Investigations into system and cow performance efficiency in pasture-based automatic milking systems

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Dedicated to my Family

CONTENTS

ABSTRACT

The adoption of automatic milking systems (AMS) as an alternative to conventional milking systems continues to increase throughout the world. Although previous research has demonstrated that AMS can be successfully integrated with pasture-based systems, performance and efficiency levels observed in pasture-based AMS present greater variability and are lower in comparison to indoor AMS. Factors specific to pasture-based systems create some challenges different from those observed in indoors systems, resulting in a greater variation in milking frequency and milking interval among individual cows and days, leading to variation in robot utilisation (a key performance indicator in AMS). Therefore, the general aim of this thesis was to identify strategies on how to improve system performance in pasture-based AMS operating with voluntary traffic. The literature review (Chapter 2) explored the current situation in regards to system and cow performance on pasture-based AMS. Gaps in knowledge and potential ways of increasing productivity and efficiency in the system were identified. The analysis of a 2-year dataset from 17 commercial pasture-based AMS farms (Chapter 3) demonstrated that the number of cows milked per robot had a greater effect than milking frequency on robot performance or utilisation. This finding, together with the high degree of variability regarding individual cow performance arising from the study reported in Chapter 2, led to developing a methodology to identify Efficient and Inefficient cows based on their combined effect of milking frequency and milk yield (Chapter 4). In this study, which was based on a large dataset from two commercial farms, Efficient cows were identified in both farms producing on average 9% more milk with 5% fewer milkings per day and Inefficient cows producing 10% less milk with a 6% higher milking frequency, both in relation to their expected values. The hypothesis that differences in cow behaviour could explain, at least in part, the differences observed between levels of efficiency in cow performance was confirmed after a field study was conducted for that purpose (Chapter 6). A validation of a recently commercially released version of an activity and rumination monitoring system was conducted (Chapter 5) to allow differences in cow behaviour to be determined (Chapter 6). Efficient cows produced more milk, with no difference in cow traffic variables compared to Inefficient cows. The difference in cow performance was therefore likely to be partially explained by cow behaviour, as Efficient cows were recorded to have longer grazing and rumination times and shorter resting times than Inefficient cows. Together, the novel and original studies reported in Chapters 3 to 6 are indicative of the

opportunities that exist to increase efficiency in AMS through manipulation of cow behaviour and individual animal efficiency.

The potential to manipulate robot utilisation at whole herd level was then explored in Chapter 7, in which the results of a field study conducted to evaluate if experienced cows could quickly adapt to a short period of voluntary-batch milking, without cow performance being affected, were summarised. This constitutes a potential management strategy for periods of underutilisation of the robotic equipment, where productivity and efficiency of the system is reduced. All combined, the original research presented in this thesis contributes with new knowledge to the novel field of pasture-based AMS and research methodology in AMS. The research has scientifically validated a (now) commercially available research tool (tags); and it has developed a new and innovative method to identify individual animals with above or below average level of performance efficiency in AMS, which use and application would be hopefully extended by future work. The thesis has also identified, and where possible quantified, key indicators that relate to the productivity of AMS, providing evidence that questions the most common strategy adopted by AMS farmers globally, namely increasing production per cow with moderate or relatively lower number of cows per robot. More research in this field is certainly warranted. In summary this thesis makes a significant contribution based on novel, original, and scientifically-generated knowledge, that together, will help to advance systems and cow performance and efficiency on pasture-based AMS in the future.

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PREFACE

All chapters within this thesis are presented in publication format using Australian English as the preferred language. I certify that all studies presented in this thesis are a result of my own original work, with Juan Molfino as the primary author, and that all contributions received in preparing it have been acknowledged. None of the content of this research has been submitted to other University previously.

Some of the chapters presented in this thesis have been published or submitted for publication to peer-reviewed journals and are indicated in the cover page. In addition, some of them have been presented in conferences and symposiums.

Juan Molfino

June 2018

LIST OF PUBLICATIONS

Manuscripts published in peer-reviewed journals

Molfino, J., Clark, C. E. F., Kerrisk, K. L., and Garcia, S. C. 2017. Evaluation of an activity and rumination monitor in dairy cattle grazing two types of forages. Animal Production Science, 57, 1557-1562.

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Non peer-reviewed conference papers

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Media stories

Kerrisk K., Molfino J. In search of the dream cow. Australian Dairy Farmer- August 2015.

Kerrisk K., Molfino J. Flexibility lifts robot efficiency. Australian Dairy Farmer- August 2017.

AUTHORSHIP ATTRIBUTION STATEMENT

This thesis includes six research papers, of which one is published in a peer-reviewed journal, one research paper have been submitted to a peer-reviewed journal, and the remaining four research papers are planned for submission.

I, Juan Molfino, was primarily responsible for the design, implementation, data collection, data analysis and writing up of each of the research studies under the supervision of Prof. Sergio Garcia, and Associate Prof. Kendra Kerrisk (Faculty of Science, School of Life and Environmental Sciences, The University of Sydney).

Chapter 6 of this thesis is published as Molfino, J., Clark, C. E. F., Kerrisk, K. L., and Garcia, S. C. 2017. Evaluation of an activity and rumination monitor in dairy cattle grazing two types of forages. Animal Production Science, 57, 1557-1562. I co-designed the study with the co-authors, conducted the experiment, co-analysed the data and wrote the drafts for the manuscript.

The submitted research papers are all with Juan Molfino as the first author and with similar responsibilities and contributions as per the published paper.

Juan Molfino

June 2018

As supervisor for the candidate upon which this thesis is based, I can confirm that the authorship attribution statements above are correct.

Professor Sergio C Garcia

June 2018

ABBREVIATIONS

The following is a list of abbreviations used throughout the thesis. Abbreviations are defined in their first use in each chapter.

%	Percent
% CC	Percentage of concentrate consumed
AMR	Automatic milking rotary
AMS	Automatic milking system (s)
CC	Concentrate consumed
CCC	Concordance correlation coefficient
CI	Confidence Interval
CMS	Conventional milking system (s)
CR	Cows per robot
d	Day (s)
DIM	Days in milk
DM	Dry matter
MF	Daily milking frequency
DMI	Dry matter intake
DY	Daily milk yield
DPI	Department of Primary Industries
EFF	Efficient cows
FN	False negative
FP	False positive
FT	Feeding area time
FTE	Full time equivalent
GBC	Grain based concentrate
GLMM	Generalised linear mixed model
h	Hour (s)
hh:mm	Hours : Minutes
INC	Incomplete milking (s)
INEF	Inefficient cows
KPI	Key Performance Indicators

kg	Kilograms
km	Kilometers
m	Meters
m2	Metres squared
min	Minute (s)
MF	Milking frequency
MHR	Milk harvested per robot
MI	Milking interval
MMI	Minimum milking interval
MY	Milk yield per milking
n	Number
NSW	New South Wales
P	*P* - value
PMR	Partial mixed ration
REML	Restricted maximum likelihood procedure
RR	Robotic rotary
RRMF	Relative residual for milking frequency
RRDY	Relative residual for daily milk yield
RT	Return time
SD	Standard deviation
SE	Standard error
SED	Average standard error of the mean
SOL	Stage of lactation
THI	Temperature humidity index
TN	True negative
TP	True positive
WT	Pre-milking waiting area time
2WG	Two-way grazing
3WG	Three-way grazing
4WG	Four-way grazing

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CHAPTER 1: General introduction

INTRODUCTION

The majority of Australian dairy farmers have the capacity to grow and graze forage on-farm for most of the year, which provides a competitive advantage in the cost of feed (Garcia and Fulkerson, 2005). It is estimated that more than 95% of the dairy farmers in Australia rely on grazed pasture (Dairy Australia, 2017). This puts the Australian dairy industry in a unique position, as it is likely that the demand for dairy products produced from pasture-based systems is going to increase, due to the green image associated with cows grazing pasture (Von Keyserlingk et al., 2013).

However, pasture-based systems cannot achieve the same levels of productivity per cow (and per unit of land) as those achieved in more intensive production systems (Garcia and Fulkerson, 2005). Thus, pasture-based systems need to keep increasing their overall efficiency of production to remain viable and competitive (Chapman et al., 2009), but without negatively impacting on animal welfare, milk quality or the environment.

One of the main issues affecting overall production efficiency in the Australian dairy industry is labour. The main concern resides not only in the associated costs but also in the difficulty to attract and retain new and skilled workers (Nettle and Oliver, 2009, Dairy Australia, 2015, Gargiulo et al., 2018). In addition, in line with a global trend, the number of dairy farms in Australia continues to decrease whilst the average size of the herd continues to increase, which is also affecting the demand for skilled labour (Dairy Australia, 2017).

The adoption of automation and sensor-based systems is helping some farmers to improve labour efficiency, reduce pressure on labour and improve management of large herds (Eastwood et al., 2016, Gargiulo et al., 2018). Automatic milking systems (AMS) is one example of technologies being increasingly adopted by dairy farmers. First commercially introduced in 1992 in Europe, there are now more than 15,000 commercial dairies around the world operating with AMS (Rodenburg et al., 2017).

Automatic milking systems typically operate with voluntary cow traffic, where cows are able to move around the farm without requiring human intervention to travel to the milking unit to be milked. In addition, milking events are distributed throughout the day and night, removing the need for defined milking sessions. Feed is used as the main incentive to motivate cows to move through the system (Prescott et al., 1998). This is key for AMS, as success of the operation relies on the motivation of cows to visit the milking unit regularly.

In spite of being originally designed for indoor systems operating with small herds (typically less than 100 cows), AMS was first introduced for pastured-based systems in the early 2000's. Since then, more than 60 farms in Australia and New Zealand have adopted this technology. Previous research studies have demonstrated that AMS can be successfully integrated into grazing systems, and that cows adapt very well to voluntary cow traffic when feed is used as the primary incentive (Jago et al., 2002, Davis, 2006).

However, pasture-based AMS present challenges that are not experienced in indoor systems, including longer walking distances, increased opportunities for social synchronisation of activities between cows (as cows have more freedom of choice), larger herd size and a greater impact of climate (e.g. cow traffic can be severely affected by hot temperature; Wildridge 2018). As a consequence, lower and more variable levels of system performance are typically observed in pastured-based AMS in comparison to indoor systems (Lyons and Kerrisk, 2017). In spite of this, no previous research has been conducted to evaluate the current level - and variability- of system performance of pasture-based AMS, and/or identify key variables and factors affecting performance.

Optimising robot performance is deemed critical to achieving farm profitability and is an objective for the vast majority of farmers operating with AMS (Sonck and Donkers, 1995). There are many factors affecting robot performance, including animal factors (stage of lactation, age, previous AMS experience, herd dynamics), management factors (e.g. timing, placement and distribution of feed, herd size, traffic system) and environmental factors (e.g. climatic conditions) (Lyons et al., 2014). All these factors can interact, which makes evaluation of robot performance more challenging. For instance, cow traffic behaviour is affected by the interaction between time of the day, location of robot relative to shade and distance to milking robot (John et al., 2016).

In practice, however, farmers operating with AMS have two main strategies to improve system performance: increasing milking frequency (MF) whilst maintaining moderate or relatively low number of cows per robot; or increasing the number of cows in the herd whilst maintaining MF (Woolford et al., 2004). In the future a modelling approach could be useful to elucidate the advantages and limitations of these two alternatives. However, current gaps in knowledge such as the extent to which the variability in individual animal efficiency can affect performance, should be addressed first. This is because, in comparison to indoor based AMS, lower and more variable levels of MF and milk yield are typically observed in pasture-based AMS (Lyons et al., 2014, John et al., 2016). In addition, there is a significant level of variation in relation to the effect of milking interval (MI) on milk yield among individual cows, with some cows being able to adapt better to long MI, which are not unusual in pasture-based AMS (Lyons et al., 2013). This variability provides the opportunity to identify, and potentially, select cows more suitable to AMS and even more specific for pasture-based AMS. Yet, no research has been published regarding differences in individual cow performance in pasture-based AMS. In particular, the question of what is an 'efficient' (or 'inefficient') cow for pasture-based AMS has not been elucidated yet. Developing a methodology, together with validating a specific sensor-based tool to be used to assess some aspects related to animal 'efficiency' in pasture-based AMS, were among the specific objectives of this thesis.

Moreover, the complex interactions between all these factors mean that not all the strategies developed from investigations in indoor AMS systems are suitable for pasture-based AMS.

