. 2), cows in both experimental groups chose to remain indoors during midday hours, despite group PROD not having access to any roughage ration indoors during pasture access hours. This demonstrated a cow preference for seeking out shade or indoor facilities during the warmer hours of the day, behaviour interpreted as a heat-abating strategy by Polsky and von Keyserlingk (2017).

This is in strong agreement with findings in earlier studies in regions with warmer summers than Sweden (Falk *et al.*, 2012; Legrand *et al.*, 2009; Ketelaar-de Lauwere *et al.*, 1999). Furthermore, hardly any of the group EX cows in the daytime study returned outdoors in the afternoon, while a large fraction of the cows in group PROD headed outdoors every day at around 1600 h. It appeared that this group was then interrupted in an intensive grazing bout, as the cows were fetched back into the house at 1800 h (Figure 9, Daytime PROD). The following trial (Paper I) was designed based on these observations. Observations by Motupalli *et al.* (2014), Charlton *et al.* (2013) and Legrand *et al.* (2009) of a seemingly increased motivation for cows to be on pasture overnight, and considering the long daylight hours of Scandinavian summer months, prompted the experiment in Paper II with night grazing.

The frequently described circadian rhythm of one eating event in the morning and a larger one around dusk (*e.g.* John *et al.*, 2017; Taweel *et al.*, 2004; Rook, 2000; Gibb *et al.*, 1998) was clearly expressed by group PROD cows in both the daytime and morning/evening trials, but not in the overnight trial. It was not expressed by group EX cows in any of the three studies. Similar percentages of the cows in group PROD went outside in the morning of the daytime and the morning/evening study. However, grazing activity was more synchronous in the daytime study than in the morning/evening study, whereas the homogeneity of evening outdoor activity in group PROD was comparable in the daytime study and both consecutive trials (Papers I-III). During the morning pasture access session in Paper I+III, members of both groups ventured outdoors and out on pasture, however cows in group PROD showed greater motivation than those in group EX for being outdoors in the period. No cows from either group were observed going out in the mornings in the overnight study (Paper II).

In contrast to the recorded behaviour of the cows in the daytime study, cows in both experimental groups in Papers I and II showed a greater motivation to be outdoors in the evening compared with the morning. Compared with the number of cows that returned to pasture after the midday rest in the daytime study, a somewhat greater fraction of group PROD and a substantially larger fraction of group EX cows went outside immediately after doors opening, both for the evening pasture access session in the morning/evening trial and in the overnight trial. The behaviour of group EX cows in Papers I and II is interesting, considering that they had an *ad libitum* access to silage indoors and that there was an ongoing afternoon silage meal in group EX in both morning/evening and overnight experiments at the time the animals gained access to pasture (Figure 10). This ongoing meal was cut short when the pasture gates opened, indicating a stronger motivation to be outdoors than to continue indoor eating. Despite the very low sward height and available herbage mass in the EX pasture, most cows in group EX were observed putting their muzzles to ground and biting off any sporadic stems found at some stage during the outdoor access period. However, with the insignificant herbage mass in the exercise paddock, this behaviour could not be explained as a continuation of the indoor silage eating bout. Rather, it must be interpreted as an expression of a motivation to exert a primary activity.

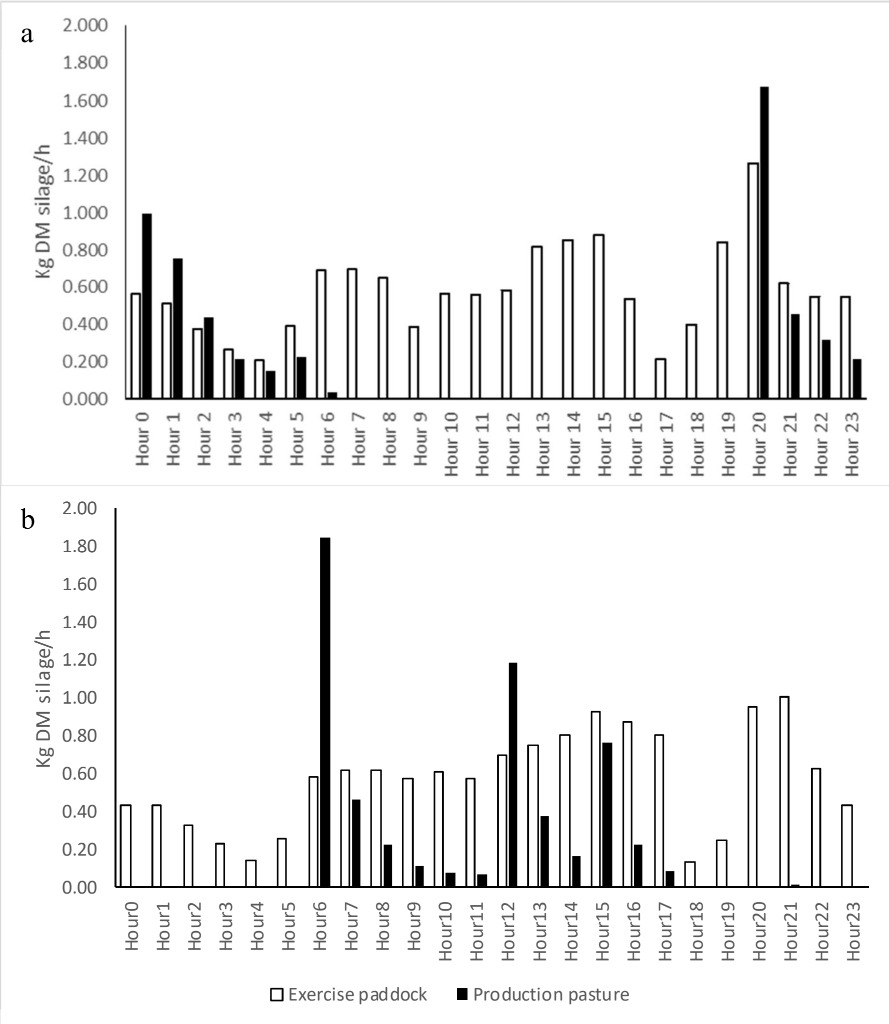

Figure 10. Average hourly silage intake (kg dry matter (DM)) per cow over 24 h as a mean across the trial period for the treatment groups with access to an exercise paddock or a production pasture in a) Paper I and b) Paper II.

The group PROD cows seemed to be interrupted mid-grazing bout at cessation of the outdoor access period in the daytime study. Similarly, group PROD cows seemed to have their second grazing bout of the evening in the morning/evening trial interrupted when fetched at cessation of the outdoor access period. This was reflected in comparatively high silage intake recorded in the group PROD directly after the barn doors were closed for the night (Figure 10a). In the overnight trial, the cows were allowed to finish their evening meal at their own leisure and in more or less synchrony, before withdrawing to the comfort of the barn (Figure 9).

While several earlier trials have reported increased motivation for dairy cows to be on pasture at night-time rather than daytime, a review by Kilgour (2012) found that most pasture intake occurs during daylight hours and that very little grazing activity takes place at night. The negligible outdoor activity and the complete absence of resting on pasture during night and early morning in the overnight study was surprising, particularly for cows in group PROD, which experienced a rather prolonged period without any roughage intake by choosing to remain indoors despite the lack of availability of any silage ration there. Considering the THI levels of the indoors climate during daytime hours (Figure 6), from which a need for heat dissipation could be assumed, and continuously higher THI levels indoors than outdoors throughout the evening and night, this absence of night-time outdoor activity was surprising also for cows in group EX.

Charlton *et al.* (2011b) observed a similar tendency of cows spending more time indoors than outdoors at night, regardless of THI levels. In a review, Lyons *et al.* (2014) suggested that overnight preference for pasture might have an element of habituation, with cows raised indoors for a considerable part of the year choosing to return from pasture to the barn more frequently than cows kept in a more pasture-based system year-round. The preference for housing at night observed in this thesis may also have been influenced by the relatively long distances cows had to walk to access pasture (Charlton *et al.*, 2011b; Spörndly & Wredle, 2004). Moreover, the motivation to lie down on pasture, identified as an important welfare asset of pasture (Charlton & Rutter, 2017; Krohn & Munksgaard, 1993), might have been lowered by the level of cow comfort provided in modern indoor cubicles, in particular when assessed by the cow in combination with closeness to concentrate feeders, drinking water and milking unit.

While synchronisation is a trait for which grazing studies are often criticised (*e.g.* Rook & Huckle, 1995), mainly as regards synchronisation of experimental groups causing differences between treatments to be washed out, synchrony within group is considered a characteristic of cow behaviour in natural and semi-natural environments (Flury & Gygax, 2016; Kilgour, 2012), and has been suggested to be an indicator of welfare (Fregonesi & Leaver, 2001).

In the morning/evening trial (Paper I), there was little evidence of between-group synchronisation in the morning pasture access session and a relatively stable heterogeneous mix of outdoor activities was performed within group PROD. During the evening pasture access session, there appeared to be some between-group synchronisation. However, while the within-group activity was quite homogenous in both groups, there were between-group differences as regards the activity in which the cows were engaged (Figure 9). Thus the two groups differed to such an extent that it is difficult to regard them as synchronous.

It is possible that the apparent synchronous behaviour of the cows in group PROD in the evening pasture session (Paper I+III) was a sign of hunger and drive for forage, rather than synchronised behaviour. However, group PROD cows in the overnight trial (Paper II) had finished the last of their ration in a silage meal event occurring just prior to pasture gates opening (Figure 10), yet exhibited the same intense drive to forage as they did in Papers I+III.

Looking at pasture intake estimates for the two trials (Table 4), cows in group PROD on overnight pasture managed to have comparable pasture intake to those on morning/evening pasture with a 1.3 h shorter grazing time and a considerably lower herbage mass in the pasture, indicating higher intake rate either by increased bite rate and/or larger bite mass. This is in contrast to findings by Mattiauda *et al.* (2013) and Pérez-Ramírez *et al.* (2008) that increased pasture access time increases grazing time and decreases intake rate. It is possible that, due to their inclination for remaining indoors at night, cows *perceived* the time available for them to be outdoors as shorter during the overnight trial than during the morning/evening trial. They may thus have modulated their timing of rumination to occur during indoor hours at night, rather than taking breaks from grazing to rest on pasture as they did in the second outdoor session of morning/evening trial, in line with findings in Gregorini *et al.* (2012).

5.2.2 Effect of daylight hours on diurnal behaviour pattern

When providing pasture access at night, light conditions could be expected to influence behaviour. If this is the case, it could be a particularly important factor to consider in high-latitude regions, with the dramatic seasonal variation in photoperiod experienced here.

Twilight (*i.e.* the period(s) between sunset and sunrise where the atmosphere is partially illuminated by the sun) is categorised according to the Sun's elevation, *i.e.* the angle of the geometric centre of the Sun to the celestial horizon, into three stages: civil, nautical and astronomical. Civil twilight is the most brightly illuminated type, where the centre of the Sun is $\leq 6^{o}$ below the horizon and sunlight is scattered and reflected by the upper atmosphere, illuminating the lower atmosphere to such an extent that the human eye does not need artificial lighting to carry out outdoor activities. Astronomical twilight is the darkest, where the centre of the Sun is $\geq 18^{o}$ below the horizon, making the angle of incidence of the Sun's rays such that the sky no longer is illuminated at all by sunlight (Bikos & Kher, n.d.). A characteristic of Scandinavian summer nights is that they are short and bright (with no astronomical twilight) close to the summer solstice, but the length of the nautical twilight period and degree of darkness (*i.e.* return of astronomical twilight) increase at an accelerating rate as summer moves towards the autumn equinox.

The overnight pasture access trial (Paper II) ran from two days after the summer solstice till 11 days prior to the September equinox (Thorsen, 2020). According to Albright (1993), presence of twilight influences cow behaviour more than actual time of the day. Thus we expected a decrease in time spent outdoors for both experimental groups and a decrease in time spent grazing for group PROD as the nights grew longer and darker, with corresponding earlier onset of twilight. Contrary to this expectation, total time spent outdoors significantly increased, by 1 h, from beginning to end of the 12-week period (Table 3 footnotes). This increase represented less than 10% of total available outdoor access time, but nevertheless gave an approximately 25-30% increase in average time spent outdoors by the two treatment groups. Approximately half of this increase was spent lying down by both groups. Over the same time span, cows in group EX reduced the time spent on pasture by approximately half an hour, meaning that by mid-September they spent an additional 1.5 h in the cow lane than they did mid-June. Cows in group PROD split their increased outdoor time between pasture and cow lane by approximately one-third and two-thirds, respectively. Furthermore, approximately half of the additional time that group PROD spent on pasture was spent grazing, resulting in an increase in total time spent grazing as the summer progressed for group PROD. Group EX showed a reduction in time spent expressing grazing behaviour over the same period.