The general aim of this thesis was therefore to identify strategies on how to improve system performance in pasture-based AMS operating with voluntary traffic. The general hypothesis was that inefficiencies at both system and cow level could be identified (and in some cases quantified) to then address them. The underlying hypothesis being that, if the relationship between key variables affecting robot performance were better understood, it would be more feasible to develop better strategies to effectively optimise robot performance in pasture-based AMS. In line with these general aim and hypothesis, the specific objectives addressed in this thesis were:

1. Assess and quantify overall system performance of pasture-based AMS (Chapter 3)
2. Develop and test a methodology to identify Efficient and Inefficient cows; and quantify the extent of possible variation (Chapter 4)
3. Test a new (now commercially available) technology to monitor aspects of individual animal efficiency in grazing conditions (Chapter 5)
4. Determine factors explaining possible causes of Efficient and Inefficient in cows (Chapter 6)
5. Assess changes in cow behaviour when cows are subject to changes in traffic (voluntary vs forced) (Chapter 7)

THESIS OUTLINE

This thesis is composed of a review of the published literature (Chapter 2), five chapters arising from five independent studies (Chapter 3 to 7) and a general discussion and conclusion (Chapter 8). Each chapter is presented as stand-alone scientific manuscript, having their own abstract, introduction, materials and methods, results, discussion and conclusion.

The objective of the literature review (Chapter 2) was to determine the current situation in regards to system and cow performance on pasture-based AMS. Gaps in knowledge and potential ways of increasing production efficiency were identified, providing justification for, and need of, the research that was subsequently undertaken in this thesis.

In Chapter 3, data from 17 commercial pasture-based AMS farms were used to investigate current levels of system performance and to get a better understanding of the relationship between key variables affecting it.

The positive effect of increasing the number of cows per robot on system productivity (Chapter 3), and the high degree of variability regarding individual cow performance (Chapter 2) led us to develop a methodology to identify efficient and inefficient cows based on their combined effect of milking frequency and milk yield (Chapter 4).

Chapter 6 summarises the results of a field study aimed at understanding behavioural aspects of the individual cows (efficient and inefficient) identified using the methodology developed in the previous chapter. In addition, the validation of a recently commercially released version of an activity- and rumination- monitoring system was conducted (Chapter 5) to enable differences in cow behaviour to be determined (Chapter 6).

Aspects related to individual animal behaviour and practical changes in management practices on farm are reported in Chapter 7, which summarises the results of a field study conducted with the aim of evaluating how cows adapt to a short-term change in traffic system.

Lastly, Chapter 8 provides a general discussion of the results on the studies included within this thesis, integrating the newly generated knowledge, identifying existing gaps, and providing direction for future research to address those gaps.

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OVERVIEW OF CHAPTER 2

The adoption of automatic milking systems in Australia continues to increase, with the vast majority being integrated into pasture-based farming systems. Chapter 2 explores the literature to determine the current situation in regards to system and cow performance on pasture-based AMS. Gaps in knowledge and potential ways of increasing productivity and efficiency in the system are identified and suggestions for future research are made.

CHAPTER 2: Literature review

ABSTRACT

Research studies conducted over more than 20 years had shown that automatic milking systems (AMS) can be successfully integrated with pasture-based dairy farming. However, new challenges that are specific of pasture-based AMS, can result in lower and more variable levels of system productivity and efficiency than those typically found in indoor AMS. The purpose of this review was to compile current knowledge on pasture-based AMS performance to identify strategies on how to improve production efficiency. As a consequence of the voluntary traffic (a system in which time and frequency of milking is decided (within boundaries) primarily by the animal's motivation to visit the dairy), a greater variability in milking frequency (MF) and milking interval (MI) between individual cows and also over time is typical in AMS. In addition, there is a significant level of variation in relation to the effect of MI on milk yield between individual cows. The present review has identified the feasibility of using AMS data from commercial herds for analysis of certain individual cow traits, including MF, MI, milking time and average flow rates, among others. The review shows that there is a significant opportunity to explore observed variability in order to identify, select and potentially breed cows more suitable to AMS, and even more specifically, for pasture-based AMS. It was also shown that current levels of robot utilisation and milk harvested per robot in commercial AMS are relatively low compared to potential, indicating that there is an opportunity to improve overall efficiency and productivity. This review has identified gaps in current understanding of the relationship between robot performance, cows per robot and MF in pasture-based AMS, which highlights the need for further investigations on ways and strategies to improve AMS performance.

INTRODUCTION

Since the first automatic milking system (AMS) was introduced in a commercial dairy farm in The Netherlands in 1992, the adoption of this technology in the world has continued to increase. Nowadays there are over 15,000 commercial dairy farms around the world operating with automatic milking systems (Rodenburg et al., 2017). Although automatic milking systems were originally developed for indoor (cows confined in barns) systems, they were firstly introduced in pasture-based systems in both Australia and New Zealand in 2001. With over 60 commercial farms currently operating with this technology in both countries, the technology is now being adopted also in countries where grazing system are predominant, such as Ireland, Chile, Uruguay and Argentina, among others.

The majority of pasture-based AMS operate with voluntary cow traffic, providing cows with the freedom, within certain limits, to set their own milking routine. This introduces variability in milking frequency (MF; number of milkings per cow per day) and milking interval (MI; time between two consecutive milkings) between and across cows and days (Lyons et al., 2014). In addition, a diurnal grazing behaviour and a greater social synchronisation in behaviour are typically observed in grazing dairy cows compared to cows confined in a barn. As a result of the combination of these factors, robot performance (defined as the amount of milk harvested per day) is typically reduced in pasture-based AMS, compared to indoor-based AMS.

Optimising robot performance is critical to achieving farm profitability and is a key objective for farmers operating with AMS (Sonck & Donkers, 1995). Therefore, the purpose of this review was to compile current knowledge on cow and robot performance to identify strategies to, ultimately, improve production efficiency in pasture-based AMS.

General overview of the Australian dairy industry

With an annual production of 9,015 million litres of milk and a value of $AUD 3.7 billion in 2016/17, the Australian dairy industry is the third largest rural industry in the country, behind beef and wheat (Dairy Australia, 2017a). During 2016-2017, 37% of Australian milk production was exported with the main exports markets being China, Singapore, Indonesia, Japan and Malaysia. Australia is the fourth major exporter of dairy products in the world, behind New Zealand, the European Union and the United States (Dairy Australia, 2017a)

Following global trends, the number of Australian dairy farms has decreased by 29% in the last 10 years, together with a 16% reduction in the number of cows. Nowadays there are approximately 5,789 dairy farms with an average herd size of 262 cows, each producing 5,819 litres/lactation on average. With 64% of the total national production, Victoria is the largest producer of milk in the country, followed by New South Wales (11%) and Tasmania (8%) (Dairy Australia, 2017a).

Australian milk production is predominantly seasonal, and although irrigation is used in some inland dairy regions, production is strongly reliant on annual rainfall. The vast majority of the dairy farms are located in the coastal areas of the south-east corner of the country, where conditions for growing pastures are favourable. The majority of Australian dairy farms are 'pasture-based systems', defined by Garcia and Fulkerson (2005) "as farms in which grazed pasture is the largest single feed stuff in the diet of the animals, or where pasture represents at least 50% of the total dry matter intake consumed by cows annually". It is estimated that more than 95% of the dairy farmers in Australia rely on grazed pasture, and that pasture accounts for about 65% of the cow's diet, with a national average of 1.6 tonnes per cow per year of concentrate supplementary feeding (Dairy Australia, 2017a). The temperate climate, which predominates in key dairying regions, provides farmers with the capacity to grow and graze forage on farm for most of the year, and this, combined with relatively inexpensive grains, gives Australian farmers a competitive advantage in the cost of feed (Garcia & Fulkerson, 2005). However, feed is still the most significant cost on farm, accounting for 47% of the total operating costs in Victoria and 46% in New South Wales during the 2016/2017 season (Dairy Australia, 2017c; Dairy Australia, 2017b). Garcia and Fulkerson (2005) and Wales and Kolver (2017) have identified the opportunity to improve on farm efficiency on pasture-based systems by growing more forage on farm, increasing its utilisation and increasing the use and efficiency of supplementary feed. It is widely recognised that the volume of home-grown feed on the average Australian dairy farm is well below the potential, supporting the suggestion that there is still much to be gained economically by identifying practical solutions that allow such efficiency gains to be achieved on farm (Garcia et al., 2008; Fariña et al., 2011).

Several studies have reported that milk produced in pasture-based systems have distinct advantages over milk produced in intensive systems, with grazing systems being associated with improved animal welfare, improved end-product quality, increased labour efficiency and global sustainability gains (O'Brien et al., 2012; Peyraud et al., 2010; Dillon et al., 2005;

Macdonald et al., 2008). With an increasing proportion of consumers becoming more informed about how their food is produced (Cembalo et al., 2016), the demand for more dairy products from pastured cows is likely to increase, associated also with the perception of improved animal welfare in these systems (Von Keyserlingk et al., 2013). In comparison to many regions of Europe where grazing is rapidly declining (van den Pol et al., 2015), Australia is in a relatively unique marketing position as 90% of the national milk volume is produced on farms where cows graze pastures for most or all of the year (Dairy Australia, 2015).

Labour: a current challenge for the dairy industry.

Over recent decades, and as a consequence of increasing herd size and farm productivity, the workload on farms has increased significantly and the majority of family-owned dairy farms are now reliant on employed labour (as opposed to the family members being the entire workforce). In Australia it is estimated that more than 98% of the dairy farms are family-owned, and that 65% of them employ people. Labour accounts for 26% of the total operating costs in Victoria and New South Wales (Dairy Australia, 2017b; Dairy Australia, 2017c), and is the second highest cost after feeding costs. The difficulty to attract and retain skilled staff has been recognised by Australian dairy farmers as one of the main challenges they currently face. Prolonged shifts, early morning starts, demanding physical work, and repetitive tasks, are some of the characteristics that make working on dairy farms somewhat unattractive to prospective employees.

Milk harvesting is the most time consuming and repetitive task performed on dairy farms, and it is estimated that up to 50% of the working day is dedicated to the process (O'Brien et al., 2007). Although the adoption of new precision technologies and automation, such as automatic cup removers, post milking disinfection and milk plant wash systems, have been shown to improve labour efficiency and accelerate the milking process, in the majority of the dairy farms the milk harvesting routine is still very labour-intensive. In addition, a recently published study by Gargiulo et al. (2018) reported that the adoption of some of the available precision technologies in Australian dairy farms is still low, and that farmers with larger herds (more than 500 cows) have a greater rate of adoption. The implementation of new technologies presents an opportunity to increase farm productivity and address current and future on-farm challenges pertaining to labour related issues.

Automatic Milking Systems

An alternative to address some of the above mentioned challenges is through adoption of Automatic milking systems (AMS). The first AMS to operate in a commercial farm was commissioned in 1992 in The Netherlands, and since then more than 15,000 commercial dairies around the world have adopted AMS (Rodenburg et al., 2017) with the majority of them located in northern and western Europe (Sandgren & Emanuelson, 2017). The AMS was originally targeted at small family farms operating indoor/confined systems, with (relatively) high yielding dairy cows, high labour costs and high milk prices (Lind et al., 2000), with only some farms allowing cows to graze pasture during some parts of the year (Ketelaar-de Lauwere et al., 1999).

In Australia, with over 40 AMS farms operating and at least another 5 being installed at time of writing (N. Lyons, personal communication) the adoption of this technology continues to increase. Although the rate of adoption is still relatively slow in Australia, mainly due high initial cost of investment, Gargiulo et al. (2018) reported that Australian dairy farmers ranked AMS among the top 5 technologies to be adopted in the next 10 years, indicating that on-farm adoption is likely to continue.

In Australia, the first AMS was commissioned in Gippsland in 2001 (Greenall et al., 2004), being a commercial pasture-based operation. In the same year, a research project installed a robotic unit, in Waikato, New Zealand (Jago et al., 2002). In 2006, the FutureDairy Project commissioned a research farm located in Camden, Australia, (García et al., 2007) with the aim of developing a better understanding of integrating AMS into pasture-based systems. Although it has been repeatedly reported that production and performance were lower in pasture-based AMS compared to those typically achieved in housed systems (Lyons et al., 2014; Woolford et al., 2004), results from FutureDairy's research (García et al., 2007; Davis, 2006) have demonstrated that AMS can successfully achieve high levels of pasture utilisation and with relatively high proportions (>50%) of grass in the diet. More recently, several research projects including one in Ireland (O'Brien, 2012) and one in the USA (Utsumi, 2011) have been developed with a clear focus on increasing the understanding of pasture-based AMS management; an area in which knowledge is still relatively limited.

Several studies in both, indoor (Mathijs, 2004; Tse et al., 2018; Karttunen et al., 2016) and pasture-based systems (Molfino et al., 2014; Shortall et al., 2016) have reported significant improvements in labour efficiency, greater flexibility in the organisation of daily routines and reduced physical workload, compared to conventional milking systems. A positive impact on lifestyle was also reported by Molfino et al. (2014) in a study where labour and lifestyle audits were conducted in 5 pasture-based farms operating with AMS in Australia. In that study it was reported that farmers spend less time in the dairy and more time in the computer (checking summary reports, setting auto-drafting for cows that need attention, reviewing daily performances, among other tasks) compared to what they did with their conventional system. In addition, not needing to schedule the whole day around defined milking sessions was reported by farmers as one of the biggest changes. It was also reported that AMS provided them with the opportunity to spend more time on the management aspects where they can have a greater impact on productivity (e.g. pasture management, nutrition, animal health, reproductive performance). On average, the labour efficiency for the case studies was 181 cows/FTE (FTE = full time equivalent, a standardised labour unit, calculated as 50 hours per week), well higher than the Australian national average (103 cows/FTE). In contrast, Karttunen et al. (2016) reported that farmers indicated an increased level of mental stress due to the demanding management of the AMS (particularly in relation to the 24-hour operation and risk of alarms and breakdowns during the night). It is important to mention that the way in which farmers adopting AMS capture the potential benefits in relation to both labour and lifestyle, is strongly affected by various factors including, but not limited to, the individual farmer's objectives, scale of the operation, farmer's personality and approach, among other factors.

General characteristics of Automatic Milking Systems

There are currently three different types of automatic milking systems commercially available: single-boxes, multi-boxes and robotic rotaries. The first type are most common globally and consists of one robotic arm attached to a single milking crate and dedicated to a single cow at any one time (i.e. only milks one cow at a time). Once the cow has gained access to the milking crate, the robotic arm performs all milking related tasks, including teat preparation, cup attaching, milking and post-milking activities. These units are able to perform between 150-180 milkings per day, normally catering for herds of between 60 and 80 cows milked between 2 and 3 times per day (de Koning, 2011; Lyons, 2013). Multi-boxes can have anything from 2 to 5 milking crates, which are serviced by just one robotic arm which allows for more than one cow to be miked at any one time (Lyons, 2013). In comparison to single-boxes, multi-boxes can milk more cows per day, but less cows per milking crate (Rotz et al., 2003), as the increase in efficiency is not directly proportional.

Single-boxes and multi-boxes allow cows to be fed a grain-based supplement during the time spent inside the crate.

The third type is the automatic milking rotary (AMR, Automatic Milking Rotary, DeLaval International AB, Tumba, Sweden), an internal 24-bail herringbone platform, with 5 robotic arms in the centre (two teat preparation arms, two cup attachment arms and one post-milking teat sanitation arm). This high-throughput robotic rotary was co-developed between DeLaval and the FutureDairy Project, and was specifically designed for large herds (>500 cows), as it has the capacity to perform between 60-90 milkings per hour or to conduct, potentially, up to 1600 milkings per day (Kolbach, 2012; García et al., 2007). The AMR could therefore be a viable solution for farms with large herds (more than 500 cows in the Australian dairy industry), which have increased from 3% in 2004 to 9% in 2012. The AMR was also designed to operate with both batch and voluntary traffic. Currently there are 12 commercial AMRs operating in Europe and 3 in Australia operating in pasture-based systems (Rodenburg et al., 2017).

There are 4 main functionality differences between the single- or multi-boxes and the AMR. First, the AMR has no automated washing; therefore, farm staff need to be present on site, at least twice-a-day to initiate the system wash of the equipment. Conversely, the washes in the boxes are fully automated and can be scheduled to occur at any time of the day or night without the reliance on human attendance.

Second, the boxes have the functionality to rinse milk residue from the unit after an ‘idle’ period (time without milkings). This is key to achieve higher-quality bulk milk as milk residues sitting in the unit for a long period of time, increase the risk of bacterial contamination. The AMR cannot perform automated rinses after idle periods, providing instead the option to automatically deactivate bails that have been idle for a settable period of time, which can then be deactivated after a full system wash. This could create the challenge that in periods of underutilisation, i.e. early hours of the mornings or months with low numbers of cows per robot, typical in farms operating with seasonal or split calving patterns, a high number of bails could be deactivated for a few hours (Kolbach et al., 2013). However, the potential efficacy of this approach has not been assessed against other practical options e.g. batch milking during periods of low utilisation, such as pre-calving in seasonal or split calving systems.

Third, different from the single- or multi-boxes, the AMR cannot automatically divert milk from an individual cow to a separate destination (i.e. 'abnormal milk' cows refers for example, to cows treated with antibiotic or fresh cows producing colostrum). Thus, cows with abnormal milk need to be managed as a separate herd and typically batch-milked twice-a-day, before a system wash is activated.

Fourth, unlike the single- or multi-boxes, feeding concentrate to cows during the milking harvesting process is not possible in an AMR, which requires individual feeders to be installed close to the dairy

Given that cows in AMS have an individual electronic identification device, detailed individual cow information from milking stations (such as, milking duration, milk yield, time of milking, parameters regarding milk quality, MI), automatic drafting gates (such as, gate passings, time spent in an specific area) and feeders (such as, amount of concentrate consumed, time of feeding) is recorded continuously. This allows the operator to monitor the performance (in real time) of not only individual cows but also the system as a whole, by regularly accessing information in the management software (de Koning et al., 2002). The enormous amount of data recorded by the system, is one of the main advantages of AMS and a potentially-very valuable tool that could help famers achieved their targets in an efficient way, although it is acknowledged that a new way of management is required to make the most of AMS capabilities and functionality (Jacobs & Siegford, 2012).

Voluntary cow traffic & distribution of milking events

As a consequence of having equipment that can perform milkings at any time of the day and night without any human intervention, in AMS there are no defined milking sessions. The majority of AMS operate with voluntary cow traffic, utilising feed as the main incentive to encourage cows to move around the different areas of the farm and milk harvesting facility. Cows can move throughout the system during the day (24-hour period) with minimal or no human intervention. Each cow is fitted with a unique electronic identification, and automatic drafting gates are used to guide cow traffic through the different areas of the farm, such as feeding areas (feed pad or paddocks), lying or loafing areas, and the milking facility. Voluntary traffic relies on the motivation of cows to attend the milking facility, and feed is the main incentive used to encourage cows to move through the system and to present themselves for milking regularly (Prescott et al., 1998b; Prescott et al., 1998a). With the aim of achieving a regular voluntarily attendance of cows to the dairy facility and an even distribution of milking events throughout the 24 hour period, farmers use different feed management strategies to manipulate cow traffic (Lyons, 2013). Type of feed, frequency, location and feeding time/s are some of the tools farmers can manage in order to encourage and manipulate cow traffic and frequency of attendance at milking stations. Automatic drafting gates and one-way gates are strategically placed on farm to direct cows between the different areas (such as feeding, lying, milking areas) based on the type of traffic system and milking settings.

In systems operating with voluntary traffic, cows have some freedom to choose, within management and operator-set software limits, their own MF (and consequently MI) over time (24-h period is the most common standard unit of time in AMS). In order to gain access to the milking station, a cow needs to have milking permission. Milking permission criteria are managed by the operator by establishing the minimum milking interval (MMI), defined as the minimum amount of time (in hours) or a minimum expected milk yield (in kg milk/milking) since the previous milking event. Cows will be granted milking permission, and therefore access to the milking station, if the time or expected yield since the previous milking exceeds the limits set by the operator. On the contrary, cows that have already been milked, or that have not been granted milking permission, are denied access to the robot and directed to a different area. By setting the MMI, the operator is also establishing the maximum amount of times cows can potentially get milked in a 24 period. For example, cows with an 8 h MMI could potentially have a maximum of three milkings in a day. This gives the farmer the opportunity to control MF on an individual cow basis, adjusting the MMI based on stage of lactation or milk production level of each cow (Svennersten-Sjaunja & Pettersson, 2008; Hogeveen et al., 2001).

The main purpose of setting the MMI is to maximise the efficiency of use of the robot whilst at the same time achieving the most efficient MI and minimising extremely long MI. The total amount of time that a cow spends at the robot/station on each milking event is the sum of a fixed time and a variable time. The fixed time is similar for every cow and is the time required for cleaning, attaching and post-milking disinfecting processes, representing between 30-50% of the total duration (Andre et al., 2010). The variable time is associated with milking duration, which in turn depends on milk yield but is also affected by factors including (but not limited to) individual cow anatomy, physiology and milk let-down rates (Koning & Ouweltjes, 2000). Therefore, cows presenting after a short MI (low expected milk yield) are likely to have reduced robot harvesting efficiency as the volume of milk harvested per minute of crate occupation will be significantly reduced, compared to cows with longer MI and higher milk yields.

Indoor housed AMS

There are 3 main types of voluntary traffic systems used in indoor AMS, typically referred as free, guided and forced cow traffic (Rodenburg et al., 2017). In free cow traffic systems cows are allowed to move between feeding, resting and milking areas without restrictions. Cows are encouraged to visit the milking station (robot) by offering them concentrate feed in the milking station as a reward (Rodenburg et al., 2017). In forced cow traffic systems cows must go through the milking station before being allowed to move from the feeding area to the resting area or vice versa. This occurs regardless of time elapsed since previous milking, although cows without milking permission will be released from the station without getting milked (de Koning, 2011). In guided cow traffic, cows moving between the resting and feeding areas are guided to an automatic drafting gate, which will grant access to the robot to those cows that have milking permission. Cows without milking permission will be diverted away from the milking station (de Koning, 2011).

Previous studies (Ketelaar-de Lauwere et al., 1998; Ipema, 1997; Bach et al., 2009) suggested that the type of traffic system has an effect on daily MF, feed access and also the number of times cows need to be fetched to the milking station. Other authors (Alexander, 2015; Rodenburg et al., 2017) have reported advantages and disadvantages for each of the traffic systems in regards to system performance, cow production, animal welfare and labour efficiency, with no clear conclusions about which is the most suitable system. In a recently published study, Rodenburg et al. (2017) suggested that high feed intake, good production levels and good cow welfare is possible with all three systems. In relation to production, however, Tremblay et al. (2016) found that free-cow traffic was associated with increased daily production per cow and per robot when compared with forced systems, after analysing data form 635 indoor AMS farms across North America.

Pasture-based AMS

The successful integration of AMS and pasture-based operations has been previously shown in several studies (Lyons et al., 2013b; Jago et al., 2002; Davis et al., 2005). As a consequence the interest in, and adoption of AMS in countries where grazing systems are predominant, such as Australia, New Zealand, Ireland and Chile has continued to increase (Shortall et al., 2018).

The majority of pasture-based AMS operate with guided voluntary cow traffic, utilising feed as the main incentive to encourage cows to move around the different areas of the farm and milk harvesting facility. Cows are allowed to voluntary traffic from pasture to the dairy to be milked at any time during the day and night using automatic drafting gates (guided traffic system). Cows exiting the dairy after being milked or when denied milking permission, had access to one of the two (when operating with two-way grazing, 2WG) or three (when operating with three-way grazing, 3WG) pasture allocations offered per day, depending on time of day. Each pasture allocation is accessible for cows for a set period of time each day, and only one allocation is open at any point in time. For example, under 3WG, access to pasture allocations may start at 0800 h, 1600 h and 0000 h. Concentrate is offered in the robots during the milking process and in some cases in out-of-parlour feeders located in pre-milking or post milking areas, depending on the design of the farm or farmer's preference. Cows that fail to return to the dairy from the pasture allocation after a pre-determined number of hours are fetched by the operator to minimise extended MI (Lyons et al., 2013b). The majority of pasture-based AMS are currently operating with 3WG, as it was shown by Lyons et al. (2013b) that offering three pasture allocations per day instead of two, increased cow MF by 40%, individual cow production by 20% and also improved system performance.

In pasture-based AMS, feed pads can be used for several reasons: to replace a pasture allocation; to supplement a pasture allocation when pasture is scarce; or to provide a fourth allocation (four-way grazing, 4WG). Anecdotal evidence from commercial operations using 4WG, suggests that this strategy might improve cow traffic; yet, no research has been conducted to confirm this.

In both indoor and pasture-based AMS the traffic system type is generally very consistent within farm. This is due in part to the constraints imposed by the facility infrastructure. However, it is also likely affected by the lack of knowledge regarding how cows adapt to big changes in traffic management system, and the effect that this might have on individual cow traffic and performance. In addition, with the commercialisation of the AMR, there has been an increasing interest in batch milking, due to the high-throughput capacity (60-90 milking per hour), the AMR can operate with both voluntary and batch cow traffic system, or a combination of both. Operating with batch milking traffic system, means that cows are fetched to the milking facility for defined milking sessions, thus reducing the need of additional infrastructure (i.e. additional laneways, automatic drafting gates). The possibility of operating an AMR with batch milking traffic system or a potential combination of both voluntary and batch traffic system to increase efficiency of the AMR has not been investigated yet. If the feasibility of this strategy is proven, it will provide farmers with another strategy that could be implemented when required.

Relationship between milking frequency, milking interval and milk production in Conventional and Automatic Milking Systems.

The strong positive relationship between MF and milk yield has been widely studied in conventional milking systems (CMS) (Stockdale, 2006; Erdman & Varner, 1995; Bar-Pelled et al., 1995). Increasing MF from two to three milkings per day, results in an increment of around 15% in milk production and a further 20% when cows are milked 6 times a day in comparison to three times-a-day (Stockdale, 2006). Regardless of the existing milk yield, increments of 3.5 kg and 4.9 kg for three times-a-day and four times-a-day, respectively, have been reported (Erdman & Varner, 1995).