There is limited knowledge of the lower limit of light detectable by a cow's eye, but it seems reasonable to assume that cattle have better night vision than humans, considering among other things their eye anatomy (Prince *et al.*, 1960) and their dichromatic vision (Jacobs *et al.*, 1998). During the two final behaviour observation events in the studies reported in this thesis, cows were out and about, walking in cow lanes, browsing for feed and grazing, while the human observers required night-vision goggles to observe their activity. Similar observations are described by Ferneborg *et al.* (2014), where cows managed to manoeuvre through an obstacle course without refusals or knockdowns at light intensities all the way down to 0 lux (although with a greater step count at 0 lux than 5 lux but no further improvement in speed or precision with further increases in light intensities). Thus it seem likely that the cows saw well enough to use pasture at night throughout the experimental period, even though darkness increased substantially over time.

The increase in time spent outdoors by both groups, and the increase in time spent on pasture and grazing by group PROD, could be an expression of the cows becoming more familiar and habituated with their outdoor area as summer progressed, rather than a response to changes in photoperiod. Furthermore, it seems reasonable to ascribe the decrease in time spent on pasture by group EX to a reduced motivation to walk the whole way down to a barren exercise paddock, when they could rest or take the air just as easily closer to the barn in the cow lane, rather than an effect or avoidance of darkness.

5.2.3 Production vs. animal welfare with different grazing strategies

Within the framework set by Norwegian and Swedish grazing legislation, comparing grazing with total confinement was never within the scope of this thesis. Several studies have found elevated milk yield in cows kept in total confinement compared with cows kept in a grazing system (*e.g.* Arnott *et al.*, 2015) or an alteration in the slope of the lactation curve caused by being let out to pasture (*e.g.* Wu *et al.*, 2001), an observation also made in Paper IV.

However, multiple studies have failed to identify any such difference when comparing partial and total confinement systems, as reported in Arnott *et al.* (2015). In an AMS set-up, this might be explained in part by the hours of confinement aiding in maintaining higher milking frequency (Charlton & Rutter, 2017), and in part by the ability of cows for adaptation of feeding and ruminant behaviour. While reducing pasture access hours has been shown to decrease total grazing time, this has also been shown to be compensated for by cows by increasing their intake rate (Gregorini *et al.*, 2009; Kennedy *et al.*, 2009), indications of which were observed in Paper II.

Spending more hours outdoors is generally considered to be more beneficial for cows (Burow *et al.*, 2013). Kennedy *et al.* (2009) reported that although restricted pasture access did not significantly affect milk production in any way, total pasture access time should not be shorter than 6 h. Armbrecht *et al.* (2019) found that in order to achieve benefits of outdoor resting, extended pasturing needed to occur for at least 10 h/day. However, other studies have shown that, compared with total confinement, even part-time pasture access can have beneficial effects (Chapinal *et al.*, 2010; Washburn *et al.*, 2002).

Wagner *et al.* (2017) found type of outdoor area to be a driver of cow welfare rather than duration of daily outdoor time, which they found to have no overall effect. Studies have indicated that some of the positive health and welfare effects of grazing could be reduced (Wagner *et al.*, 2017), or even reversed (Burow *et al.*, 2013; Höglund, 2010), by simply offering a more densely stocked and continuously used exercise pasture or bedded pack, rather than a production pasture. This suggests that the zero grazing (Paper IV) and exercise pasture (Papers I-IV) solutions used here for comparison with production pasture access on either response to pasture turnout (Paper IV) or milk yields throughout grazing season (Papers I-II) might be less desirable from a holistic point of view.

This is supported by the behaviour observations in Papers I-II, where cows in group EX spent less time outdoors than those in group PROD, both in terms of total time spent outdoors and time spent on pasture. Furthermore, the EX group in Paper II showed a reduction over the course of the experimental period in time spent on pasture in general and in time spent grazing, whereas group PROD showed increased time prioritisation for the same two behaviours as the study progressed. Similarly, Smid *et al.* (2018) found that, when given a simultaneous choice between pasture and sand bedded pack, cows showed preference for pasture.

It is worth noting, however, that the soft bedding and additional space allowance of outdoor bedded packs provide some positive effects on social interactions, lying, standing and walking behaviour (Smid *et al.*, 2020). Thus while perhaps not ideal, it must be considered as an alternative that is at least more beneficial than total confinement. However, in farm set-ups with limited suitable grassland sufficiently close to the milking unit, making the provision of continuous production pasture access non-feasible, implementation of part-time access to production pasture might be a better compromise than continuous access to a small outdoor bedded pack.

No clear image was obtained of the optimal duration of part-time pasture access from the studies in this thesis. However, a rudimentary indication of when and how to offer part-time pasture access to best exploit the daily rhythm of cows, to optimise grazing as a feed resource and a health and welfare resource, was obtained from the series of behaviour observations and production analysis.

Splitting the pasture access time into two shorter sessions and following the crepuscular activity pattern of wild ruminants (Paper I) gave greater utilisation of available outdoor time than providing one longer session (Table 3). This was the case regardless of whether the single longer session occurred in daytime (Spörndly *et al.*, 2015) or overnight (Paper II). Increased utilisation of available pasture access time with allocation divided into two periods has also been reported by Kennedy *et al.* (2009).

Increased utilisation of outdoor time was seen not only in terms of percentages of available time, but also in terms of total hours spent outdoors. Furthermore, the morning/evening solution saw a greater time slot allocated to resting on pasture than the overnight study (Table 3). As time spent resting outdoors has been shown to be more beneficial than indoor rest (Krohn & Munksgaard, 1993), this seems to be a further benefit of morning/evening part-time grazing, compared with other part-time outdoor access allocations.

However, a revision of the Swedish grazing legislation setting a minimum requirement of six continuous hours with pasture access (SJVFS, 2016) came into force after completion of the experiment described in Paper I. With the duration of grazing sessions used in the morning/evening study, this requirement would not have been fulfilled and an elongation of one of the pasture access sessions would have been required. Taking into consideration the drive to remain indoors at midday seen in the daytime pilot-study (Spörndly *et al.*, 2015), the seemingly interrupted evening grazing bout in Paper I and the voluntary return to the barn after the end of the evening meal in Paper II, elongating the evening session would perhaps also better suit the diurnal rhythm of the dairy cow (Figure 9).

5.3 Feed intake

In a somewhat artificial subdivision, nutrient requirements can be roughly separated into maintenance, deposition and production requirements. In Papers I-III we estimated nutrient requirements using Swedish Feeding Standards (Spörndly, 2003) amended by National Research Council (2001) requirements for increased activity with outdoor access and increased eating time for grazing. Amount of milk produced is closely related to nutrient intake, as ECM yield and change in body weight are the two factors influencing the ME requirement calculations the most.

The pre-determined concentrate rations in Papers I-III were calculated on the basis of pre-trial milk recording and live weight, and an assumption of daily roughage intake (silage + pasture) of 126 MJ ME/cow and day. During the experiments, silage with an average ME content of 11.6 and 11.2 MJ ME/kg DM for Papers I+III and Paper II, respectively, was fed to both experimental groups, while the pasture of group PROD had a mean ME content of 10.7, 10.3 and 11.1 MJ ME/kg DM in Papers I, II and III, respectively. Mean silage intake (Table 4) of group EX in Papers I, II and III was 14.0, 13.7 and 13.6 kg DM/cow and day, respectively, or 28.8%, 25.2% and 21.8% greater, respectively, than planned when making the concentrate rations. Overall, the recorded nutrient intake of group EX, as a group average, in Paper I and Paper II was 112.1% and 112.6%, respectively, of the estimated energy requirement taking into account milk yield, body weight, change in body weight, age and activity. Group PROD cows in Paper I, II and III had recorded silage intake of 5.5, 5.6 and 5.2 kg DM/cow and day, respectively. These intakes were somewhat lower than their 6 kg DM silage allowance. However, with the greater than planned silage ME content, energy intake from silage was 63.8, 62.7 and 58.2 MJ ME in Paper I, II and III, respectively, which was quite close to the 63 MJ assumed while formulating their concentrate rations.

Nutrient intake of an animal depends on the nutritive value of the diet consumed and the actual DM intake, both of which are difficult to quantify for grazing animals. Some methodology is quite accurate, but also expensive, laborious and requiring laboratory analysis. Examples of such methods are use of various markers, *e.g.* plant cuticula wax alkenes (Dove & Mayes, 1996), or difference in digestibility of consumed herbage and total faecal output. Other methods are of an intermediate accuracy and intermediate labour input, but with clear restrictions as to the situations to which they are

Table 4. Calculated metabolisable energy (ME) requirements for animal groups on production pasture (PROD) and exercise pasture (EX), measured ME intake of EX group and calculated ME requirement for PROD group assuming equal ME balance between treatments. Recorded intake from feeds in kg DM and pasture intake estimates for production pasture group in kg DM (MJ ME in brackets) from controlled trials (Papers I-III)

	Paper I		Paper II		Paper III	
	Production	Exercise	Production	Exercise	Production	Exercise
Requirement (100% supply), MJ ME	273	267	247	240	276	269
Requirement (equal ME balance), MJ ME	306	299	278	270	310	301
ME intake, kg DM (MJ ME)						
Silage	5.5 (63.8)	14.0 (162.4)	5.6 (62.7)	13.7 (153.4)	5.3 (61.5)	13.6 (157.8)
Concentrates	11.0 (145.5)	10.4 (137.5)	9.1 (124.6)	8.4 (115.0)	10.8 (142.6)	10.2 (34.6)
Pasture intake estimates, kg DM (MJ ME)						
By difference, 100% ME req.	5.9 (63.1)	0 (0)	5.7 (58.7)	0 (0)	6.52 (72.2)	0 (0)
By difference, equal ME balance	9.0 (96.3)	0 (0)	8.7 (89.6)	0 (0)	9.52 (105.4)	0 (0)
Regression DMI: drinking water					6.51 (72.1)[2]	0 (0)
Regression DMI: urine					7.76 (85.9)[2]	0 (0)
Regression CP intake: urea_N_{out}					9.75 (107.9)[2]	0 (0)
Regression K_{in}: urine					8.62 (95.4)[2]	0 (0)
Regression K_{in}: K_{out}					9.28 (102.7)[2]	0 (0)
Regression K_{in}: K_{out} corr. for K_{milk}					8.99 (103.5)[2]	0 (0)

applicable. An example of this could be the by-difference calculation of available herbage mass pre- and post-grazing (Lyons *et al.*, 2013b). This method can produce relatively good DMI estimates in systems with a high degree of pasture utilisation, *i.e.* restricted herbage allowance of low sward heights on pastures that are dense and relatively homogenous. The sward height to herbage mass regressions are more representative under such conditions than they are *e.g.* for the tall sward of Scandinavian pastures, as large herbage allowances will give uncertain estimates of residual herbage (Lantinga *et al.*, 2004). Other methods can be cheaper to perform, but carry a greater degree of uncertainty. Backward estimation by difference of known intake of supplemental feeds and calculated requirements is a commonly used example of this. The accuracy relies heavily on how accurately the system predicts animal requirements, how accurately intake and nutritive quality of supplementary feed are measured, and how accurately the feed evaluation system predicts animal response to a certain feed intake in all situations, and there will always be inherent uncertainties.

With a focus on yield per cow unit, rather than yield per pasture unit, high pasture intake, rather than high pasture utilisation, was the aim in this thesis. Pre-grazing sward height influences pasture intake – the greater the herbage allowance, the greater the intake (Bargo *et al.*, 2003). However, this comes at a cost of greater losses and leaves behind more unevenly grazed pastures, for which sward height measurements to herbage mass regressions, and other methods of herbage mass estimations for pasture intake estimates, are less reliable than in systems aiming for a very even graze-off. The pre- and post-grazing compressed sward heights reported in Papers I-III (Figure 7) were greater than commonly reported (*e.g.* Ganche *et al.*, 2014; Phelan *et al.*, 2013). However, Scandinavian pastures are typically composed of pasture mixes of species that are relatively winter-hardy, but with less herbage mass per cm sward height than the globally more common ryegrass-dominated pastures (Virkajärvi, 2004). Thus greater post- and pre-grazing height are recommended for Scandinavian swards (Johansen & Höglind, 2007). On analysing DMI potential of dairy cows from a series of experiments with a pasture-only diet, van Vuuren and van den Pol-van Dasselaar (2006) found maximum daily intake of 110-120 g DM per kg metabolic body weight. This translates to a maximum potential pasture DMI of 14.1-15.4 kg in Paper I+III and 14.9-15.3 kg in Paper II, disregarding the substitution effect of supplemental feeding. With a pasture allowance of minimum 15 kg DM pasture/cow and day in group PROD (Papers I-III), daily pasture DMI of 6 kg was assumed in feed ration calculations. However, this allowance made it theoretically possible for the animals to have a considerably greater intake. Applying the pasture intake estimation method of using herbage mass removed from pasture by grazing on data from production pasture measurements, the method resulted in estimated pasture intake of 11.0 and 41.9 kg DM/cow and day in Paper I and II, respectively. While the 11.0 kg estimate is considerably greater than that obtained by any other method (Table 4), it is not outside the conceivable limits. The 41.9 kg estimate is, however, clearly nonsensical and highlights the inappropriateness of using this method for systems with large herbage allowances and consequently great herbage accumulation.

Having fortnightly test-milking events, the requirement estimation equation extended to include outdoor activity and expected portion of grazed grass in diet, available registrations of individual measurements of DMI from concentrates and grass silage, daily silage sampling of silage from feed troughs and directly from the bunker silo for analysis of DM, ash, CP, NDF, digestibility, pH, fermentation alcohols and ammonia analysis, we deemed the backward calculation approach to have an appropriate degree of accuracy in pasture intake estimates required for the controlled trials. The high pasture allowance might have given group PROD cows freedom to select toward higher pasture quality (Johansen & Höglind, 2007). To alleviate this source of error when estimating nutrient content of grazed pasture DM, daily pasture samples were hand-picked in the newly allocated pasture area, aiming to select herbage typical of the strata grazed in previous days while mimicking the grab-and-pull foraging method of a grazing cow. In Papers I-III, pasture DMI intake was calculated by subtracting the amount of consumed silage and concentrates from the estimated requirements. As there was no likely reason why energy efficiency would differ between the two treatment groups, an additional pasture intake estimate was made by difference in requirements relative to equal energy efficiency in group EX and ME intake from feeds (Table 4).

Using data from Paper I, Overrein *et al.* (2018) applied the more complex intake-capacity based Nordic feed evaluation system NorFor (Volden, 2011) to predict feed intake for the two groups. For group EX, NorFor-predicted silage DMI was identical to actual voluntary silage intake, validating comparison of the two methods. For group PROD, silage and concentrate intake were entered into the NorFor model and a pasture intake estimate of 8.6 kg DM was obtained, which is close to the estimate of 9.0 kg DM in Paper I when assuming equal ME balance as for EX cows.

The additional pasture intake estimates from the regressions in Paper III (Table 4) were within the same range as the two by-difference estimates in Paper I. The estimates with poorer correlations with individual grazing time and with the product of grazing time and intake rate were closer to the 100% ME requirement estimates. Those with higher R^2 values were closer to the estimates of equal energy efficiency and the NorFor estimates. The best correlation was found for urinary K output and pasture K content, corrected for milk K excretion. Estimates from drinking water intake were poorly correlated with eating rate for the PROD group, although the regression had R^2 of 0.52 for the EX group, where it was developed. It is likely that the feed water from pasture with low and varying DM caused this poorer correlation. The average and range of estimates from drinking water were reasonable, and it is still possible that group-wise values can be useful indicators of pasture intake.

Dividing the pasture intake estimates based on calculated energy requirements (Table 4) by hours of observed grazing activity (Table 3), estimated intake rates ranged from 1.6 to 2.4 kg DM/h in Paper I and from 2.3 to 3.5 kg DM/h in Paper II. These intake rate estimates partly exceeded the maximum intake rates suggested in a meta-analysis by Pérez-Prieto and Delagarde (2013). However, during their outdoor access hours there were no limiting conditions for pasture harvesting by cows in group PROD. Furthermore, part-time grazing combined with a restricted silage ration has been reported to increase intake rates (Pérez-Ramírez *et al.*, 2009; Pérez-Ramírez *et al.*, 2008). In both experiments, the cows in group PROD had for some time prior to pasture turnout been largely without access to a silage ration, either due to design (evening grazing session of Paper I; Figure 10a) or due to having finished their daily silage ration early (Paper II; Figure 10b). Chilibroste *et al.* (1997) observed pasture intake rates as high as 2.6-3.6 kg DM/h for up to 2.7 h after a feed withdrawal period of only 2.5 h, so even the highest estimated intake of silage ration in Papers I and II is within plausible levels.

5.4 External factors influencing success with grazing

External factors such as the weather affect grazing dairy cows directly through the thermal environment and indirectly through pasture amount and quality. The weather of the two summers with controlled trials (Papers I-III) and the summer from which registry data was collected for the observational study (Paper IV) varied greatly (Figure 6).

The grazing season for which production data were analysed in Paper IV was, on a national scale, somewhat warmer and had 30% more precipitation than the Norwegian 30-year average (Norwegian Meteorological Institute, 2020). The summer study period in Paper I + III was, as previously described, close to the regional 30-year average in temperature and somewhat wetter, while the summer study period in Paper II was considerably warmer and drier than the long-term average (SMHI, 2017) (Figure 6). Outdoor mean hourly THI values and mean daily THI values during the controlled trials (Papers I-III) never exceeded the threshold limit of 72 suggested by Kibler (1964) to be the critical point at which milk yield is reduced. However, individual hourly and daily maximum value exceeded this threshold during both summers.

Kibler's suggested threshold was based on observations made during the 1950s. Taking into account the advances in the physical and genetic constitution of the modern cow, with increased milk production and associated increases in metabolic activity and in body and gastrointestinal tract size, arguments have been made for this threshold to be lowered (Kadzere *et al.*, 2002). The proposal for a lower THI threshold is further supported by Vitali *et al.* (2009), who observed THI 70 to be the point at which heat-induced death started increasing. Discomfort, stress and any production losses would presumably start to occur at a lower level than death. A rule of thumb used by the Norwegian advisory services is that at RH of around 80%, heat stress may occur already from temperatures of 20ºC. By Kibler's equation, that would represent a THI value of 67. Igono *et al.* (1992) found a THI value of 64 to be the lower limit at which they detected adverse effects of ambient climate on milk production.

Had the assumed threshold for heat stress been lowered to the tentative THI 65 (Figure 6a), some hours of the day would have on average had an outdoor climate that exceeded the risk of inducing heat stress in summer 2016 (Paper II), although not during outdoor access hours. More noteworthy are the indoor THI values from the same year. THI levels moved towards the tentative threshold already from early morning and remained above it during the whole of the indoor period and into the evening, waning only towards midnight. Bearing in mind that these were mean hourly recordings for 93 days, there is a strong possibility that animals in both experimental groups experienced some excessive heat load during the experiment in Paper II. Daily mean THI never rose above the conservative 72 (Figure 6b), but most days had a maximum THI well above this limit and several days had a mean THI above the tentative limit of 65. Wildridge *et al.* (2018) found average daily milk yield and milking frequency to be negatively affected for as long as three days after an elevated THI event, primarily by high mean THI but also to some extent high maximum THI. Igono *et al.* (1992) observed that non-availability of a cool night further removed any safety margins minimising the negative effects of hot environments.

The elevated 24-h THI seen throughout the experimental period could be expected to have affected feed intake, behaviour and production of the cows, thus explaining the failure of group PROD in Paper II to maintain yield. However, similar THI levels were experienced by animals in both groups, as there was only a difference of approximately one hour between when group EX and group PROD withdrew from pasture and went indoors (Figure 9). Furthermore, estimated energy requirements and silage and concentrate intakes were comparable between groups PROD and EX across the two studies (Table 3). It is therefore reasonable to assume that any negative impact of weather (THI) on production was similar for the two groups.

Essentially a nature-based production, dairy farming in general (and grazing in particular) is highly vulnerable to weather and climate. Results from different seasons should thus be compared with caution. The trials and data collection in Papers I-IV were carried out in summer 2015-2017. Although differing from each other, none of these years showed extreme deviations from the 30-year average of the relevant regions. The season following the last data collection, summer 2018, was characterised by extreme drought, extreme temperatures and feed scarcity in most of Europe. This was also the case in the whole of Sweden and in large parts of Norway. Had either of the controlled trials in Papers I-III by chance been conducted that summer, or had the survey in Paper IV collected registry data for summer 2018, it is reasonable to assume that results would have been quite different from those reported in this thesis. The extreme conditions would presumably have disadvantaged those systems relying on intake of fresh herbage.

"…a scientist must also be absolutely like a child. If he sees a thing, he must say that he sees it, whether it was what he thought he was going to see or not. See first, think later, then test. But always see first. Otherwise you will only see what you were expecting."
– Douglas Adams

6. Conclusions and practical implications

One of the original goals of this thesis was to investigate the role of grazing strategy (*i.e.* proportion of grazed grass in diet) in relation to milk yield and milk quality. In controlled trials with various partial confinement set-ups and in an observational study scrutinising registry data, cows on production pasture did not respond any differently than cows on exercise pasture to being allowed outdoors. In general:

- Being turned out to pasture caused a steeper decline in weekly milk yield than expected according to standardised lactation curves, but there was no evidence that cows in AMS herds responded to pasture turnout any differently than cows milked in manual milking systems.
- For cows allowed outdoor access, changes in milk synthesis and udder health as response to pasture turnout were not affected by whether these cows were restricted to an outdoor bedded pack, or allowed access to either production or exercise pasture.
- Group mean yield (kg ECM, kg fat, kg protein) and SCC were similar throughout the trials regardless is the cows had access to production pasture or an exercise paddock (although cows on production pasture with pasture access restricted to night-time had significantly lower recorded kg milk/d than cows in exercise paddock). These results indicate that the strongly held assumption that milk yield suffers if grazed grass is included as *part* of a high-yielding dairy cow ration may be unfounded.
- When given a choice, cows with access to production pasture spent a longer time on pasture than cows with access to a recreation area only. The novelty of outdoor access seemed to diminish as summer proceeded for cows with access to an exercise area only, suggesting

that access to production pasture improves dairy cattle welfare relative to alternative outdoor solutions.

- Absence or duration of twilight seemed not to influence grazing activity or motivation to be on pasture at night.

Practical implications and future prospects

For farmers to remain in control of feed intake and maintain good cow traffic and high milking frequency in an AMS system, part-time grazing on a high pasture allowance may be a good compromise in order to include a substantial portion of grazed pasture in the diet of high-yielding dairy cows. To enhance farmers' control over daily feed intake, in order to offer supplemental indoor feed during confinement hours with greater precision and reduced feed waste, automated recordings of drinking water intake might be a useful indicator of pasture DMI on group level. However, more work and further validation is needed before this approach can be applied in an everyday farming situation.

Should outdoor access provision for whatever reason be achievable only at night, offering a comfortable and hygienic near-barn exercise paddock or bedded pack for outdoor rest and leisure might suffice. Little grazing occurs at night, giving poor returns on investments in land area, grazing infrastructure and time in maintaining production pasture. Although a larger pasture can be both more hygienic and appealing for resting, longer distance to outdoor area may outweigh the attraction of being outdoors.

The outdoor access provision strategy of offering outdoor access twice per day, morning and evening, seemed to encourage cows to spend the greatest amount of time outdoors, and the greatest amount of time spent both grazing and resting outdoors. Is, however, provision of pasture feasible only once per day, ensuring that cows have pasture access in late afternoon and evening would seem to achieve the greatest exploitation of pasture access.

References

Alban, L. & Agger, J.F. (1996). Welfare in Danish dairy herds 2. Housing systems and grazing procedures in 1983 and 1994. *Acta veterinaria Scandinavica,* 37(1), pp. 65-77.