Inversely, when MF is reduced there is a negative effect on milk yield. In New Zealand, several studies have been conducted looking at the effect of once-a-day milking on milk yield, with the aim of improving labour efficiency, farmer's lifestyle and potential benefits on animal welfare (Phyn et al., 2010; Clark et al., 2006; Davis et al., 1999). Milk yield losses ranging from 22 to 50% have been reported (Clark et al., 2006; Davis et al., 1999) in full lactation studies and between 7 and 40% in partial lactation studies (Davis et al., 1999). The responses in milk production to changes in MF are dependent on stage of lactation and parity. Positive responses to an increase in MF tend to be more significant in early lactation cows in comparison to late lactation cows with the magnitude of response declining as days in milk increases (Pettersson et al., 2011). In their review of once-a-day milking, Stelwagen et al. (2013) reported that production losses due to milking cows once-a-day are relatively greater in early lactation in comparison to late lactation cows. Moreover, the authors concluded that the reduction in milk production is relatively greater in primiparous cows than in multiparous cows. Despite the commonly reported associations between MF and milk yield, it should be noted that, in general, milk yield would be expected to increase (over the medium-long term) with an increase in MF, only if MF is the most limiting factor. If for instance, nutrition, physiological status or genetic potential are the most limiting factors, then an increase in MF would not be expected to generate a significant and sustained increase in milk production (Bargo et al., 2002; Lyons et al., 2014).

All of the above mentioned studies were conducted in CMS, and so were the result of applying quite regular intervals between consecutive milkings (e.g. 24 h for once-a-day milking, 12 h MI for twice-a-day milking, 8 h MI three times-a-day milking). In AMS, and as a result of the voluntary and distributed cow traffic, a large variation in MF and MI within and between both cows and days is typical (Lyons et al., 2014; Winter & Hillerton, 1995; Lovendahl & Chagunda, 2011; de Koning, 2011). Consequently, in AMS, two cows could have the same MF but completely different MI (both average and level of variability in MI). In addition, due to the nature of voluntary cow traffic, and in contrast to CMS where cows are typically milked twice-a-day, in AMS some cows within a herd will access the robots to be milked more often than others, which is in turn a potential advantage of the system compared to CMS. In an experiment investigating the impact on daily milk yield when cows were milked twice-a-day at different MI, Rémond et al. (2009) reported that when the variation in MI increased from 11 h:13 h to 5 h:19 h and 3 h:21 h, daily milk yield was reduced at an increasing rate. However, in the same study the authors showed that when comparing cows milked twice-a-day (with 11:13 h and 10:14 MI regime), with cows milked with a 7:17 h and 5:19 h MI regime respectively, daily milk yield was not significantly different showing that some cows might adapt to different length of MI. This might indicate a different response from individual cows to variable MI (Lyons et al., 2014). Several studies (Knight et al., 1994; Schmidt, 1960a) have previously reported a positive effect of MI on milk yield. There is a positive albeit non-linear relationship between MI and milk yield in which milk accumulation rate in the udder increases up to a threshold when milk secretion rate decreases. Thresholds of 12 h (Knight et al., 1994), 16 h (Schmidt, 1960b; Lyons et al., 2013a) and 18 h (Stelwagen et al., 2008) have been reported in the literature, denoting that there is certain level of variability with regards to when the relationship changes. Together with a negative impact on daily milk yield, MI longer than 16 h has been shown to increase the risk of developing mastitis (Hammer et al., 2012) and reduce secretion rate (Lyons et al., 2013a). At the other extreme, Koning and Ouweltjes (2000) reported that reductions in MI were associated with a reduction in milk yield. An increased variability in MF and MI was also reported to have a negative effect on milk yield (Bach & Busto, 2005). This might explain at least in part why increases in milk yield observed in AMS due to cows being milk more frequently are usually lower than those obtained in CMS (Lyons et al., 2014; Pettersson et al., 2011). In pasture-based systems Lyons et al. (2013a) reported a decreasing response in daily milk yield to incremental increases in MF; thus milk yield increased by 33% when MF changed from 1 to 2 milkings/cow/day but only by 13% when MF increased from 2 to 3 milkings/cow/day.

It has been demonstrated that increments in milk yield can be achieved by milking cows more frequently in AMS when comparing to CMS (twice-a-day milking). However, a level of variability exists among studies, with increments in milk yield of 2% (Wagner-Storch & Palmer, 2003), 7% (Svennersten-Sjaunja et al., 2000), 8% (Speroni et al., 2006) and up to 15% being reported when the increased frequency was maintained throughout the lactation (Svennersten-Sjaunja & Pettersson, 2008). In these studies MF with AMS averaged 2.5 milkings per day in comparison to twice-a-day in CMS. Overall, average responses in milk production in AMS due to increments in MF are lower than those observed in CMS, and this might be due to the lack of consistency of MF along the lactation, together with a greater variability in MI (Lyons et al., 2014). In AMS, in order to achieve high production per cow it is evident that regular and consistent MI and MF through lactation must be achieved.

It is also important to mention that increments in production per cow observed after the introduction of AMS might not be due only to an increase in MF, and those increments are the result of other factors, such us improvements in management and genetics and adjusting of cows to the system (e.g., greater comfort for the animals due to new infrastructure). It is evident that with time, better management decisions are made. Veysset et al. (2001) reported a higher increment in production per cow in farms that had been operating with AMS for more than two years (9%) in comparison to those that had been operating for less than two years (3%). In addition, in an retrospective study investigating the economic efficiency of AMS analysing a large amount of data (over 6 million test days from 346,349 cows, over 12 years), Wade et al. (2004) estimated an increase in milk production of approximately 2% after the introduction of AMS, and also a large variation among dairy farms, suggesting that the magnitude of response is greatly dependent on management.

Individual variability in AMS

In AMS, the large individual variability in MF, leads to a high variation in MI, where typical MI’s can range between 4 h (for cows that access the robot as soon as milking permission is granted) to MI greater than 24 h (generally only occurring when cows are fetched to the dairy by the operator) (Jacobs & Siegford, 2012; Lyons et al., 2013a; Andre et al., 2010). In AMS indoor systems, the greatest proportion of MI typically range between 6 to 12 h (67%, (Gygax et al., 2007)), although short MI (<4) and long MI (>12 h) also occur (Hogeveen et al., 2001; Gygax et al., 2007; Abeni et al., 2005). Hogeveen et al. (2001) reported that only a very small (4.2%) proportion of MI were greater than 16 h, due to the fact that cows that fail to traffic within a given timeframe are regularly fetched to the milking robot by the operator throughout the day. In a study conducted in Australia, Lyons et al. (2013a) reported a large variability in MF and MI, with a relatively high proportion (30%) of MI >16 h, when cows were milked in a pasture-based AMS. This was one of the few studies conducted in pasture-based system, with a large number of cows (243 cows) and analysing data from a relatively long period of time (2 years). Part of the variability observed in MI and MF, in both indoor and pasture-based system has been reported to be due to stage of lactation and parity (Lyons et al., 2013a; Lovendahl & Chagunda, 2011; Pettersson et al., 2011; Dzidic et al., 2004). Early lactation cows and high yielding cows are more likely to present higher MF, lower average MI, and are more motivated and move rapidly through the system in comparison to late lactation and lower yielding cows (Jacobs & Siegford, 2012; Lyons et al., 2013a). A greater proportion of pasture in the diet, lower pre-grazing pasture covers and longer distances between the dairy and paddocks were also identified by Lyons et al. (2013a) as factors specific to pasture-based AMS associated with increased MI. In addition, Andre et al. (2010) reported a significant level of variation in relation to the effect of MI length on milk yield between individual cows. It is, however, apparent that some cows are able to withstand longer MI's without decreasing milk yield as shown in a study by Tol et al. (2013) when data from 130 cows milked in commercial indoor AMS was analysed. This variability among individual cows in apparent tolerance to MI provide the opportunity to increase the AMS efficiency by determining individual optimal MI (Andre et al., 2010). The implementation of different management practices might allow optimal MI's to be harnessed for individual cows within a herd.

It follows from the discussion above that the variability observed among individual animals in regards to cow performance and MI, potentially mean that there are some cows that are more efficient than others to produce milk in pasture-based AMS. If these differences exist, it would be beneficial to identify cows with different levels of efficiency, in order to manage them separately or differently to increase the whole farm system performance. Therefore, a method to categorise cows in relation to cow performance efficiency and to assess the magnitude of the variability in potential efficiency needs to be developed for AMS. As the management software of all AMS brands continuously capture large volume of data about the individual cows, there is a clear opportunity to use existing datasets from commercial farms for such purpose.

Several research studies have looked at variation in MF and milk yield due to differences among individual cows milked in AMS (Andre et al., 2010; Lovendahl & Chagunda, 2011; Gäde et al., 2006; Nixon et al., 2009; Pettersson et al., 2011), however, not all of them analysed complete lactations, and none of them were conducted with data from pasture-based systems. After analysing data form 664 lactation of cows milked in AMS indoor system, Lovendahl and Chagunda (2011) concluded that the variation observed in MF is an attribute of the individual cow and that random residual variance remains large and stable throughout lactation. Furthermore, an in agreement with Nixon et al. (2009), they concluded that MF is a repeatable trait (intermediate repeatability ~ 0.40) and that some of the variability might be explained by genetics differences. In contrast, König et al. (2006) reported heritabilities of just 0.16 and 0.22 for MF in cows milked in an indoor AMS. Pettersson et al. (2011) reported milking frequencies in different lactations for the same cow that demonstrated only average repeatability and highlighted the need for more research in this area.

In addition, Carlstrom et al. (2013) showed that the feasibility of using AMS data from commercial herds for analysis of certain individual cow traits, including MF, MI, milking time and average flow rates, among others. Thus, there is a significant opportunity to explore observed variability in MF and milk yield in order to identify, select and potentially breed cows more suitable to AMS, and even more specific for pasture-based AMS. For example, a more robust cow, able to handle long MI without milk yield being significantly affected. Moreover, a herd comprised of cows that are able to tolerate low milking frequencies and/or long MI would allow more cows to be run per robot (and therefore more milk to be harvested) per AMS. However, a simple method that allows managers/operators to quantify existing differences among individual cows and identify those more efficient and suitable to pasture-based AMS has not been developed yet. This could have a significant impact on the economic return on investment for the technology. The 'typical cow' in today's commercial dairy herd is the result of decades of selection made for CMS, where cows were herded by the operator and milked with rather strict and regular MI.

System capacity and performance

Given the large initial capital investment required to commission a milking robot, it is crucial for farmers to optimise the amount of milk harvested per robot (kg milk/robot/day) to achieve the highest economic return for that investment (Sonck & Donkers, 1995). Milk harvested per robot is the result of the number of milkings conducted per day by the AMS and the milk yield harvested at each milking.

Thus, high levels of robot utilisation, defined as the total amount of time the robot is actually milking (generally expressed as % of a 24-h period), is a goal for the majority of farmers operating with AMS (John et al., 2016). As the milking robot is not available to perform milkings during the full 24 h period (some time is required for technical maintenance, system washes, technical failures absence of cows), the upper utilisation level ranges between 20 and 22 h per day (Lyons et al., 2014; John et al., 2016; Halachmi, 2004). A constant and evenly distributed number of cows presented to be milked through the day and night is required to obtain high levels of robot utilisation (Van Dooren et al., 2004) and prevent unduly long waiting times for cows prior to milking.

Robot utilisation and therefore milk harvested per robot are affected by factors related to feed (feeding system, feed quantity and time of allocation), animal (temperature, herd dynamics, physiological status, appetite), management factors (herd size, distance from feed to milking robot, number of cows per robot) (John et al., 2016) and environmental factors (climatic conditions). In addition, there are arguably only three main strategies to maximise the numbers of milkings: increase the number of times each cow visits the robotic unit (if milk yield per cow increases accordingly), increase the number of cows per milking robot, and/or a combination of both strategies (Pettersson et al., 2011). Whilst the number of cows in the milking herd cannot be changed in the short term and it is somewhat predetermined on a day-to-day basis, increasing milkings per cow can be the focus for short term management decisions. Focussing on highest priority cows – those that will respond more to a decrease in MI will likely have greater impact on milk harvested per robot.

Current status of pasture-based-AMS performance

In a comprehensive review about robot utilisation conducted by John et al. (2016), 15 datasets from 13 studies were analysed and categorised based on the predominant feeding system (pasture-based AMS, n=8 or indoor AMS, n=7). In that study it was reported that although there are some examples of consistent levels of robot utilisation across 24 h in both indoor and pasture-based AMS, inconsistent (variable) patterns of utilisation are more common. In addition, although in both types of feeding systems robot utilisation was reduced during the early hours of the morning (0200 h and 0600h), the reduction was significantly greater and more variable in the pasture-based systems. This is a key area that needs to be addressed if pasture-based AMS are to reach their full potential. In a recently published study, Lyons and Kerrisk (2017) analysed current and potential system performance from 8 commercial Australian AMS farms (7 of them pasture-based) and reported lower levels of robot utilisation (13.50 h/day). Furthermore, lower levels of robot utilisation during the early hours of the morning were also observed (Lyons and Kerrisk 2017).