Albright, J.L. (1993). Feeding Behavior of Dairy Cattle. *Journal of Dairy Science,* 76(2), pp. 485-498.

Almås, R. (2002). *Frå bondesamfunn til bioindustri : 1920-200 (*4). Oslo: Samlaget.

Almås, R. (2016). *Omstart : forslag til ein ny landbrukspolitikk*. Melhus: Snøfugl.

Almås, R. & Brobakk, J. (2012). Norwegian Dairy Industry: A Case of Super-Regulated Co-Operativism. *Research in Rural Sociology and Development,* 18, pp. 169-189.

Alvasen, K., Mork, M.J., Sandgren, C.H., Thomsen, P.T. & Emanuelson, U. (2012). Herd-level risk factors associated with cow mortality in Swedish dairy herds. *Journal of Dairy Science,* 95(8), pp. 4352-4362.

Armbrecht, L., Lambertz, C., Albers, D. & Gauly, M. (2018). Does access to pasture affect claw condition and health in dairy cows? *The Veterinary Record,* 182(3), p. 79.

Armbrecht, L., Lambertz, C., Albers, D. & Gauly, M. (2019). Assessment of welfare indicators in dairy farms offering pasture at differing levels. *animal,* 13(10), pp. 2336-2347.

Arnott, G., Ferris, C. & O'Connell, N. (2015). *A comparison of confinement and pasture systems for dairy cows: What does the science say?* Belfast: AgriSearch

Arnott, G., Ferris, C.P. & O’Connell, N.E. (2017). Review: welfare of dairy cows in continuously housed and pasture-based production systems. *animal,* 11(2), pp. 261-273.

Asheim, L.J. & Hegrenes, A. (2006). *Verdi av fôr frå utmarksbeite og sysselsetting i beitebaserte næringar*. Oslo: Norsk institutt for landbruksøkonomisk forskning.

Aune, S., Bryn, A. & Hovstad, K.A. (2018). Loss of semi-natural grassland in a boreal landscape: impacts of agricultural intensification and abandonment. *Journal of Land Use Science,* 13(4), pp. 375-390.

Bargo, F., Muller, L.D., Kolver, E.S. & Delahoy, J.E. (2003). Invited Review: Production and digestion of supplemented dairy cows on pasture. *Journal of Dairy Science,* 86(1), pp. 1-42.

Barkema, H.W., Schukken, Y.H., Lam, T., Beiboer, M.L., Benedictus, G. & Brand, A. (1999). Management practices associated with the incidence rate of clinical mastitis. *Journal of Dairy Science,* 82(8), pp. 1643-1654.

Batalla, I., Knudsen, M.T., Mogensen, L., del Hierro, O., Pinto, M. & Hermansen, J.E. (2015). Carbon footprint of milk from sheep farming systems in Northern Spain including soil carbon sequestration in grasslands. *Journal of Cleaner Production,* 104, pp. 121-129.

Bates, D., Maechler, M., Bolker, B. & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software,* 67(1), p. 48.

Beaver, A., Proudfoot, K.L. & von Keyserlingk, M.A.G. (2020). Symposium review: Considerations for the future of dairy cattle housing: An animal welfare perspective. *Journal of Dairy Science,* 103(6), pp. 5746-5758.

Becker, T., Kayser, M., Tonn, B. & Isselstein, J. (2018). How German dairy farmers perceive advantages and disadvantages of grazing and how it relates to their milk production systems. *Livestock Science,* 214, pp. 112-119.

Beggs, D.S., Jongman, E.C., Hemsworth, P.H. & Fisher, A.D. (2019). The effects of herd size on the welfare of dairy cows in a pasture-based system using animal- and resource-based indicators. *Journal of Dairy Science,* 102(4), pp. 3406-3420.

Bellarby, J., Tirado, R., Leip, A., Weiss, F., Lesschen, J.P. & Smith, P. (2013). Livestock greenhouse gas emissions and mitigation potential in Europe. *Global Change Biology,* 19, pp. 3-18.

Bengtsson, J., Bullock, J.M., Egoh, B., Everson, C., Everson, T., O'Connor, T., O'Farrell, P.J., Smith, H.G. & Lindborg, R. (2019). Grasslands—more important for ecosystem services than you might think. *Ecosphere,* 10(2):e02582.

Bergslid, I.K.R. & Støbet Lande, U. (2013). *Verdifulle beiter; Kartlegge, prioritere og tilrettelegge*. (Bioforsk Rapport, 8). Ås, Norway: Bioforsk.

Bergsten, C. (2001). Effects of conformation and management system on hoof and leg diseases and lameness in dairy cows. *Veterinary Clinics of North America-Food Animal Practice,* 17(1), pp. 1-23.

Bikos, K. & Kher, A. *Twilight, Dawn and Dusk*. Available at: https://www.timeanddate.com/astronomy/different-types-twilight.html [13.01.2019].

Bir, C., Widmar, N.O., Thompson, N.M., Townsend, J. & Wolf, C.A. (2020). US respondents' willingness to pay for Cheddar cheese from dairy cattle with different pasture access, antibiotic use, and dehorning practices. *Journal of Dairy Science,* 103(4), pp. 3234-3249.

Blytt, H. (1997). *Berøringsgrad og investeringsbehov for melkeproduksjonsbruk som følge av nye forskrifter*.

Bruun, J., Ersboll, A.K. & Alban, L. (2002). Risk factors for metritis in Danish dairy cows. *Preventive Veterinary Medicine,* 54(2), pp. 179-190.

Bryn, A., Flø, B.E., Daugstad, K., Dybedal, P. & Vinge, H. (2013). *Cultour - et forskningsprosjekt om reiseliv, kulturminner og gjengroing*.

Burow, E., Rousing, T., Thomsen, P.T., Otten, N.D. & Sørensen, J.T. (2013). Effect of grazing on the cow welfare of dairy herds evaluated by a multidimensional welfare index. *animal,* 7(5), pp. 834-842.

Burow, E., Thomsen, P.T., Rousing, T. & Sørensen, J.T. (2014). Track way distance and cover as risk factors for lameness in Danish dairy cows. *Preventive Veterinary Medicine,* 113(4), pp. 625-628.

Burow, E., Thomsen, P.T., Sørensen, J.T. & Rousing, T. (2011). The effect of grazing on cow mortality in Danish dairy herds. *Preventive Veterinary Medicine,* 100(3-4), pp. 237-241.

Butler, D. & Holloway, L. (2016). Technology and restructuring the social field of dairy farming: Hybrid capitals, 'stockmanship' and automatic milking systems. *Sociologia ruralis,* 56(4), pp. 513-530.

Bühlen, F., Ivemeyer, S., Krutzinna, C. & Knierim, U. (2014). Potential effects of automatic milking systems on grazing in organic dairy farming. *Organic Agriculture,* 4(4), pp. 301-308.

Cardoso, C.S., Hötzel, M.J., Weary, D.M., Robbins, J.A. & von Keyserlingk, M.A.G. (2016). Imagining the ideal dairy farm. *Journal of Dairy Science,* 99(2), pp. 1663-1671.

Cardoso, C.S., von Keyserlingk, M.A.G. & Hötzel, M.J. (2019). Views of dairy farmers, agricultural advisors, and lay citizens on the ideal dairy farm. *Journal of Dairy Science,* 102(2), pp. 1811-1821.

Chapinal, N., Goldhawk, C., de Passillé, A.M., von Keyserlingk, M.A.G., Weary, D.M. & Rushen, J. (2010). Overnight access to pasture does not reduce milk production or feed intake in dairy cattle. *Livestock Science,* 129(1), pp. 104-110.

Charlton, G.L. & Rutter, S.M. (2017). The behaviour of housed dairy cattle with and without pasture access: A review. *Applied Animal Behaviour Science,* 192, pp. 2-9.

Charlton, G.L., Rutter, S.M., East, M. & Sinclair, L.A. (2011a). Effects of providing total mixed rations indoors and on pasture on the behavior of lactating dairy cattle and their preference to be indoors or on pasture. *Journal of Dairy Science,* 94(8), pp. 3875-3884.

Charlton, G.L., Rutter, S.M., East, M. & Sinclair, L.A. (2011b). Preference of dairy cows: Indoor cubicle housing with access to a total mixed ration vs. access to pasture. *Applied Animal Behaviour Science,* 130(1–2), pp. 1-9.

Charlton, G.L., Rutter, S.M., East, M. & Sinclair, L.A. (2013). The motivation of dairy cows for access to pasture. *Journal of Dairy Science,* 96(7), pp. 4387-4396.

Chilibroste, P., Tamminga, S. & Boer, H. (1997). Effects of length of grazing session, rumen fill and starvation time before grazing on dry-matter intake, ingestive behaviour and dry-matter rumen pool sizes of grazing lactating dairy cows. *Grass and Forage Science,* 52(3), pp. 249-257.

Crump, A., Jenkins, K., Bethell, E.J., Ferris, C.P. & Arnott, G. (2019). Pasture access affects behavioral indicators of wellbeing in dairy cows. *Animals,* 9(11).

Czortek, P., Eycott, A.E., Grytnes, J.A,, Delimat, A., Kapfer, J. & Jaroszewicz, B. (2018). Effects of grazing abandonment and climate change on mountain summits flora: a case study in the Tatra Mts. *Plant Ecology,* 219(3), pp. 261-276.

Dhakal, K., Maltecca, C., Cassady, J.P., Baloche, G., Williams, C.M. & Washburn, S.P. (2013). Calf birth weight, gestation length, calving ease, and neonatal calf mortality in Holstein, Jersey, and crossbred cows in a pasture system. *Journal of Dairy Science,* 96(1), pp. 690-698.

Directorate-General for Health and Food Safety, European Commission & TNS Political & Social (2016). *Attitudes of Europeans towards Animal Welfare*. (Special Eurobarometer).

Djurskyddsförordning 2019:66 (2019). (2019:66). Stockholm: The Swedish Ministry of Enterprise and Innovation.

Dove, H. & Mayes, R.W. (1996). Plant wax components: a new approach to estimating intake and diet composition in herbivores. *The Journal of Nutrition,* 126(1), pp. 13-26.

Dufrasne, I., Robaye, V., Knapp, E., Istasse, L., Hornick, J.L. & Warda, M. Effects of environmental factors on yield and milking number in dairy cows milked by an automatic system located in pasture. In: Golinski, P., Warda, M. & Stypinkski, P. (eds) *Proceedings of the 24th General Meeting of the European Grassland Federation, EGF 2012 Grassland - a European Resource?*, Lublin, Poland, 3-7 June 2012. Poznan, Poland: Oficyna Wydawnicza Garmond, pp. 231-233.

Emanuelsson, U. (2009). *The Rural Landscapes of Europe: How Man Has Shaped European Nature*: Swedish Research Council Formas.

Falk, A.C., Weary, D.M., Winckler, C. & von Keyserlingk, M.A.G. (2012). Preference for pasture versus freestall housing by dairy cattle when stall availability indoors is reduced. *Journal of Dairy Science,* 95(11), pp. 6409-6415.

Ferneborg, S., Eriksson, J., Olsson, P., Agenäs, S. & Ternman, E. Effect of Low Light Intensity on Stress Indicators in Dairy Cows. In: Hatcher, S., Krebs, G.L. & Holman, B.W.B. (eds) *Proceedings of Harnessing the Ecology and Physiology of Herbivores - 30th Biennial Conference of the Australian Society of Animal Production*, Canberra, Australia 2014: Australian Society of Animal Production.

Ferris, C.P., Binnie, R.C., Frost, J.P. & Patterson, D.C. (2008). Effect of offering silage during housing at night on the performance of grazing dairy cows and on labour requirements. *Grass and Forage Science,* 63(1), pp. 138-151.

Flury, R. & Gygax, L. (2016). Daily patterns of synchrony in lying and feeding of cows: Quasi-natural state and (anti-) synchrony factors. *Behavioural Processes,* 133, pp. 56-61.

Forskrift om hold av storfe FOR-2004-04-22-665 (2004). (FOR-2004-04-22-665). Oslo: Landbruks- og matdepartementet.

Forskrift om hold av storfe og svin FOR-1996-01-15 nr 0091 (1996). (FOR-1996-01-15 nr 0091). Oslo: Landbruks- og matdepartementet.

Fregonesi, J.A. & Leaver, J.D. (2001). Behaviour, performance and health indicators of welfare for dairy cows housed in strawyard or cubicle systems. *Livestock Production Science,* 68(2), pp. 205-216.

Ganche, E., Delaby, L., O'Donovan, M., Boland, T.M. & Kennedy, E. (2014). Short-term response in milk production, dry matter intake, and grazing behavior of dairy cows to changes in postgrazing sward height. *Journal of Dairy Science,* 97(5), pp. 3028-3041.

Garnett, T., Appleby, M.C., Balmford, A., Bateman, I.J., Benton, T.G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., Herrero, M., Hoffmann, I., Smith, P., Thornton, P.K., Toulmin, C., Vermeulen, S.J. & Godfray, H.C.J. (2013). Sustainable intensification in agriculture: premises and policies. *Science,* 341(6141), pp. 33-34.

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A. & Tempio, G. (2013). *Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities*. Rome: Food and Agriculture Organization of the United Nations (FAO).

Gibb, M.J., Huckle, C.A. & Nuthall, R. (1998). Effect of time of day on grazing behaviour by lactating dairy cows. *Grass and Forage Science,* 53(1), pp. 41-46.

Giovanetti, V., Cossu, R., Molle, G., Acciaro, M., Mameli, M., Cabiddu, A., Serra, M.G., Manca, C., Rassu, S., Decandia, M. & Dimauro, C. (2020). Prediction of bite number and herbage intake by an accelerometer-based system in dairy sheep exposed to different forages during short-term grazing tests. Computers and Electronics in Agriculture, 175, p. 105582.

Gregorini, P., Clark, C.E.F., Jago, J.G., Glassey, C.B., McLeod, K.L.M. & Romera, A.J. (2009). Restricting time at pasture: Effects on dairy cow herbage intake, foraging behavior, hunger-related hormones, and metabolite concentration during the first grazing session. *Journal of Dairy Science,* 92(9), pp. 4572-4580.

Gregorini, P., DelaRue, B., McLeod, K., Clark, C.E.F., Glassey, C.B. & Jago, J. (2012). Rumination behavior of grazing dairy cows in response to restricted time at pasture. *Livestock Science,* 146(1), pp. 95-98.

Hansen, B.G. (2015). Robotic milking-farmer experiences and adoption rate in Jæren, Norway. *Journal of Rural Studies,* 41, pp. 109-117.

Haskell, M.J., Rennie, L.J., Bowell, V.A., Bell, M.J. & Lawrence, A.B. (2006). Housing system, milk production, and zero-grazing effects on lameness and leg injury in dairy cows. *Journal of Dairy Science,* 89(11), pp. 4259-4266.

Hennessy, D., Delaby, L., van den Pol-van Dasselaar, A. & Shalloo, L. Possibilities and constraints for grazing in high output dairy systems. In: Van den Pol-van Dasselaar, A., Aarts, H.F.M., De Vliegher, A., Elgersma, A., Reheul, D., Reijneveld, J.A., Verloop, J. & Hopkins, A. (eds) *Proceedings of the 18th Symposium of the European Grassland Federation, EGF 2015 Grassland and forages in high output dairy farming systems*, Wageningen, The Netherlands, 15-17 June 2015. Wageningen, The Netherlands: Wageningen Academic Publishers, pp. 151-162.

Henriksen, S. & Hilmo, O. (2015). *Norsk rødliste for arter 2015*.

Hernandez-Mendo, O., von Keyserlingk, M.A.G., Veira, D.M. & Weary, D.M. (2007). Effects of pasture on lameness in dairy cows. *Journal of Dairy Science,* 90(3), pp. 1209-1214.

Higashiyama, Y., Nashiki, M., Narita, H. & Kawasaki, M. (2007). A brief report on effects of transfer from outdoor grazing to indoor tethering and back on urinary cortisol and behaviour in dairy cattle. *Applied Animal Behaviour Science,* 102(1-2), pp. 119-123.

Hogeveen, H., Ouweltjes, W., de Koning, C.J.A.M. & Stelwagen, K. (2001). Milking interval, milk production and milk flow-rate in an automatic milking system. *Livestock Production Science,* 72(1), pp. 157-167.

Höglund, J. (2010). Parasite surveillance and novel use of anthelmintics in cattle. *Acta veterinaria Scandinavica,* 52(Suppl 1).

Hötzel, M.J., Cardoso, C.S., Roslindo, A. & von Keyserlingk, M.A.G. (2017). Citizens' views on the practices of zero-grazing and cow-calf separation in the dairy industry: Does providing information increase acceptability? *Journal of Dairy Science,* 100(5), pp. 4150-4160.

Igono, M.O., Bjotvedt, G. & Sanford-Crane, H.T. (1992). Environmental profile and critical temperature effects on milk production of Holstein cows in desert climate. *International Journal of Biometeorology,* 36(2), pp. 77-87.

Isselstein, J. & Kayser, M. Functions of grassland and their potential in delivering ecosystem services. In: Hopkins, A., Collins, R.P., Fraser, M.D., King, V.R., Lloyd, D.C., Moorby, J.M. & Robson, P.R.H. (eds) *Proceedings of the 25th General Meeting of the European Grassland Federation, EGF at 50: The Future of European Grasslands*, Aberystwyth, Wales, 7-11 September 2014. Aberystwyth, Wales: IBERS, Wales, pp. 199-214.

Jackson, A., Green, M., Millar, K. & Kaler, J. (2020). Is it just about grazing? UK citizens have diverse preferences for how dairy cows should be managed. *Journal of Dairy Science,* 103(4), pp. 3250-3263.

Jacobs, G.H., Deegan, J.F. & Neitz, J.A.Y. (1998). Photopigment basis for dichromatic color vision in cows, goats, and sheep. *Visual Neuroscience,* 15(3), pp. 581-584.

Jago, J., Copeman, P., Bright, K., McLean, D., Ohnstad, I. & Woolford, M. An innovative farm system combining automated milking with grazing. In: *Proceedings of the New Zealand Society of Animal Production*, Palmerston North 2002: New Zealand Society of Animal Production, pp. 115-119.

Johansen, A. & Höglind, M. (2007). Herbage intake, milk production and sward utilization of dairy cows grazing grass/white clover swards at low, medium and high allowances. *Acta Agriculturae Scandinavica, Section A — Animal Science,* 57(3), pp. 148-158.

John, A., Garcia, S., Kerrisk, K.L., Freeman, M.J., Islam, M.R. & Clark, C.E.F. (2019). The effect of temporal variation in feed quality and quantity on the diurnal feeding behaviour of dairy cows. *animal,* 13(11), pp. 2519-2526.

John, A.J., Clark, C.E.F., Freeman, M.J., Kerrisk, K.L., Garcia, S.C. & Halachmi, I. (2016). Review: Milking robot utilization, a successful precision livestock farming evolution. *animal,* 10(9), pp. 1484-1492.

John, A.J., Garcia, S.C., Kerrisk, K.L., Freeman, M.J., Islam, M.R. & Clark, C.E.F. (2017). Short communication: The diurnal intake and behavior of dairy cows when access to a feed of consistent nutritive value is restricted. *Journal of Dairy Science,* 100(11), pp. 9279-9284.

Johnson, P.C.D. (2014). Extension of Nakagawa & Schielzeth's R^2 GLMM to random slopes models. *Methods in Ecology and Evolution,* 5(9), pp. 944-946.

Jørgensen, G.H.M., Eilertsen, S.M., Hansen, I. & Aanensen, L. The behaviour and production of dairy cattle when offered green pasture or exercise pen. In: Van den Pol-van Dasselaar, A., Aarts, H.F.M., De Vliegher, A., Elgersma, A., Reheul, D., Reijneveld, J.A., Verloop, J. & Hopkins, A. (eds) *Proceedings of the 18th Symposium of the European Grassland Federation, EGF 2015 Grassland and forages in high output dairy farming systems*, Wageningen, The Netherlands, 15-17 June 2015. Wageningen, The Netherlands: Wageningen Academic Publishers, pp. 107-109.

Kadzere, C.T., Murphy, M.R., Silanikove, N. & Maltz, E. (2002). Heat stress in lactating dairy cows: a review. *Livestock Production Science,* 77(1), pp. 59-91.

Kennedy, E., Curran, J., Mayes, B., McEvoy, M., Murphy, J.P. & O'Donovan, M. (2011). Restricting dairy cow access time to pasture in early lactation: the effects on milk production, grazing behaviour and dry matter intake. *animal,* 5(11), pp. 1805-1813.

Kennedy, E., McEvoy, M., Murphy, J.P. & O'Donovan, M. (2009). Effect of restricted access time to pasture on dairy cow milk production, grazing behavior, and dry matter intake. *Journal of Dairy Science,* 92(1), pp. 168-176.

Ketelaar-de Lauwere, C.C., Ipema, A.H., Lokhorst, C., Metz, J.H.M., Noordhuizen, J.P.T.M., Schouten, W.G.P. & Smits, A.C. (2000). Effect of sward height and distance between pasture and barn on cows' visits to an automatic milking system and other behaviour. *Livestock Production Science,* 65(1–2), pp. 131-142.

Ketelaar-de Lauwere, C.C., Ipema, A.H., van Ouwerkerk, E.N.J., Hendriks, M.M.W.B., Metz, J.H.M., Noordhuizen, J.P.T.M. & Schouten, W.G.P. (1999). Voluntary automatic milking in combination with grazing of dairy cows: Milking frequency and effects on behaviour. *Applied Animal Behaviour Science,* 64(2), pp. 91-109.

Kibler, H.H. (1964). Environmental physiology and shelter engineering. LXVII. Thermal effects of various temperature-humidity combinations on Holstein cattle as measured by eight physiological responses. *University of Missouri Agricultural Experiment Station Research Bulletin, Missouri Agricultural Experiment Station*(862), pp. 1-42.

Kilgour, R.J. (2012). In pursuit of "normal": A review of the behaviour of cattle at pasture. *Applied Animal Behaviour Science,* 138(1), pp. 1-11.

Kristensen, T., Madsen, M.L. & Noe, E. The use of grazing in intensive dairy production and assessment of farmers' attitude towards grazing. In: Schnyder, H., Isselstein, J., Taube, F., Auerswald, K., Schellberg, J., Wachendorf, M., Herrmann, A., Gierus, M., Wrage, N. & Hopkins, A. (eds) *Proceedings of the 23rd General Meeting of the European Grassland Federation, EGF 2010 Grassland in a changing world*, Kiel, Germany, 29th August - 2nd September 2010. Duderstadt, Germany: Mecke Druck und Verlag, pp. 964-966.

Krohn, C.C. (1994). Behaviour of dairy-cows kept in extensive (loose housing pasture) or intensive (tie stall) environments. 3. Grooming, exploration and abnormal behaviour. *Applied Animal Behaviour Science,* 42(2), pp. 73-86.

Krohn, C.C. & Munksgaard, L. (1993). Behaviour of dairy-cows kept in extensive (loose housing/pasture) or intensive (tie stall) environments. 2. Lying and lying-down behaviour. *Applied Animal Behaviour Science,* 37(1), pp. 1-16.

Kätterer, T., Bolinder, M.A., Berglund, K. & Kirchmann, H. (2012). Strategies for carbon sequestration in agricultural soils in northern Europe. *Acta Agriculturae Scandinavica, Section A - Animal Science,* 62(4), pp. 181-198.

Lacy-Hulbert, S.J., Woolford, M.W., Nicholas, G.D., Prosser, C.G. & Stelwagen, K. (1999). Effect of milking frequency and pasture intake on milk yield and composition of late lactation cows. *Journal of Dairy Science,* 82(6), pp. 1232-1239.

Lantinga, E., Neuteboom, J.H. & Meijs, J.A.C. (2004). Sward methods. In: Penning, P.D. (ed.) *Herbage intake handbook*. 2. ed British Grassland Society.

Legrand, A.L., von Keyserlingk, M.A.G. & Weary, D.M. (2009). Preference and usage of pasture versus free-stall housing by lactating dairy cattle. *Journal of Dairy Science,* 92(8), pp. 3651-3658.

Lessire, F., Moula, N., Hornick, J.-L. & Dufrasne, I. (2020). Systematic review and meta-analysis: Identification of factors influencing milking frequency of cows in automatic milking systems combined with grazing. *Animals,* 10(5):913.