The reduction in voluntary cow traffic occurring during the night that is typically observed in pasture-based AMS (John et al., 2016) can be mainly attributed to the diurnal grazing behaviour of cows (Gregorini, 2012). Cows typically exhibit the majority of the grazing activity during the day (Granzin, 2003), but even more predominantly during dusk and dawn (Gibb et al., 1998; Gregorini, 2012) and in a more synchronised mode compared to equivalent feeding patterns of cows housed indoors. In addition, pasture-based AMS tend to operate with larger herds than indoor systems, and in order to maintain a high proportion of pasture in the diet, cows are often required to walk significant distances (Islam et al., 2015). When operating with large herds, distances between pasture and the dairy facilities extending out to 3 km are not uncommon in countries like Australia and New Zealand (Jago et al., 2004). Although Woolford et al. (2004) reported that pasture-based AMS can successfully operate with distances of up to 900 m (and with milking frequencies of up to 2.5 milkings/day), Lyons et al. (2013a) reported increases in MI length when distances were greater than 500 m. Overall increased walking distances divert energy from milk production, reduce available grazing time (Sporndly & Wredle, 2004; Islam et al., 2015) and have the potential to negatively impact dairy cow welfare (Coulon et al., 1998).

Lyons and Kerrisk (2017) reported an average of 120 milkings/robot/day and highlighted the theoretical potential to increase the number of milkings in Australian AMS farms by a maximum of ~60%. Similar results were previously reported by Davis et al. (2005) in New Zealand when looking at factors influencing milk harvesting efficiency in pasture-based AMS (average of 95 milkings/robot/day).

There are two key ways to increase the number of total milkings performed by the robot on a daily basis: increasing individual cow MF or increasing the number of cows in the herd. Both strategies are possible in pasture-based AMS, although they have different implications and they implementation or execution is dependent on factors like land size, current stocking rate, feed availability, type of calving system, and farmer preferences, among others (Lyons & Kerrisk, 2017). These two strategies and factors affecting them are discussed below.

Increasing Milking frequency

Increasing individual cow MF has been highlighted as one of the strategies to increase milk harvested per robot (Pettersson et al., 2011). However, the integration of grazing and AMS introduces new challenges that tend to result in lower and more variable levels of MF in comparison to indoor AMS (Garcia & Fulkerson, 2005; Lyons et al., 2014) as well as reduced milk production levels (Lyons et al., 2013a). Lyons et al. (2014) reported a reduction in MF of approximately 40% when comparing data from 21 studies where cows were managed in a pasture-based AMS (n= 11; MF of 1.61 ± 0.12 milking events/cow per day, range 1.10-2.30 milking events/cow per day) were compared with studies where cows were managed in indoor-based AMS and allowed to graze for less than 24h/d (access times range between 6-15 h/day) (n=10; MF of 2.64 ± 0.06 milking events/cow per day, range 2.40-2.85 milking events/cow per day). This suggests that in some cases it might not be possible for cows in pasture-based system to respond to an increase in MF by increasing milk yield since MF is not the most limiting factor (Lyons et al., 2014). For example, in pasture-based systems it is not uncommon for cows to be restricted in terms of pasture quality by seasonality and in terms of pasture quantity by management factors (Hills et al., 2015), resulting in a limited intake of dry matter and/or energy (Utsumi, 2011). In addition, long walking distances (Lyons et al., 2013a), climatic conditions (Wildridge et al., 2018), and genetic potential may be more limiting than MF itself.

There are several factors affecting MF in pastured-based AMS, and a complex interaction between them, resulting in high variability in MF and milk yield within and between cows and throughout lactation. It is evident that in pasture-based systems, although possible, it is generally more difficult to increase MF on individual cows in comparison to indoor system. Lyons et al. (2014) recognised that there are animal related factors such as: cow dominance, training and previous experience, cow behaviour; farm management factors such as: pasture allocation, supplementary feed and environmental factors such as climatic conditions that all play a significant role in the interactions.

As feed is the main incentive for cows to move through the system, several studies successfully focused (Lyons et al., 2013b; Scott et al., 2014; John et al., 2013) on manipulating feed (timing, placement and distribution) to encourage cows to move frequently around a pasture-based AMS. For example, Lyons et al. (2013b) demonstrated an increase in MF (+40%), milk production (+20%) and robot utilisation through the day when cows were offered three allocations of pasture over 24 h (3WG) instead of two (2WG). In the study conducted by Lyons and Kerrisk (2017) farms presented an average MF 2.38 milkings/cow/day, which is considerable higher than that reported in the review conducted by Lyons et al. (2014) and comparable to MF obtained in indoor systems, with relatively low levels of robot utilisation (56%) and low milk harvested per robot (1,171 kg milk/robot day). Although all farms involved in the study conducted were managing three (3WG) or even four allocations (4WG) per day, denoting that farmers are adopting recommended strategies to increase cow traffic; the majority of them are still not achieving higher levels of robot utilisation, and by association milk harvested per robot (Koning & Ouweltjes, 2000). Considering that high production per robot is not being achieved currently by most commercial AMS in Australia, an alternative approach might be to look at individual variability among cows in regards to cow performance and in addition, to select for those cows who better respond to increased MI. This will allow farmers to increase robot production efficiency.

Cow welfare also needs to be carefully considered when targeting or achieving high MF, as cows would travel greater distances (expending more time and energy) and might spend greater times on concrete, increasing the risk of lameness. In addition, cows with a relatively high MF may face some trade-offs in their time-budget allocation (increased time away from feed and increased time in waiting yards) which might also negatively affect health and performance particularly in the medium-long term. As a consequence of high MF, it is also likely that some cows will present at the dairy with a relative short MI (low yield), which might reduce robot harvesting efficiency as the volume of milk harvested per minute of crate occupation will be lower than optimal. This is particular relevant when the AMS if operating close to full capacity. The challenge is in deciding when to release a cow unmilked (to prevent lower efficiency milking sessions) whilst minimising the risk of causing a longer than desirable MI. Anecdotal evidence indicates that some farmers are utilising nearby holding paddocks for ‘short-term-parking’ solutions to address this challenge.

Increasing cows per robot

Increasing the number of cows per robot is another strategy to increase the number of milkings, and therefore robot performance. In a study where data from 34 single AMS units was analysed, Castro et al. (2012) estimated that robot utilisation could be improved from 72% to 90%, if 17 cows were added, without impairing robot performance and with 33% increased in total daily milk volume harvested per robot. The average number of cows of those farms was 52.7, with cows producing between 19 and 34 litres/cow/day. In addition, as a consequence of adding more cows, MF would decrease from 2.69 to 2.48 milkings/cow/day. This decrease in MF when number of cows increases in indoor AMS was also reported by Deming et al. (2013) and Artmann (2004) and is frequently associated with a reduction in production per cow and an increment in the proportion of cows that required fetching (Rodenburg et al., 2017). With the aim of identifying factors associated with milk production in AMS, Tremblay et al. (2016) analysed data from 635 AMS farms from a 4-year period, concluding that increasing cow number had a positive effect on robot performance. Andre et al. (2010) also reported that robot utilisation could be increased from 64% to 85%, if the herd were increased from 60 to 80 cows, increasing milk production per robot by 34%, without increasing the MF. In this last study estimations were based on data collected form 311 cows kept in 5 herds for 1 week. In a study conducted in an indoor AMS where cows were allowed to grazed pasture (24 h access), Van Dooren et al. (2004) estimated that robot utilisation could increase from 76% to 92% by milking an additional 14 cows, harvesting further 336 kg milk/robot/day. It is evident that optimisation of milk harvested per robot requires careful fine tuning of cow:robot ratios to ensure that neither production/cow, nor cow welfare, is significantly compromised.

Although these four studies conducted in indoor systems have demonstrated the positive effect of increasing the number of cows on robot performance, caution is required in extrapolating these results to pasture-based systems, as differences in type of cow (high vs. low genetic potential cows) and traffic system (free cow traffic vs guided cow traffic) create some limitations.

Increasing the number of cows per robot and decreasing the number of milkings expected per cow was a strategy suggested by researchers for pasture-based AMS in New Zealand for low input grazing systems operating with lower yielding cows (Woolford et al., 2004; Jago et al., 2007) in a bid to optimise milk harvested per robot. Davis et al. (2005) reported a robot utilisation rate of 60% with 75 cows per robot, harvesting 1087 kg milk/robot/day and a MF of 1.13 milkings/cow/day. In another study Jago and Burke (2010) compared a low feed input farmlet (self-contained, 2% feed imported) and a high feed input farmlet (18% feed imported) farming system milking 92 and 72 cows per robot respectively. Results from the economic evaluation determined that both were financially viable achieving milking frequencies of 1.5 and 1.8 milkings/cow/day respectively. The average MF observed in the above mention studies is significantly lower, and the number of cows is higher than values typically observed nowadays in commercial pasture-based AMS (Lyons & Kerrisk, 2017; John et al., 2016; Woodford et al., 2015) and might be indicative of changes in the pricing of supplementary feeds and milk value. Lyons and Kerrisk (2017) reported an average ratio of 51 cows per robot (range 14-75), a MF of 2.38 milkings/cow/day, and an average robot utilisation of 56%. In this study it was estimated that the difference between current and potential system performance, (assuming detailed increases in number of milkings, robot utilisation, cows per robot, and milk harvested per robot) could theoretically increase by up to ~ 60%. John et al. (2016) suggested that although pasture-based AMS are operating with low robot utilisation, AMS farmers might be choosing not to increase the number of cows significantly, but targeting higher MF instead. This might be explained by the commitment and investment that is required to increase the herd size in a commercial farm. It is often the case that the herd size is perfectly suited to the size of the farm and availability of feed and increasing the herd size just to optimise the utilisation of the AMS might not be the most economically viable solution.

The need for a better understanding on the effect of higher number of cows on robot performance was recently highlighted by Rodenburg et al. (2017) and John et al. (2016). It might be possible to achieve high levels of robot performance with low levels of MF and high number of cows, but this still not clear. If the relationship between robot performance, cows per robot and MF in pasture-based AMS is better understood, farmers would be better positioned to develop more feasible strategies to effectively optimise MHR. This emphasises the need for further investigations into how to improve robot utilisation.

However, a limitation of this approach is that in farms operating with seasonal calving system, the majority of the cows will be in peak lactation at the same time, and the robot capacity will be the limiting factor as will not be able to handle large number of cows. This will result in a relatively higher proportion of extended MI and potentially in congestions in the dairy yards. Additionally, factors like farm size, size of waiting yards or feed availability, among others, might limit the possibility of increasing the number of cows per robot, without compromising cow welfare. It is recognised that having an understanding of management strategies that can allow milk harvesting to be optimised will empower farmers to make informed decisions on their own farms. However, those decisions also need to take into consideration the likely impact on whole farm system performance (both physical and financial) and need to be tailored to the individual operation.

Another consequence of integrating AMS with seasonal or split calving patterns is that there are some months of the year in which the system will operate with a particularly low number of cows. This results in an underutilisation of the milk harvesting equipment during those months, reducing overall system efficiency. Furthermore, in some cases it could be difficult to achieve and maintain good voluntary cow traffic with low cow numbers where pasture allocations are particularly small. This can result in low milking frequency and/or a high proportion of cows requiring fetching to the dairy, increasing labour requirements. A reduction in labour use efficiency (despite the reduced herd size many tasks still need to be done and the operator also needs to on-call 24 h) and issues with milk quality (due to the intermittence of fresh milk flushing through the plant) might be also encountered. In addition, higher operating costs (particularly power consumption), as a consequence of running the dairy continuously during 24 h and low levels of milk being harvested, might be possible.

In order to maintain a relatively consistent number of cows per robot during this period, farms operating with multiple box-robots can address this issue by turning some boxes off. With the AMR it is possible to deactivate some of the 24 bails on the platform (Kolbach et al., 2013) which might address some of the mentioned challenges, but certainly not all of them. Due to the high-throughput capacity (60-90 milking per hour), the AMR provides the option to operate with batch milking. In some cases it might be a viable option for farmers to batch milked the cows in a defined milking session, for the period of underutilisation. A management strategy such as this would provide the operator the opportunity to turn on the milk harvesting equipment for defined hours, saving electricity, controlling milking frequency of the cows and increasing labour efficiency (it would negate the need for on-call staff during the night hours if the dairy was shut down). In addition, having the dairy shut down for a period of time creates the opportunity to do major services to the equipment before the commencement of the next calving season without negatively impacting cow traffic. However, as it was previously mentioned, there is lack of knowledge regarding how cows adapt to big changes in the traffic management system, and the effects that this might have on individual cow traffic and performance. This issue therefore warrants further investigation.