Loberg, J., Telezhenko, E., Bergsten, C. & Lidfors, L. (2004). Behaviour and claw health in tied dairy cows with varying access to exercise in an outdoor paddock. *Applied Animal Behaviour Science,* 89(1-2), pp. 1-16.

Lüdecke, D., Makowski, D., Waggoner, P. & Patil, I. (2020). *performance: Assessment of Regression Models Performance*. (Version: R package version 0.4.6) [Computer Program]. Available from: https://CRAN.R-project.org/package=performance.

Lyons, N.A., Kerrisk, K.L., Dhand, N.K. & Garcia, S.C. (2013a). Factors associated with extended milking intervals in a pasture-based automatic milking system. *Livestock Science,* 158(1–3), pp. 179-188.

Lyons, N.A., Kerrisk, K.L. & Garcia, S.C. (2013b). Comparison of 2 systems of pasture allocation on milking intervals and total daily milk yield of dairy cows in a pasture-based automatic milking system. *Journal of Dairy Science,* 96(7), pp. 4494-4504.

Lyons, N.A., Kerrisk, K.L. & Garcia, S.C. (2013c). Effect of pre- versus postmilking supplementation on traffic and performance of cows milked in a pasture-based automatic milking system. *Journal of Dairy Science,* 96(7), pp. 4397-4405.

Lyons, N.A., Kerrisk, K.L. & Garcia, S.C. (2014). Milking frequency management in pasture-based automatic milking systems: A review. *Livestock Science,* 159(0), pp. 102-116.

Marshall, S.A., Campbell, C.P. & Buchanan-Smith, J.G. (1998). Seasonal changes in quality and botanical composition of a rotationally grazed grass-legume pasture in southern Ontario. *Canadian Journal of Animal Science,* 78(2), pp. 205-210.

Mattiauda, D.A., Tamminga, S., Gibb, M.J., Soca, P., Bentancur, O. & Chilibroste, P. (2013). Restricting access time at pasture and time of grazing allocation for Holstein dairy cows: Ingestive behaviour, dry matter intake and milk production. *Livestock Science,* 152(1), pp. 53-62.

Mee, J.F. & Boyle, L.A. (2020). Assessing whether dairy cow welfare is “better” in pasture-based than in confinement-based management systems. *New Zealand Veterinary Journal,* 68(3), pp. 168-177.

Melin, M., Svennersten-Sjaunja, K. & Wiktorsson, H. (2005). Feeding patterns and performance of cows in controlled cow traffic in automatic milking systems. *Journal of Dairy Science,* 88(11), pp. 3913-3922.

Miele, M., Veissier, I., Evans, A. & Botreau, R. (2011). Animal welfare: Establishing a dialogue between science and society. *Animal Welfare,* 20.

Motupalli, P.R., Sinclair, L.A., Charlton, G.L., Bleach, E.C. & Rutter, S.M. (2014). Preference and behavior of lactating dairy cows given free access to pasture at two herbage masses and two distances. *Journal of Animal Science,* 92(11), pp. 5175-84.

Nakagawa, S. & Schielzeth, H. (2013). A general and simple method for obtaining R^2 from generalized linear mixed-effects models. *Methods in Ecology and Evolution,* 4(2), pp. 133-142.

National Research Council (2001). Energy. In: *Nutrient Requirements of Dairy Cattle: Seventh Revised Edition*. 7th. ed. Washington, DC: The National Academies Press, pp. 13-27.

NMSMt (2020). *Automatic Milking System - AMS Statistics for the Nordic countries 2019*. (Automatic Milk Systems - AMS).

Nordtømme, B.K.B., Sæther, N.H. & Vangen, O. (2007). *Beitende husdyr i Norge*. Oslo: Tun.

Norwegian Meteorological Institute (16.06.2020). *Klima fra 1900 til i dag*. Available at: https://www.met.no/vaer-og-klima/klima-siste-150-ar [16.09.2020].

Olmos, G., Boyle, L., Hanlon, A., Patton, J., Murphy, J.J. & Mee, J.F. (2009). Hoof disorders, locomotion ability and lying times of cubicle-housed compared to pasture-based dairy cows. *Livestock Science,* 125(2-3), pp. 199-207.

Olynk, N.J., Tonsor, G.T. & Wolf, C.A. (2010). Consumer willingness to pay for livestock credence attribute claim verification. *Journal of Agricultural and Resource Economics,* 35(2), pp. 261-280.

Overrein, H., Aunsmo, G. & Næss, G. (2018). Economic considerations of part-time grazing on exercise and production pasture on farms with automated milking: an analysis based on Norwegian and Swedish conditions (In Norwegian). *FoU-rapport.* Bodø, Norway: Nord universitet.

Pelve, M.E., Spörndly, E., Olsson, I. & Glimskär, A. (2020). Grazing and fouling behaviour of cattle on different vegetation types within heterogeneous semi-natural and naturalised pastures. *Livestock Science,* 241, p. 104253.

Penry, J.F., Crump, P.M., Hernandez, L.L. & Reinemann, D.J. (2018). Association of milking interval and milk production rate in an automatic milking system. *Journal of Dairy Science,* 101(2), pp. 1616-1625.

Pérez-Prieto, L.A. & Delagarde, R. (2013). Meta-analysis of the effect of pasture allowance on pasture intake, milk production, and grazing behavior of dairy cows grazing temperate grasslands. *Journal of Dairy Science,* 96(10), pp. 6671-6689.

Pérez-Ramírez, E., Delagarde, R. & Delaby, L. (2008). Herbage intake and behavioural adaptation of grazing dairy cows by restricting time at pasture under two feeding regimes. *animal,* 2(9), pp. 1384-1392.

Pérez-Ramírez, E., Peyraud, J.L. & Delagarde, R. (2009). Restricting daily time at pasture at low and high pasture allowance: Effects on pasture intake and behavioral adaptation of lactating dairy cows. *Journal of Dairy Science,* 92(7), pp. 3331-3340.

Peyraud, J.L. & Delagarde, R. (2013). Managing variations in dairy cow nutrient supply under grazing. *animal,* 7(1), pp. 57-67.

Phelan, P., Casey, I.A. & Humphreys, J. (2013). The effect of target postgrazing height on sward clover content, herbage yield, and dairy production from grass-white clover pasture. *Journal of Dairy Science,* 96(3), pp. 1598-1611.

Polsky, L. & von Keyserlingk, M.A.G. (2017). Invited review: Effects of heat stress on dairy cattle welfare. *Journal of Dairy Science,* 100(11), pp. 8645-8657.

Prescott, N.B., Mottram, T.T. & Webster, A.J.F. (1998). Relative motivations of dairy cows to be milked or fed in a Y-maze and an automatic milking system. *Applied Animal Behaviour Science,* 57(1), pp. 23-33.

Prickett, R.W., Norwood, F.B. & Lusk, J.L. (2010). Consumer preferences for farm animal welfare: results from a telephone survey of US households. *Animal Welfare,* 19(3), pp. 335-347.

Prince, J.H., Diesem, C.D., Eglitis, I. & Ruskell, G.L. (1960). *Anatomy and histology of the eye and orbit in domestic animals*. Springfield, Ill.: C. C. Thomas. Available from: http://hdl.handle.net/2027/mdp.39015003811109.

R Core Team (2020). *R: A Language and Environment for Statistical Computing*. [Computer Program]. Vienna, Austria: R Foundation for Statistical Computing. Available from: https://www.R-project.org/.

Reijs, J.W., Daatselaar, C.H.G., Helming, J.F.M., Jager, J.H. & Beldman, A.C.G. (2013). *Grazing dairy cows in North-West Europe : Economic farm performance and future developments with emphasis on the Dutch situation*. The Hague: LEI Wageningen UR.

Rodenburg, J. (2017). Robotic milking: Technology, farm design, and effects on work flow. *Journal of Dairy Science,* 100(9), pp. 7729-7738.

Rook, A.J. (2000). Principles of foraging and grazing behaviour. In: Hopkins, A. (ed.) *Grass: Its Production and Utilization*. 3rd. ed. Oxford, UK: Blackwell Science, pp. 229-246.

Rook, A.J. & Huckle, C.A. (1995). Synchronization of ingestive behaviour by grazing dairy cows. *Animal Science,* 60(1), pp. 25-30.

Röös, E., Bajželj, B., Smith, P., Patel, M., Little, D. & Garnett, T. (2017). Greedy or needy? Land use and climate impacts of food in 2050 under different livestock futures. *Global Environmental Change,* 47, pp. 1-12.

Sans, P. & Combris, P. (2015). World meat consumption patterns: An overview of the last fifty years (1961–2011). *Meat Science,* 109, pp. 106-111.

Schils, R., Philipsen, B., Hoekstra, N., Holshof, G., Zom, R., Hoving, I., van Reenen, K., Stienezen, M., Klootwijk, C., van der Werf, J., Sebek, L., van Eekeren, N., van Dixhoorn, I. & van den Pol-van Dasselaar, A. (2019). Amazing grazing: A public and private partnership to stimulate grazing practices in intensive dairy systems. Sustainability (Basel, Switzerland), 11(20), p. 5868.

Schukken, Y.H., Grommers, F.J., Vandegeer, D., Erb, H.N. & Brand, A. (1991). Risk-factors for clinical mastitis in herds with a low bulk milk somatic-cell count. 2. Risk-factors for Escherichia coli and Staphylococcus aureus. *Journal of Dairy Science,* 74(3), pp. 826-832.

Schuppli, C.A., von Keyserlingk, M.A.G. & Weary, D.M. (2014). Access to pasture for dairy cows: Responses from an online engagement. *Journal of Animal Science,* 92(11), pp. 5185-92.

Schütz, K.E., Cox, N.R. & Matthews, L.R. (2008). How important is shade to dairy cattle? Choice between shade or lying following different levels of lying deprivation. *Applied Animal Behaviour Science,* 114(3), pp. 307-318.

Schütz, K.E., Rogers, A.R., Cox, N.R. & Tucker, C.B. (2009). Dairy cows prefer shade that offers greater protection against solar radiation in summer: Shade use, behaviour, and body temperature. *Applied Animal Behaviour Science,* 116(1), pp. 28-34.

Scott, V.E., Kerrisk, K.L., Thomson, P.C., Lyons, N.A. & Garcia, S.C. (2015). Voluntary cow traffic and behaviour in the premilking yard of a pasture-based automatic milking system with a feed supplementation regime. *Livestock Science,* 171, pp. 52-63.

SJVFS (2016). *Djurskyddsförordningen*. Stockholm: Justisdepartementet.

SMHI (2010). *Väderdata och statistik*. Available from: https://www.smhi.se/kunskapsbanken/klimat/normaler/normalperioden-1931-1960-1.12507 [20.08.2015].

Smid, A.-M.C., Weary, D.M., Costa, J.H.C. & von Keyserlingk, M.A.G. (2018). Dairy cow preference for different types of outdoor access. *Journal of Dairy Science,* 101(2), pp. 1448-1455.

Smid, A.-M.C., Weary, D.M. & von Keyserlingk, M.A.G. (2020). The influence of different types of outdoor access on dairy cattle behavior. *Frontiers in veterinary science,* 7:257.

Smid, A.M.C., Burgers, E.E.A., Weary, D.M., Bokkers, E.A.M. & von Keyserlingk, M.A.G. (2019). Dairy cow preference for access to an outdoor pack in summer and winter. *Journal of Dairy Science,* 102(2), pp. 1551-1558.

Smith, P. (2014). Do grasslands act as a perpetual sink for carbon? *Global Change Biology,* 20(9), pp. 2708-2711.

Spooner, J.M., Schuppli, C.A. & Fraser, D. (2014). Attitudes of Canadian citizens toward farm animal welfare: A qualitative study. *Livestock Science,* 163, pp. 150-158.

Spörndly, E., Andersson, S., Pavard, N. & Goc, S.l. Production pasture versus exercise and recreation pasture for cows in automatic milking systems. In: Van den Pol-van Dasselaar, A., Aarts, H.F.M., De Vliegher, A., Elgersma, A., Reheul, D., Reijneveld, J.A., Verloop, J. & Hopkins, A. (eds) *Proceedings of the 18th Symposium of the European Grassland Federation, EGF 2015 Grassland and forages in high output dairy farming systems*, Wageningen, The Netherlands, 15-17 June 2015. Wageningen, The Netherlands: Wageningen Academic Publishers, pp. 125-127.