CONCLUSIONS AND RESEARCH POSSIBILITIES

The purpose of this review was to bring together and analyse current knowledge on pasture-based AMS performance, compared this knowledge with indoor AMS and CMS when relevant, in order to identify strategies on how to improve production efficiency in pasture-based AMS. A number of conclusions can be drawn.

First, it is clear that automatic milking can be successfully integrated with pasture-based dairy farm systems, despite some new challenges not previously encountered in indoor systems, including long walking distances, diurnal grazing behaviour, greater social synchronisation of activities between cows, large herd sizes and the impact of climate.

Second, the nature of the voluntary cow traffic in AMS introduces great variability in MF and MI between both individual cows and days. Pasture-based AMS present lower and more variable average MF and MI values in comparison to indoor based AMS. In addition, there is an important level of variation in relation to the effect of MI on milk yield between individual cows, with some cows being able to adapt better to long MI, which are not unusual in pasture-based AMS. There are no studies analysing the variation in MF and milk yield among cows in whole lactations among individual cows in pasture-based AMS. Therefore, there is a significant opportunity to explore that variability in order to identify, select and potentially breed cows more suitable to AMS and even more specific for pasture-based AMS. It has been also shown that using AMS data from commercial herds provides sufficient accuracy to evaluate certain cow traits.

Third, it can be concluded that commercial pasture-based AMS are currently achieving lower and more variable levels of robot utilisation and milk harvested per robot in relation to those observed in indoors systems and that is room for improvement. Increasing MF whilst maintaining moderate or relatively low number of CR; or increasing the number of cows in the herd whilst maintaining MF are the two main strategies to improve system performance. However, there is a need for a better understanding of the relationship between robot performance, CR and MF in pasture-based AMS.

In addition, pasture-based AMS operating with seasonal or split calving systems, present a period of time of underutilisation of the milk harvesting equipment, reducing overall system efficiency. Given that the AMR provide the option to operate with batch milking, there is an opportunity to address this issue by exploring a management strategy. It might be possible to batch milk cows for a short period of time, or potentially combine voluntary and batch cow traffic systems. However, how cows adapt to big changes in traffic management system, and the effect that this might have on individual cow traffic and performance has not been reported.

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OVERVIEW OF CHAPTER 3

The literature review in Chapter 2 has identified current gaps in knowledge in relation to pasture-based automatic milking systems (AMS) performance efficiency. Factors like individual milking frequency and the ratio of cows to robots are key to optimise production per robot. If the relationships between these variables were better understood, farmers would be better positioned to develop more feasible strategies to effectively optimise production efficiency. In Chapter 3, data from 17 commercial pasture-based AMS farms was used to investigate the relationships between these two key variables and other key performance indicators.

CHAPTER 3: Relationship between milking frequency, cows per robot and milk harvested per robot in commercial automatic milking farms

ABSTRACT

Optimising milk harvested per robot (MHR, kg milk/robot/day) is critical to achieve high farm profitability in pasture-based automatic milking systems (AMS). Understanding the relationship between MHR, cows per robot (CR) and milking frequency (MF, milkings/cow/day) will enable farmers to develop strategies to effectively optimise MHR. The initial aim of this study was to analyse the relationship between MHR, MF and CR in pasture-based AMS. The second aim was to determine the probabilities of achieving High MHR with different levels and combinations of MF and CR. Monthly averaged data from a two-year period from 17 pasture-based AMS commercial farms from Australia, New Zealand, Ireland and Chile were obtained. On a monthly basis, farms averaged 1,171 kg milk/robot/day, 2.22 milking/cow/day, 51 cows per robot and 22.94 kg milk/cow/day. Results indicate that although MHR increased ($P < 0.001$) when either CR or MF increased, CR had a greater effect than MF on MHR. In addition, the combination of High levels of MF and CR had the potential to negatively affect MHR. Moreover, farms were 4 and 17 times more likely ($P < 0.001$) to achieve High MHR (greater than 1,600 kg milk/day/robot) with High MF (>2.5) compared to Mid MF (2-2.5) and Low MF (<2) levels, respectively. In order to optimise system performance, alternative approaches (for example, explore individual cow performance variability) together with strategies such as increasing CR and increasing production per cow, should be explored.

INTRODUCTION

The adoption of automatic milking systems (AMS) in countries where the majority of dairy farms are pasture-based such as Australia (Lyons & Kerrisk, 2017), New Zealand (Woodford et al., 2015) and Ireland (Shortall et al., 2018), continues to increase. In Australia, currently there are over 40 farms operating with AMS and at least another five are being installed (Lyons & Kerrisk, 2017). The majority of them operate with voluntary cow traffic where cows move from the paddock to the dairy facility to get milked and back to pasture, throughout the 24 h period, largely without human assistance.

Optimising the amount of milk harvested per robot (MHR, kg milk/robot/day) is critical to achieving high farm profitability and is a goal for the majority of farmers operating with AMS (Sonck & Donkers, 1995). The MHR is the result of the number of daily milkings and the amount of milk harvested in each milking. To maximise the number of daily milkings performed by the AMS unit, the operator can decide to either increase the number of cows, increase the number of times each cow visits the robotic unit (if yield per cow increased accordingly) or a combination of both strategies (Pettersson et al., 2011).

In pasture-based AMS, increasing individual cow milking frequency (milkings/cow/day) to optimise MHR comes with many challenges (Woolford et al., 2004). The combination of grazing and AMS results in a lower and more variable milking frequency in comparison to indoor AMS (Lyons et al., 2014) as well as lower overall production levels (Lyons et al., 2013a). Pasture-based AMS typically operate with larger herds than indoor systems and in order to maintain a high proportion of pasture in the diet, cows are required to walk significant distances (Islam et al., 2015). This, together with the greater synchronisation of behavioural activities typically observed in pastured-based, could explain the lower milking frequencies and why visitation is unlikely to be evenly spread across the day and night. This in turn affects occupation rate, defined as the proportion of time the automatic milking unit is actually milking per day (Lyons et al., 2013b; John et al., 2016) and by association, MHR (Koning & Ouweltjes, 2000).

An alternative approach to optimise MHR is to increase the number of cows per robot. However, operating with a high number of cows per robot increases the pressure on the system and requires that the system is managed very efficiently (Lyons & Kerrisk, 2017). In a study conducted in Spain that analysed data from 29 commercial AMS farms, Castro et al. (2012) reported that an increment in the number of cows per robot (from 52 to 68 cows per robot) increased the milk harvested per robot at a rate of 22.53 kg milk/robot/day for each additional cow. However, this was associated with a decrease in milking frequency per cow. In that study, farms averaged 1,506 kg milk/robot/day, 52 cows per robot and 2.69 milkings/cow/day. In a more recent study where data from 635 North-American dairy farms with AMS were analysed, Tremblay et al. (2016) also reported a significant positive effect of cows per robot on MHR. Farmers harvested on average 1,626 kg milk/robot/day, milking 50 cows per robot at an average individual milking frequency of 2.91 milkings/cow/day. All of the farms in the above two studies had cows housed in indoor systems, with relatively high milking frequency and MHR in comparison to the values typically observed in pasture-based systems. The different type of cow (high yielding cows vs med/low yielding cows) and traffic system typically used in indoor systems (free cow traffic vs guided cow traffic) also create limitations in the potential to accurately extrapolate results to pasture-based systems.

In New Zealand, Davis et al. (2005) as well as Jago and Burke (2010) aimed to optimise MHR, by establishing a higher number of cows per robot. The former study reported 75 cows per robot, with an average milking frequency of 1.13 milkings/cow/day to achieve only 1,087 kg milk/robot day. In the latter study, researchers were able to increase cows per robot to a maximum of 92 cows, and milking frequency to 1.5 milkings/cow/day, achieving a MHR of 1,386 kg milk/robot/d. It is important to acknowledge that these two studies were implemented on low-input grazing systems, with smaller and lower yielding cows (New Zealand Holstein-Friesian strains, Jerseys and Crossbreds). Although these two studies were conducted in pasture-based AMS, the average milking frequencies were significantly lower than values recently reported by Lyons and Kerrisk (2017). In the study by Lyons and Kerrisk (2007), nine Australian AMS farms were monitored on a monthly basis for one year, with an average ratio of 51 cows per robot (range 14-75), a milking frequency of 2.38 milkings/cow/day, and an average MHR of 1,263 kg milk/robot/day. Probably more important is the fact that this study also highlighted the difference between current and potential system performance, suggesting that milkings per robot per day, cows per robot, MHR and milking time could (potentially) be increased by up to 60%. The average potential MHR and cows per robot reported in that study was 1,956 kg milk/robot/day and 78 cows per robot, respectively. This suggests that there is an opportunity for MHR improvement and that the majority of commercial AMS farmers are not maximizing MHR levels.

While these studies give some reference values in regards to cows per robot, individual milking frequency and MHR, most of them either focus on one single low-input farm (the

New Zealand studies) or do not analyse the relationship between these variables (the Australian study) for pasture-based AMS. If the relationship between MHR, cows per robot and milking frequency in pasture-based AMS is better understood, farmers would be better positioned to develop more feasible strategies to effectively optimise MHR. Therefore, the aim of this study was to analyse the relationship of MHR with milking frequency and number of cows per robot for pasture-based systems. The second aim was to determine the likelihood of achieving high levels of MHR with different levels (and combinations) of milking frequency and cows per robot.

MATERIALS AND METHODS

General information

Data were obtained from the NSW DPI's Automatic Milking Systems Key Performance Indicators (AMS KPI) Project (N. Lyons, personal communication), which comprised data form Australian (year 1 and 2) and from overseas farms (year 2). In year 1, all Australian AMS farmers were invited to participate and in year 2 the invitation was extended to include AMS farms in New Zealand, Ireland and Chile. This resulted in nine farms from Australia in year one (July 2015-June 2016) and 19 farms (12 from Australia, 2 from New Zealand, 4 from Ireland and 1 from Chile) in year two (July 2016-June 2017). A total of 20 farms were monitored during the 2 years, but only 8 farms participated in both years. Agreeing to participate involved extracting reports from the AMS support software on a monthly basis (during the first five days of each month). Data collection also included some capture of general information about farm characteristics and variables related to the farm system and animal performance. More details on this dataset can be found on Lyons and Kerrisk (2017).

Farm demographics

Only farms operating with single box robots (average 3 boxes/farm, range 1 - 6) were included. Thus data from the two farms operating with a robotic rotary (AMR™, DeLaval International AB, Tumba, Sweden) were excluded given that MHR is not directly comparable. One Australian farm was an indoor operation with cows confined to the barn all year round with a 'free cow traffic' system and was also excluded from the study.

Seven farms had seasonal calving systems (all cows calved within a defined period each year, usually late winter to early spring), seven had split calving patterns (cows calved in two or three defined periods each year, typically spring and autumn) and three had year-round calving patterns (cows calved throughout the year). The majority of the farms analysed in this study milked Holstein Friesians, Brown Swiss, Norwegian Reds or crossbreds (predominantly Holstein x Jersey). Nine farms had no out-of-parlour concentrate feeding stations and relied on feeding only within the milking station, whilst the other eight had between two and six feeding stations allowing cows to consume concentrate in the milking stations and/or in the out-of-parlour stations. All farms were pasture-based, operated with voluntary traffic and provided between one and four feed allocations of fresh pasture per day.

Data analysis

Outcome variables

The outcome variables of interest in this study were: (1) MHR (kg milk/robot/day) and (2) probability of obtaining High levels of MHR. The MHR were categorised as either Low (< 1000 kg milk/robot/day), Mid (≥ 1000 to < 1600 kg milk/robot/day) or High (≥ 1600 kg milk/robot/day).

Explanatory variables

Explanatory variables used in the analysis were: calving pattern (as year round, seasonal and split), milking frequency (MF, in milkings/cow/day, which was calculated as the average number of milkings per cow per day of the herd for that month); cows per robot (CR, cows per robot, calculated by dividing the herd size for that month by the number of robots), season (as summer, autumn, winter and spring) and milk yield (MY, kg milk/cow/milking, calculated as the average yield per milking of all miking events for that particular month).

Milking frequency was categorised as either Low (< 2 milkings/cow/day), Mid (≥ 2 to < 2.5 milkings/cow/day) or High (≥ 2.5 milkings/cow/day). Additionally, CR were categorised as either Low (< 45 cows per robot), Mid (≥45 to < 60 cows per robot) or High (≥ 60 cows per robot). Milk yield was categorised as either Low (< 9.5 kg milk/cow/milking), Mid (9.5 ≥ to 11.5 < kg milk/cow/milking) or High (≥ 11.5 kg milk/cow/milking). For MHR, MF and CR the cut-off values were determined after exploring the distribution of variables within this dataset and also in relation to average values observed in the available literature (Castro et al., 2012; Lyons & Kerrisk, 2017; Andre et al., 2010; Woodford et al., 2015; Tremblay et al., 2016; Jago & Burke, 2010). For example, Castro et al. (2012) categorised MHR into Low (< 1500 kg milk/robot/day), Mid (≥ 1500 to < 1944 kg milk/robot/day) or High (≥ 1944 kg); however, because that study was conducted in indoor systems, these cut-off values are higher than those typically observed in pasture-based systems, therefore new values were determined.

Statistical analysis

Data were first summarised using descriptive statistic and numeric variables were checked for normality. A multivariable linear mixed model was used to analyse the association of explanatory variables with the numerical outcome variable (MHR, kg milk/robot/day), with parameter estimates calculated using residual maximum likelihood (REML) (Model 1). Farm ID was included as a random effect to account for repeated measures within farms and differences between farms. The model included MF, CR, MY, season and calving pattern as fixed effects. Interactions between fixed effects were tested.

In addition a generalised linear mixed model (GLMM) was used for binary data to test the association between the explanatory categories (MF and CR) and the probability of achieving High MHR (Model 2). Farm ID was included as a random effect to account for repeated measures within farms and differences between farms. The model included MF, CR, season and calving pattern as fixed effects. Interactions between fixed effects were tested.

All analyses were conducted in Genstat 16th Edition (VSN International Ltd., UK) and *P* values lower than 0.05 were considered significant. Residual analysis was performed to check for normality. Least significant differences were used to determine any significant differences

RESULTS

On average, the 17 farms participating in the study produced 3,729 kg milk/day with 4.25% Milk Fat, 3.44% Milk Protein and a Somatic Cell Count of 181,000 cells/mL. Average MHR was 1,171 kg milk/robot/day, with 51 cows per robot. Individual cows had an average milking frequency of 2.22 milkings/cow/day and produced on average 22.94 kg milk/day (Table 1).

Table 1. Descriptive statistics for the analysed data set for all farms and all months (*n*=228).

Variable	Mean	Minimum	Maximum	SD[1]	SEM[2]
Cows in milk (n)	168	38	330	66.8	3
Number of robots (n)	3	1	6	1	0.06
Cows per robot (CR, cows per robot)	51	13	81	12.46	0.71
Milk harvested per robot (MHR, kg milk/robot/day)	1,171	377	2,484	434	25
Milk Fat composition (%)	4.25	3.23	5.53	0.48	0.03
Milk Protein composition (%)	3.44	2.98	4.13	0.24	0.01
Somatic cell count (x1000)	181	25	419	73	4
Daily milk yield (kg milk/cow/day)	22.94	12.07	36.59	5.79	0.33
Milk yield (MY, kg milk/cow/milking)	10.41	5.11	16.90	2.28	0.13
Milking frequency (MF, milkings/cow/day)	2.22	1.51	3.06	0.32	0.02
Milking time (h/robot/day)	13.26	0.72	21.12	3.36	0.24
Daily milk production (kg milk /day)	3729	17	9,665	1594	90
Milkings (milkings/robot/day)	112	5	164	26	1
Concentrate intake (kg milk/cow/day)	5.41	0.15	11.29	2.22	0.13

[1]Standard deviation
[2]Standard error of the mean

The final linear mixed model (Model 1) to explain the outcome variable MHR included the terms MF, season, CR and MY (all significant $P<0.001$) and calving pattern (not significant, $P>0.05$), as fixed effects. There was a significant interaction between CR and MF ($P=0.009$), between MF and MY ($P=0.045$) and between CR and MY ($P<0.001$).

For the interaction between MF and CR, MHR was lowest when Low MF coincided with Low CR whilst the highest MHR occurred with High CR and Mid MF (Table 2). The average increment in MHR within each category of CR (10%) was proportionally lower in comparison to the increment observed when CR increases for each category of MF (26%). Within each category of MY there was no difference when MF increases from Mid to High (Table 3).

Table 2. Milk harvested per robot (kg milk/robot/day) predicted means for the interaction between cows per robot and milking frequency (milkings/cow/day).

		Cows per robot		
		Low (< 45)	Mid (≥45 to < 60)	High (≥ 60)
Milking frequency	Low (< 2)	802[a]	983[b]	1349[d]
	Mid (≥ 2 to < 2.5)	947[b]	1203[c]	1537[e]
	High (≥ 2.5)	984[b]	1310[d]	1426[d]

[a-g]Different letters indicate significant effect (*P*<0.001) differences between categories.

Table 3. Milk harvested per robot (kg milk/robot/day) predicted means for the interaction between milk yield (kg milk/cow/milking) and milking frequency (milkings/cow/day).

		Milking frequency		
		Low (< 2)	Mid (≥ 2 to < 2.5)	High (≥ 2.5)
Milk yield	Low (< 9.5)	899[a]	999[b]	949[ab]
	Mid (9.5 ≥ to < 11.5)	975[ab]	1220[c]	1281[c]
	High (≥ 11.5)	1260[c]	1468[d]	1491[d]

[a-d]Different letters indicate significant effect (*P*<0.001) differences between categories.

Table 4. Milk harvested per robot (kg milk/robot/day) predicted means for the interaction between milk yield (kg milk/cow/milking) and cows per robot.

		Cows per robot		
		Low (< 45)	Mid (≥45 to < 60)	High (≥ 60)
Milk yield	Low (< 9.5)	748[a]	1017[c]	1081[c]
	Mid (9.5 ≥ to < 11.5)	867[b]	1201[e]	1408[f]
	High (≥ 11.5)	1117[cd]	1278[e]	1824[g]

[a-g]Different letters indicate significant effect (*P*<0.001) differences between categories

The final model for the outcome variable, probability of achieving High milk harvested per robot (Model 2) included a significant effect of MF, CR and Season with no significant interaction between MF and CR (Table 5). The likelihood of obtaining High MHR increased significantly when MF increased. Systems that presented Low MF (<2 milkings/cow /day) were the least likely to obtain High MHR and those operating with High CR (≥ 60 cows per robot) had the highest chance of achieving High MHR per robot. In spring it was 15 times more likely to achieve High MHR than in Winter.

Table 5. Final generalised linear mixed model to investigate the association of explanatory variables with the outcome variable and the probability of achieving High milk harvested per robot.

Effect	Categories	Estimate	Standard error	Odds (95%CI[1])	P-value
Intercept		-9.61	0.24		
Milking Frequency					0.033
	Low (<2)	0	0.64	1	
	Mid (2-2.5)	2.58	0.64	13.19 (11.91, 14.47)	
	High (>2.5)	2.89	0.64	17.99 (16.71, 19.27)	
Cows per robot					<0.001
	Low (<45)	0	0.92	1	
	Mid (45-60)	3.86	0.92	47.65 (45.81, 49.49)	
	High (>60)	7.92	0.92	2760 (2758.16, 2761.84)	
Season					<0.001
	Winter	0	0.50	1	
	Spring	2.72	0.50	15.28 (14.28, 16.28)	
	Summer	1.68	0.50	5.40 (4.40, 5.40)	
	Autumn	0.08	0.50	1.22 (0.22, 1.22)	

[1]Confidence interval

DISCUSSION

The main objective of this study was to investigate the relationships between MHR, MF and CR on commercial pasture-based AMS farms. Milk harvested per robot increased when MY, CR and MF increased. The second objective was to determine the probability of achieving High levels of MHR for different levels of MF and CR. Results indicate that the probabilities of achieving High MHR increased when either of those variables increased.

The average MHR in this study was 1,171 kg milk/robot/day, which is in line with the previous 1,271 kg milk/robot/day published in studies involving pasture-based farms (Lyons and Kerrisk (2017). These figures are still lower in comparison to results reported from indoor housed systems, which range between 1506 kg milk/robot/day and 1883 kg milk/robot/day (Castro et al., 2012; Tremblay et al., 2016; Andre et al., 2010). Given the average number of cows per robot was fairly similar in all studies (~51 cows per robot), this difference with housed systems may be mostly explained by 2 main factors: the difference in MF and MY, which in turn can be explained predominantly by feeding system and walking distances; and possibly, genetic potential. In the three studies conducted in indoor systems, the mean MF was above 2.5 milking/cow/day, which is higher in comparison to those typically observed in pasture-based systems (2.22 milking/cow/day for this study). Pasture-based AMS typically present lower MF than those observed in indoor systems, as there are many factors affecting cow movement including animal factors (stage of lactation, age, previous AMS expertise, herd dynamics), management factors (e.g. timing, placement and distribution of feed, herd size) and environmental factors (e.g. climatic conditions) (John et al., 2016; Lyons et al., 2014). John et al. (2016) also reported that the interaction between time of the day, location of robot relative to shade and distance to milking robot, might also affect cow traffic behaviour.

The daily milk yield (DY, kg milk/cow/day) in this study (22.94 kg milk/cow/day) was lower in comparison to DY in the studies of Castro et al. (2012), Tremblay et al. (2016) and Andre et al. (2010), who reported 28.52, 31.98 and 30.0 kg milk/cow/day, respectively. This difference might be explained by MF, together with other factors like breed, genetic merit and feeding system. Tremblay et al. (2016) found that farms milking Jersey cows produced 216 kg milk/robot/day less than systems operating with Holstein cows, although there was no difference between Holstein and other breeds (including Ayrshire, Brown Swiss, Guernsey and Crosses). In our study only 10 out of the 17 farms milked only Holstein cows, whereas in the other studies the majority, if not all, of the records were from Holstein cows (90% in Tremblay et al. (2016), and all records in Castro et al. (2012) and Andre et al. (2010)). No information regarding genetic merit was available for any of the studies. In regards to feeding systems, as all farms in our study were pasture-based, on an annual basis the majority of the forage is offered as grazed pasture; and although in most of the farms cows received additional supplements, like grain based concentrates, cows would have been (as it occurs in pasture-based systems) restricted in quantity by grazing management and in quality by seasonality, which would typically be expected to limit milk production potential (Hills et al., 2015).

The lower values of MF observed in our study means that milking intervals (defined as the total time between two consecutives milking events) were increased. Lyons et al. (2013a) reported a positive non-linear relationship between milking interval and MY, with proportionally lower MY for intervals greater than 16 h. In the study by Lyons et al. (2013a), a wide distribution of MI was reported and 30% of the total milking events had intervals greater than 16h. This might lead to (expected) higher MY in pasture-based systems, however the MY in this study was no different from the one reported by Castro et al. (2012) (10.4 kg milk/cow/milking and 10.6 kg milk/cow/milking, respectively) and it was lower in comparison to those presented by Tremblay et al. (2016) and Andre et al. (2010) (12.34 kg milk/cow/milking and 12.68 kg milk/cow/milking, respectively). This difference might be related to breed, genetic merit and feeding system.

The fact that MHR did not increase when MF increased from Mid to High levels for each category of MY (Table 3), suggests that MF was not limiting production beyond 2 milkings/cow/day. Other factors like a limitation in dry matter intake, which typically occurs in grazing systems (Bargo et al., 2003); and milk production levels (Lyons et al., 2014) might have been greater limiting factors at High MF levels. This is in agreement with Utsumi (2011), who suggested that an increase in MF will not produce significant positive effects on milk production if dry matter intake and/or energy is limited.

The highest MHR, which was found for the combination of High CR and High MY (1,824 kg milk/robot/day), was still 7% lower than the potential maximum calculated by Lyons and Kerrisk (2017) (1,956 kg milk/robot/day). However, to calculate potential maximum MHR, Lyons and Kerrisk (2017) assumed certain levels of linearity of response within farm and that certain system variables remained constant while others changed. Although this is a valid modelling exercise approach, this method denotes the technical capability of the equipment and does not take into account the variability that exists in physical commercial operations with current farm system management practices and types of cows. However, the highest MHR reported by Lyons and Kerrisk (2017) was 2,484 kg milk/robot and is higher than the potential maximum. That value was achieved only on one month, on a seasonal calving farm in spring with 75 cows per robot and a MF of 2.3 milkings/cow/day. This showed that the combination of High CR, cows in early lactation, mid values of MF, spring (assuming high quality and quantity of pasture, favourable environmental conditions) and good management, commercial farmers are already achieving very High MHR.

However, this period in which the robot might be the limiting factor, is only for a few months of the year (usually spring-summer in farms with seasonal calving systems), and then the systems will run at lower than potential utilisation levels for the remainder of the year, so there is still an opportunity to find alternatives on how to improve productivity in some months of the year. It is evident from the present study that the main limiting factor for achieving high levels of system performance on commercial farms is in having the right combination of animal, management and feed factors; rather than in the technical capability of the robotic equipment. However, modifying the animal, management and feed factors will come at a cost that might be greater than the performance benefits that are trying to be optimised. Clearly more research is warranted to elucidate this.