Spörndly, E. & Karlsson, M. Production and cow-traffic management during the pasture season in large herds with automatic milking. In: Van den Pol-van Dasselaar, A., Aarts, H.F.M., De Vliegher, A., Elgersma, A., Reheul, D., Reijneveld, J.A., Verloop, J. & Hopkins, A. (eds) *Proceedings of the 18th Symposium of the European Grassland Federation, EGF 2015 Grassland and forages in high output dairy farming systems*, Wageningen, The Netherlands, 15-17 June 2015. Wageningen, The Netherlands: Wageningen Academic Publishers, pp. 131-133.

Spörndly, E. & Kumm, K.I. (2010). Lönar det sig med mer ensilage och bete till korna? - Ekonomiska beräkningar på gårdsnivå. Uppsala, Sweden: Department of Animal Nutrition and Management, Swedish University of Agricultural Sciences.

Spörndly, E. & Wredle, E. (2004). Automatic milking and grazing—effects of distance to pasture and level of supplements on milk yield and cow behavior. *Journal of Dairy Science,* 87(6), pp. 1702-1712.

Spörndly, R. (ed.) (2003). *Fodertabeller för idisslare*. Uppsala: Swedish University of Agricultural Science Department of Animal Nutrition and Mangement.

St-Pierre, N.R. (2001). Invited review: Integrating quantitative findings from multiple studies using mixed model methodology. *Journal of Dairy Science,* 84(4), pp. 741-755.

Statistics Norway (2015). *Minifacts about Norway*. web: Norwegian Ministry of Foreign Affairs. Available from: https://www.ssb.no/befolkning/artikler-og-publikasjoner/_attachment/225814?_ts=14d005aeb20 [16.09.2020].

Statistics Norway (2020a). *Dette er Norge 2020. Tall som forteller*. (Dette er Norge, 10). Oslo: Statistisk Sentralbyrå.

Statistics Norway (2020b). Gardsbruk, jordbruksareal og husdyr. ssb.no/statbank: Statistisk Sentralbyrå.

Statistics Norway (2020c). Gårdbrukerens inntekter og gjeld. 09824: Gjeld og renteutgifter for brukere, etter driftsform, 2010-2018. ssb.no/statbank: Statistisk Sentralbyrå.

Stelwagen, K. & Lacy-Hulbert, S.J. (1996). Effect of milking frequency on milk somatic cell count characteristics and mammary secretory cell damage in cows. *American Journal of Veterinary Research,* 57(6), pp. 902-905.

Stelwagen, K., Phyn, C.V.C., Davis, S.R., Guinard-Flament, J., Pomiès, D., Roche, J.R. & Kay, J.K. (2013). Invited review: Reduced milking frequency: Milk production and management implications. *Journal of Dairy Science,* 96(6), pp. 3401-3413.

Svennersten-Sjaunja, K.M. & Pettersson, G. (2008). Pros and cons of automatic milking in Europe. *Journal of Animal Science,* 86(13), pp. 37-46.

Swedish Board of Agriculture (2014). *Beteslagstiftningens effekter på lönsamheten i mjölkföretagen - en studie av tre typgårdar*: Jordbruksverket.

Taweel, H.Z., Tas, B.M., Dijkstra, J. & Tamminga, S. (2004). Intake regulation and grazing behavior of dairy cows under continuous stocking. *Journal of Dairy Science,* 87(10), pp. 3417-3427.

Thomsen, P.T., Kjeldsen, A.M., Sorensen, J.T., Houe, H. & Ersboll, A.K. (2006). Herd-level risk factors for the mortality of cows in Danish dairy herds. *Veterinary Record,* 158(18), pp. 622-626.

Thorsen, S. (2020). Solstices & Equinoxes for Uppsala (Surrounding 10 Years). Stavanger, Norway: Time and Date AS.

TINE Produsentrådgiving (2003). *Statistikksamling fra Ku- og Geitekontrollen 2002*. (Statistikksamling 2003): TINE Produsentrådgiving.

TINE Produsentrådgiving (2020). *Statistikksamling fra Ku- og Geitekontrollen 2019*. (Statistikksamling 2020): TINE Rådgiving Husdyrkontrollen.

TINE SA (2020). *TINE Annual Report 2019*. Oslo, Norway.

Tse, C., Barkema, H.W., DeVries, T.J., Rushen, J. & Pajor, E.A. (2018). Impact of automatic milking systems on dairy cattle producers' reports of milking labour management, milk production and milk quality. *animal,* 12(12), pp. 2649-2656.

UN (2015). Transforming our world: the 2030 Agenda for Sustainable Development. Resolution adopted by the General Assembly, New York, U.S., 25-27 September 2015. A/RES/70/1. New York: United Nations

UN (2019). *World Population Prospects 2019: Highlights* United Nations, Department of Economic and Social Affairs.

USDA (2007). *Highlights Part I: Reference of dairy cattle health and management practices in the United States*. Fort Collins, CO, USA: USDA-APHIS-VS, CEAH.

10.6.2010/592 Valtioneuvoston asetus nautojen suojelusta (2010). Helsinki: Maa- ja metsätalousministeriö.

van den Pol-van Dasselaar, A., Hennessy, D. & Isselstein, J. (2020). Grazing of Dairy Cows in Europe—An In-Depth Analysis Based on the Perception of Grassland Experts. *Sustainability,* 12(3):1098.

van den Pol-van Dasselaar, A., Philipsen, B. & de Haan, M.H.A. The effect of social factors on the extent of grazing. In: Höglind, M., Bakken, A.K., Hovstad, K.A., Kallioniemi, E., Riley, H., Steinshamn, H. & Østrem, L. (eds) *Proceedings of the 26th General Meeting of the European Grassland Federation, EGF 2016 The multiple roles of grassland in the European bioeconomy*, Trondheim, Norway, 4-8 September 2016. Wageningen, The Netherlands: NIBIO, Norway, pp. 62-64.

van den Pol-van Dasselaar, A., Vellinga, T.V., Johansen, A. & Kennedy, E. (2008). To graze or not to graze, that's the question. In: Hopkins, A., Gustafsson, T., Dalin, G., Nilsdotter-Linde, N. & Spörndly, E. (eds) *Proceedings of the 22nd General Meeting of the European Grassland Federation, EGF 2008 Biodiversity and Animal Feed Future Challenges for Grassland Production* Uppsala, Sweden, 9-12 June 2008. Uppsala, Sweden: European Grassland Federation, pp. 706-716.

van Vuuren, A.M. & van den Pol-van Dasselaar, A. (2006). Grazing systems and feed supplementation. In: Elgersma, A., Dijkstra, J. & Tamminga, S. (eds) *Fresh Herbage for Dairy Cattle : the Key to a Sustainable Food Chain*. (Wageningen UR Frontis Series, 18). Dordrecht, The Netherlands: Springer, pp. 85-101.

Vik, J., Stræte, E.P., Hansen, B.G. & Nærland, T. The social robot: A study of the social and political aspects of automatic milking systems. In: *Proceedings of System Dynamics and Innovation in Food Networks*2017: International Journal on Food System Dynamics, pp. 220-233.

Vik, J., Stræte, E.P., Hansen, B.G. & Nærland, T. (2019). The political robot – The structural consequences of automated milking systems (AMS) in Norway. *NJAS - Wageningen Journal of Life Sciences,* 90-91, p. 100305.

Vinge, H. & Flø, B.E. (2015). Landscapes lost? Tourist understandings of changing Norwegian rural landscapes. *Scandinavian Journal of Hospitality and Tourism,* 15(1-2), pp. 29-47.

Virkajärvi, P. (2004). *Growth and utilization of timothy – meadow fescue pastures.* Diss. Helsinki, Finland: University of Helsinki.

Vitali, A., Segnalini, M., Bertocchi, L., Bernabucci, U., Nardone, A. & Lacetera, N. (2009). Seasonal pattern of mortality and relationships between mortality and temperature-humidity index in dairy cows. *Journal of Dairy Science,* 92(8), pp. 3781-3790.

Volden, H. (ed.) (2011). *NorFor – The Nordic feed evaluation system*. (EAAP Scientific Series. Wageningen, The Netherlands: Wageningen Academic Publishers.

von Keyserlingk, M.A.G., Amorim Cestari, A., Franks, B., Fregonesi, J.A. & Weary, D.M. (2017). Dairy cows value access to pasture as highly as fresh feed. *Scientific reports,* 7, pp. 44953-44953.

Wagner-Storch, A.M. & Palmer, R.W. (2003). Feeding behavior, milking behavior, and milk yields of cows milked in a parlor versus an automatic milking system. *Journal of Dairy Science,* 86(4), pp. 1494-1502.

Wagner, K., Brinkmann, J., March, S., Hinterstoißer, P., Warnecke, S., Schüler, M. & Paulsen, H. (2017). Impact of daily grazing time on dairy cow welfare—Results of the Welfare Quality® Protocol. *Animals,* 8:1.

Washburn, S.P., White, S.L., Green, J.T. & Benson, G.A. (2002). Reproduction, mastitis, and body condition of seasonally calved Holstein and Jersey cows in confinement or pasture systems. *Journal of Dairy Science,* 85(1), pp. 105-111.

Wehn, S., Olsson, G. & Hanssen, S. (2012). Forest line changes after 1960 in a Norwegian mountain region - implications for the future. *Norsk Geografisk Tidsskrift - Norwegian Journal of Geography,* 66(1), pp. 2-10.

Weinrich, R., Kühl, S., Zühlsdorf, A. & Spiller, A. (2014). Consumer attitudes in Germany towards different dairy housing systems and their implications for the marketing of pasture raised milk. *The International Food and Agribusiness Management Review,* 17, pp. 205-222.

Weiss, B. (2014). Eating Ursula. *Gastronomica: The Journal of Critical Food Studies,* 14(4), pp. 17-25.

Wildridge, A.M., Thomson, P.C., Garcia, S.C., John, A.J., Jongman, E.C., Clark, C.E.F. & Kerrisk, K.L. (2018). Short communication: The effect of temperature-humidity index on milk yield and milking frequency of dairy cows in pasture-based automatic milking systems. *Journal of Dairy Science,* 101(5), pp. 4479-4482.

Wilkinson, J.M. (2011). Re-defining efficiency of feed use by livestock. *animal,* 5(7), pp. 1014-1022.

Wu, Z., Kanneganti, V.R., Massingill, L.J., Wiltbank, M.C., Walgenbach, R.P. & Satter, L.D. (2001). Milk production of fall-calving dairy cows during summer grazing of grass or grass-clover pasture. *Journal of Dairy Science,* 84(5), pp. 1166-1173.

Zuur, A.F., Hilbe, J.M. & Ieno, E.N. (2013). *A beginner's guide to GLM and GLMM with R : a frequentist and bayesian perspective for ecologists*. Newburgh: Highland Statistics.

Zuur, A.F. & Ieno, E.N. (2016). A protocol for conducting and presenting results of regression-type analyses. *Methods in Ecology and Evolution,* 7(6), pp. 636-645.

Zuur, A.F., Ieno, E.N. & Elphick, C.S. (2009). A protocol for data exploration to avoid common statistical problems. *Methods in Ecology and Evolution,* 1(1), pp. 3-14.

Popular science summary

Background AMS and grazing season

The growing use of automatic milking systems (AMS) in the European dairy sector has been accompanied by a decline in grazing and in time the animals can spend outdoors. Grazing is a natural behaviour of cattle, and the opportunity to go outdoors is widely considered an important animal welfare factor. Dairy cows with access to pasture get more exercise, experience a more varied and natural environment than cows confined year-round and have a lower stocking density than during confinement. These factors are all beneficial for animal health and welfare. In addition, grazing ruminants can utilise land areas otherwise unsuitable for food production, while maintaining ecosystem services such as maintaining biodiversity and increased carbon sequestration. Consequently, many stakeholders in society want farmers to apply management systems that include grazing.

The climate in high-latitude countries does not permit year-round grazing. The cold winter conditions in the Nordic countries, combined with strong public interest in animal welfare, has led to a dairy sector characterised by high animal housing standards and strong national animal welfare legislation. Driven by an impending ban on tie-stalls and the high cost of living and corresponding high wages, transition to AMS has been rapid and substantial in the Nordic region. In parallel with this transition, the agriculture sector has seen a decline in active farms, an increase in herd size and higher yields per cow.

While the growing season in the Nordic region is short, its relatively low average temperatures, abundant and evenly distributed precipitation and long daylight hours are highly favourable for grass growth. However, weather causes fluctuations in pasture availability and nutritive quality and, since high-producing cows have high nutrient requirements, supplementary feeding is often necessary. Including a high proportion of pasture in the roughage ration could thus decrease farmers' perceived control over the energy balance of dairy cows. This problem is often overcome by the costly solution of feeding a full winter ration indoors, in addition to providing pasture access. This, together with other constraints, *e.g.* a need for continuous access between pastures and milking unit, greater area requirements for larger herds and high costs of grazing infrastructure, can reduce farmers' motivation to allow dairy cows to graze outdoors.

Aims of this thesis

This thesis examined some of the constraints frequently associated with combining grazing with AMS. Field studies were carried out to test the validity of these associations under practical conditions and identify feasible and applicable solutions for dairy farmers to offer their high-yielding lactating cows pasture access and grazed grass in their diet, without risking farm finances through inflicting yield loss.

Specific objectives of the work were to: a) compare production; b) study behaviour and time budgeting of time spent outdoors; c) investigate whether and how decreasing day length and increasing degree of darkness at night throughout the Scandinavian summer influence the behaviour of cows offered time-restricted access to either production pasture or an outdoors exercise paddock; d) investigate the relationship between milking system and change in milk production parameters in response to pasture turnout, by comparing cows milked in AMS to cows milked in a manual system; e) investigate the relationship between grazing strategy (in terms of expected roughage intake from pasture) and change in milk production parameters at pasture turnout; and f) evaluate the suitability of using drinking water intake to predict dry matter intake (DMI).

The studies

Three experimental animal studies and one survey were performed. In the first and second animal studies, daily milk yield, outdoor behaviour, body weight and intake of grass silage and concentrates by 39 and 41 cows was recorded for 49 and 81 days, respectively, along with weather data and recordings of pasture mass, height and quality. Two different pasture allowances in two different part-time grazing strategies were compared on the basis of milk yield and animal behaviour. In the third experiment, which was carried out within the frame of experiment 1, estimated DMI in a pasture management system was compared with known DMI of cows with access to an outdoor area without grass to graze, based on drinking water consumption. In the survey study, a questionnaire about farm management, milking system and grazing strategy was distributed to all Norwegian dairy farmers. It documented the current occurrence of grazing in Norwegian dairy herds and the strategies used by Norwegian dairy farmers to meet national grazing requirements. Milking systems and grazing strategies were compared on the basis of objective measures of response to pasture turnout.

Results

Cows in both treatment groups in the animal experiments showed motivation to be outdoors, particularly in late afternoon and evening. The group with only access to an exercise paddock interrupted a silage meal indoors in order to go out to a pasture with virtually no available grass to feed on. Despite the very low sward height, they still put their noses to the ground and expressed basic grazing behaviour. The group with access to a lush pasture, which had to obtain half their daily roughage ration for themselves, spent a longer time outdoors. Much of this time was spent grazing, for obvious reasons, but these cows also spent a considerable time resting and in social interactions. However, motivation for being outdoors did not overcome the nightly comforts or familiarity of the barn for either of the groups when offered overnight outdoor access only.

No systematic difference in response to pasture turnout was found, based on either milking system or type of outdoor access solution. On offering pasture access twice per day, following the natural rhythm of wild ruminants, there was no difference in production between the group given a full indoor ration and access to an exercise paddock and the group that was expected to harvest half the daily ration themselves. In contrast, offering pasture access only at night caused a decrease in yield in the cows which had to rely on grazing to fulfil their needs.

Conclusions

Analysis of production data showed that it is possible to maintain milk production in high-yielding cows on a diet with a substantial proportion of pasture in the roughage ration. There was no apparent relationship between milking system used and yield response to being turned out on pasture. Cows in all cases showed a strong inner motivation for being outdoors and expressing grazing behaviour, even when satiated.

(Double cow track – left lane to exercise paddock, right lane to production pasture)

"When you have eliminated all which is impossible, then whatever remains, however improbable, must be the truth."

- Sir Arthur Conan Doyle

Populärvetenskaplig sammanfattning

Under det senaste årtionde har andelen automatiska mjölkningssystem (AMS) i europeiska mjölkkobesättningar ökat, det sammanfaller med minskad betesdrift och tiden som mjölkkon spenderar utomhus. Betande är ett naturligt beteende hos kor, och möjligheten att få vara utomhus anses viktig för djurvälfärden, speciellt hos konsumenten. Mjölkkor med tillgång till betesmark får mer motion och upplever en mer varierad och naturlig miljö jämfört med besättningar som enbart hålls inomhus. Betessäsongen medför också en lägre djurtäthet än under inomhussäsongen. Dessa faktorer gynnar djurens hälsa och välfärd. Vidare kan betande idisslare utnyttja områden som annars är oanvändbara för livsmedelsproduktion, och skött på rätt sätt kan betesdrift även bidra till ekosystemtjänster som gynnar den biologiska mångfalden och ge en ökad koldioxidbindning. De nämnda positiva effekterna bidrar till intressenters önskan om att upprätthålla betesdriften.

Klimatet i Norden tillåter inte bete året runt. Vinterförhållandena i kombination med ett starkt allmänintresse för djurvälfärd har lett till att nordiskt lantbruk kännetecknas av en hög byggnadsstandard och en stark djurskyddslagstiftning. Med ett förestående förbud mot uppbundna stall, höga levnadskostnader och motsvarande höga löner har övergången till AMS varit snabb och omfattande i regionen. Parallellt med denna övergång har sektorn sett en nedgång i antalet aktiva gårdar men ökande besättningsstorlekar och högre avkastning per ko.

Även om växtsäsongen är kort i Norden är regionens relativt låga medeltemperatur, riklig och jämnt utspridd nederbördsmängd samt långa dagar mycket gynnsamma för växtligheten på beten. Vädret har dock alltid orsakat stor variation i tillgängligheten till och näringskvaliteten av bete. Detta gör att det ofta krävs tillskottsutfodring, speciellt till högproducerande kor som har ett högt näringsbehov. Mycket bete i foderstaten kan därmed minska lantbrukarens upplevda kontroll över sina djurs energibalans. Detta motiverar ofta den dyra lösningen att både ge tillgång till betesmark och utfodra en full vinterfoderstat med ensilage inomhus. Detta, tillsammans med ytterligare begränsningar - t.ex. behov för fri kotrafik mellan AMS och betesmarker, ett ökad arealkrav för stallnära beten vid större besättningar och höga kostnader för betesinfrastruktur - kan orsaka en minskande motivation för lantbrukare för att upprätthålla betesdriften.

Syfte

Det övergripande syftet med studierna som presenteras i avhandlingen var att utvärdera ett urval av de begränsningar som ofta tillskrivs att kombinera bete med AMS, genom att testa giltigheten av dessa antagna sammanhang under praktiska förhållanden och undersöka tillämpbara lösningar för att erbjuda utomhusvistelse och betat gräs i foderstaten till högavkastande kor utan att riskera sänkt avkastning och ekonomisk förlust.

De specifika delmålen var att a) jämföra mjölkproduktion, b) studera beteende och hur korna använder den tid de tillbringar utomhus, och c) undersöka om och eventuellt hur den ökande längden på natten under en skandinavisk sommar påverkade beteendet hos kor som under en tidsbegränsad del av dygnet erbjöds tillgång till antingen produktionsbete eller en motionsfålla. Ytterligare delmål var att d) undersöka sambandet mellan mjölkningssystem och förändring av mjölkavkastning vid betessläppning genom att jämföra kor och besättningar som mjölkades i AMS med kor som mjölkades vid rörmjölkning, e) undersöka sambandet mellan olika betesstrategier - i form av grovfoderintag förväntat komma från bete - och förändring av mjölkavkastning vid betessläppning, och f) göra en utvärdering av lämpligheten med att använda mätningar av dricksvattenintag för att uppskatta torrsubstansintag.

Studiernas genomförande

Denna avhandling bygger på fyra artiklar som bestod av tre experimentella djurförsök och en enkätstudie. I det första och andra experimentet registrerades daglig mjölkavkastning, utomhusbeteende, kroppsvikt och intag av ensilage och kraftfoder från 39 och 41 kor under 49 respektive 81 dagar, dessutom registrerades väderdata, beteshöjd och -kvalité, samt uppskattad mängd torrsubstans bete per hektar. Produktionsbete och rastbete jämfördes beträffande mjölkavkastning och beteende under två olika strategier för deltidsbete, med betespass morgon och kväll eller nattbete. Det tredje experimentet genomfördes inom ramen för experiment 1. Genom att använda mätningar av dricksvattenintag skattades torrsubstansintag från bete. Dessa skattningar jämfördes med kor som vistades i en rastfålla, och som hade ett känd torrsubstansintag från ensilage och kraftfoder. En enkät om management, mjölkningssystem och betesstrategi skickades ut till alla norska lantbrukare med mjölkkor. Genom enkäten dokumenterades förekomsten av betesdrift i norska mjölkkobesättningar och de strategier som norska mjölkproducenter använde för att uppfylla beteskravet. Mjölkningssystem och betesstrategier jämfördes med avseende på objektiva mått på avkastningsrespons vid betessläpp.

Resultat

Kor i båda behandlingsgrupperna i de kontrollerade försöken var motiverade att vistas utomhus, speciellt sent på eftermiddagen och under kvällstid. Gruppen med tillgång till rastfålla avbröt en ensilagemåltid inomhus för att gå ut på en betesfålla där det nästan inte fanns gräs att beta på. Trots den mycket låga gräshöjden satte de fortfarande mulen mot marken och uttryckte sitt grundbeteende genom att tugga av ett grässtrå här och ett där. Gruppen med tillgång till rikligt bete, och med en restriktiv ensilagegiva inomhus som förutsatte att de själva skördade delar av sitt grovfoder, tillbringade längre tid utomhus. Mycket av den extra tiden användes av naturliga skäl till att beta, men korna använde också mycket tid till att vila och att umgås socialt under tiden de var utomhus. I försöket där korna bara fick vistas utomhus under kvällen och natten så var kor från båda grupper utomhus på kvällstid, men under natten vann stallets bekvämligheter och hemmakänsla över motivationen för att vara på bete för båda grupperna.

Någon systematisk skillnad mellan olika mjölkningssystem och mellan olika typer av utomhusvistelse upptäcktes inte när dessa jämfördes på ändring i produktion vid betessläppning. Det fanns inte heller någon skillnad i avkastning mellan gruppen med full inomhusutfodring och tillgång till rastfålla och gruppen som förväntades skörda hälften av sin dagliga ranson själva. Likaså följde båda grupperna vilda idisslares dygnsrytm när de hade möjlighet att gå ut två gånger per dag, morgon och kväll. Att erbjuda betesåtkomst endast under natten orsakade dock en minskning i avkastning för korna som var tvungna att beta själv.

Sammanfattningsvis visar resultaten att det är möjligt att upprätthålla mjölkproduktionen hos högavkastande kor genom att erbjuda en hög andel bete i grovfoderransonen. Det fanns inte heller något tydligt samband mellan mjölkningssystem och kornas respons på betessläpp.

“When we try to pick out anything by itself, we find it hitched to everything in the Universse”

– John Muir

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– Lewis Carrol

“Done is better than perfect”
– Mark Zuckerberg

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Parallel with the influx of automatic milking systems (AMS) seen in European dairy herds the past decades a lapse in grazing and in time cows spend outdoors has been seen. Addressing a selection of constraints frequently ascribed to combining grazing with AMS by testing the validity of these associations under experimental and practical conditions, this thesis is exploring feasible and applicable solutions for farmers to offer their high-yielding lactating cows pasture access and grazed grass in their diet.

Haldis Kismul received her postgraduate education at the Department of Animal Nutrition and Management. Her Doctorate of Veterinary Medicine was received from Faculty of Veterinary Science, Szent István University (now University of Veterinary Medicine Budapest), Hungary.

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