Castro et al. (2012) and Artmann (2004) reported that when then numbers of CR increased, MHR increased together with a declined in MF. The same trend was observed in this study (data not shown). This limitation in MF, might compromise individual cow production, as they are strongly positively associated (Lyons et al., 2013a). Therefore the optimum or efficient number of cows per robot would be the one that will allow the systems to achieve a High MHR, with a high individual cow production (not necessarily maximised).

The optimum CR that will allow farmers to optimise MHR in pasture-based AMS, with cows having lower MF and lower individual milk production seems to be higher in comparison those observed in indoor systems. However, given that the average CR in this study (~51 cows per robot) is similar to that of indoor-housed systems studies, it is evident that farmers are prioritising an increment in MF rather than an increment in CR, or a combination of both, as a strategy to maximise MHR, although they are not achieving it. In a practical way, an increment in MF is easier to target in the short term than an increment in CR, which requires additional cows (either purchased, retained or reared). Lyons and Kerrisk (2017) reported that in Australian AMS farms there is a potential to increase CR by a maximum 60%. However, they also suggested that operating with High CR creates a lot of pressure on the system and therefore requires very good management, and this might be a reason to explain why the majority of pasture-based AMS operators do not seem to be seeking to achieve High CR.

For the interaction between CR and MF (Table 2), the highest MHR (1,537 kg milk/robot/day) was achieved with High CR and Mid MF and increasing the MF from Mid to High at a High level of CR, resulted in a decrease in MHR. Moreover, on average the effect of increasing CR was greater than the effect of increasing MF for all categories. The same was true for MY and MF. An increment in MF from Mid to High did not result in higher MHR. Furthermore, it was shown in table 4 that MHR increased significantly when CR increased for Mid and High MY levels. These findings indicate that, when operating with

High CR, the effect of increasing the amount of times a cow visit the robotic unit on a daily basis above 2.5 milkings/cow/day, negatively affect MHR. Several reasons could potentially explain this effect including: (1) at High levels of MF there is a lack of response in milk production, as cows start to be limited by other factors (e.g. nutrition, animal genetics), as previously mentioned; (2) combined higher levels of CR and MF likely results in longer waiting times in the pre-milking area, negatively impacting on cow performance; (3) there is an increasing inefficient use of robot time, given that every milking has a fixed ‘unproductive’ handling time (identification, entry and exit of the cow, cleaning, attaching and post-milking disinfecting processes) and a milk-yield related milking time, and that with cows getting milking too often, the MY will be smaller.

Similarly to the results published by Lyons and Kerrisk (2017) there was a significant effect of season on MHR. In pasture-based AMS operating with either seasonal or split-calving systems (14 out of the 18 farms in this study) higher levels of system utilisation are typically observed in spring-summer, whereas during the rest of the year they run at lower than potential utilisation levels. This is because farmers typically try to match herd requirements and pasture growth (Holmes et al., 2002), therefore most of the cows calve and reach their peak production during the periods of highest pasture quality and supply. Conserving surplus pasture to feed at other times of the year is costly and time consuming and is minimised through the matching of feed supply/demand making this the most profitable farm management system unless cheap supplementary feed is reliably available. Moreover, the seasonal variability in pasture quality and quantity typically observed in pastured-based systems (Chapman et al., 2009; Roche et al., 2009) affects milk production unless cost effective supplementary feed is available to negate this seasonal variability. Environmental factors such as high temperatures can also have a dramatic impact on voluntary cow traffic thereby affecting the full farm system performance (John et al., 2016). In a recently published study in which data from 6 pasture-based Australian AMS farms were analysed, Wildridge et al. (2018) showed that high temperature-humidity index (THI) conditions were negatively associated with milking frequency and daily milk yield. Cold, wet and windy conditions, typical in many dairy regions of Australia and New Zealand, affect dairy cow behaviour (Webster et al., 2008; Redbo et al., 2001) and it might also negatively affect milk production (Bryant et al., 2007).

Overall, results from this study indicate that CR had a greater effect than MF on MHR. Moreover, with current management practices, feeding systems and cow types, the likelihood of achieving High MHR (greater than 1,600 kg milk/day/robot) with Low and mid-levels of MF in commercial pasture-based AMS, is low. An alternative approach, also in line with strategies such as increasing CR and increasing production per cow, might be to explore individual cow variability in order to identify those cows that are more suitable for pasture-based AMS. Data generated by AMS creates the opportunity to explore individual cow variability regarding milking efficiency traits, such as MF, MY, MI, milk flow rate and milking time (Carlstrom et al., 2013). Despite the numerous research studies about individual cow variability in AMS, the vast majority of them (Lovendahl & Chagunda, 2011; Andre et al., 2010; Nixon et al., 2009; Penry et al., 2018) were conducted in indoor-systems. Although still relevant for pasture-based systems, the differences between systems (feeding management strategies, environmental conditions, herd size, animal related factors) limit direct data extrapolation onto pasture-based AMS. More research focusing on pasture-based AMS is needed to assist farmers in making more informed decisions on how to improve system performance.

CONCLUSION

Results from this study indicate that commercial pastured-based AMS are achieving lower levels of MHR, together with lower levels of MF and similar levels of cows per robot in comparison with those commonly reported in indoor systems. Although MHR increased when either MF or number of CR increased, the latter had a greater effect on production per robot. Moreover, with current management practices, feeding systems and cow types, the likelihood of achieving high levels of milk harvested per robot with Low (<2) and Mid (2-2.5) MF, are currently low. From a robot performance aspect, it would therefore be more beneficial for farmers to increase CR, rather than targeting higher MF levels. In order to optimise system performance, alternative approaches (for example, exploration of individual cow performance variability) together with strategies to increase cows per robot and production per cow, should be explored.

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OVERVIEW OF CHAPTER 4

Chapter 3 highlighted the positive effect of increasing the number of cows per automatic milking unit on both robot and system productivity. The high degree of variability regarding individual cow performance observed in pasture-based automatic milking systems (AMS) was identified in Chapter 2 as an area with potential for capturing some efficiency gains. Linking these key previous findings, it follows that if individual cows could be accurately identified and classified according to their efficiency (as defined specifically for AMS), then a number of strategies could be developed to capture additional gains by reducing losses and/or increasing efficiency, e.g. allocating limited resources like feed tailored to specific levels of efficiency (or inefficiency). In Chapter 4 individual cow data from two pasture-based AMS farms were used to develop and evaluate a methodology to identify efficient and inefficient cows based on their combined effect of milking frequency and milk yield.

CHAPTER 4: Identifying efficient and inefficient cows with regard to milking performance in pasture-based automatic milking system

ABSTRACT

In pasture-based automatic milking systems (AMS) operating with voluntary traffic, anecdotal evidence indicates that there are cows which are more efficient (produce more milk from relatively fewer milkings) and some which are less efficient. The aim of this study was to a) develop a methodology to objectively identify Efficient and Inefficient cows through analysis of milk production and milking frequency data across whole lactations; and b) quantify the differences between Efficient and Inefficient cows. Two large historical datasets (spanning over a 4-year period) from two commercial farms were collected. Linear mixed models were used to determine the effect of stage of lactation and parity and to obtain predicted means and residuals for daily milk yield (DY) and milking frequency (MF). Relative residuals (RR (%) = residual/predicted mean) were calculated and used to estimate the DY and MF of each cow in relation to her predicted mean. Average DY, MF and RR were calculated for the whole lactation of each cow. Cows presenting a positive RRDY and a negative RRMF were categorised as Efficient and cows presenting a negative RRDY and a positive RRMF were categorised as Inefficient. Efficient cows were identified in both farms producing on average 9% more milk with 5% less milkings per day and Inefficient cows producing 10% less milk with a 6% higher MF in relation to their predicted means (P<0.001). These findings demonstrate a) the success of the methodology designed in this study to identify Efficient and Inefficient cows as defined specifically for pasture-based AMS cows; and b) the magnitude of the differences between Efficient and Inefficient cows, which indicate potential for productivity gains. Developing an understanding of the causes of the differences will be an important next step which may help to determine the potential to lift Inefficient cows into the Efficient category.

INTRODUCTION

The adoption of Automatic Milking Systems (AMS) in Australia continues to increase. In 2018 there are 40 farms operating and another five are in an installation phase. Most of them (87%, N. Lyons pers. comm.) are pasture-based and operate with predominantly voluntary cow traffic system (i.e. cows bring themselves to the dairy, get milked and walk back to pasture largely without human assistance). The smoother and the more evenly distributed (over 24 h) the voluntary cow traffic, the better the utilisation of the milking robots; less time spent by cows queuing for a given milking session; the greater the general efficiency of the system. Cow movement in voluntary traffic is affected by many factors including (but not limited to) animal (e.g. genetics, breed, age, stage of lactation, production level, social dominance), management (e.g. timing, placement and distribution of feed) and environmental factors (e.g. climatic conditions) (Lyons et al., 2014).

It is known that in AMS there is a strong positive relationship between milking frequency (determined predominantly by voluntary cow traffic) and milk production levels (Lyons et al., 2013a; Pettersson et al., 2011). In conventional milking systems, milking frequency is controlled by the farm operators and is typically twice-a-day in Australia. In contrast, AMS farms operating with voluntary traffic create opportunity for cows to access the robots and get milked more often and therefore the possibility to achieve greater milk yields. However, anecdotal evidence suggests that some cows are more ‘efficient’ (produce more milk from relatively less milkings) than other cows in the same herd (assuming all influencing factors are accounted for). If the ‘inefficient’ cows (those that produce less milk from relatively more milkings) were identified, they could be managed separately or differently to increase the whole farm system performance.

A higher proportion of ‘efficient’ cows in a herd will allow an increase in the number of cows milked per robot and resultant increased volumes of milk harvested per AMS, thereby positively influencing the profitability of the operation (Jago & Burke, 2010). ‘Efficient’ cows could also be more suitable for farms milking large herds under pasture-based conditions, as every milking session is associated with walking (from paddock to the dairy) in which cows spend a considerable amount of time and energy. Increased walking distances divert energy from milk production, reduce available grazing time (Spörndly & Wredle, 2004; Islam et al., 2015) and has the potential to negatively impact dairy cow welfare (Coulon et al., 1998).

The management software of AMS capture a large volume of data about the individual cows, most of which is not readily utilised by the farmer. We hypothesise that some of this data could be used to identify cows with different levels of 'efficiency' and that the variability between Efficient and Inefficient cows is large enough to allow different management practices to be implemented on each group of cows. Thus, we used whole lactation data from two commercial AMS farms to firstly develop a methodology to identify efficient and inefficient cows; and secondly, assess the magnitude of the associated variability.

MATERIALS AND METHODS

General information

The study involved whole lactation data collected automatically by the AMS software on 2 commercial farms (New South Wales and Victoria, Australia). Farm 1 had 4 single box milking units and Farm 2 had 2 single box milking units (both Lely Astronaut, Lely Industries, Rotterdam, The Netherlands). Both farms operated as pasture-based systems with voluntary cow traffic and were managed with a '3 way grazing system' (cows had access to 3 allocations of fresh pasture over a 24 h period; Lyons et al. (2013b)) all year round. Cows in both herds had access to concentrate feed (allocated based on their production level), during milking in the automatic milking unit and automated feed stations after milking. Farm 1 managed a seasonal (Spring) calving pattern with a Holstein-Friesian herd and Farm 2 operated with a year-round calving pattern with a mixed-breed herd of Holstein-Friesian (90%) and Brown Swiss (10%).

Data Collection

Raw data were obtained from the management software of each farm and included cow number, parity, days in milk, daily milk yield and milking frequency. Daily milk yield was defined as the accumulated milk production of all individual milking events in a given 24-hour period (DY, kg milk/cow/day) and milking frequency (MF) was defined as the sum of all individual milking events per cow in a given 24-hour period. Historical data from January 2012 to January 2015 were collected from both farms.

A total of 238,902 daily records from both farms were collected. The dataset was organised, filtered and aberrant values where deleted. A total of 33,015 daily records were discarded (13% of the original data). Reasons to discard data included a) daily records from cows with <5 and > 310 days in milk; b) milk yield values that were > 50 kg/cow/milking (considered outliers) c) milkings with interval > 48 h. The final dataset contained a total of 100,388 daily records from 206 cows from Farm 1 and 105,499 daily records from 179 cows from Farm 2. Farm datasets were analysed separately throughout the study. The data capture period extended across several years which resulted in some cows contributing to the dataset across more than one lactation.

Due to the variability (between days) of DY and MF typically observed in AMS, seven-day averages were used in the analysis.

The following variables were categorised: parity (5 categories, lactation number 1=1, lactation number 2=2, lactation number 3=3, lactation number 4=4, lactation number ≥5 = 5) and days in milk as stage of lactation (SOL as 31 categories using a span of 10 days per category).

Data processing and Statistical Analysis

A linear mixed model (REML) was used to determine the effect of stage of lactation and parity on the two outcome variables DY and MF, to obtain predicted means and calculate residual values. In both models, stage of lactation, parity and their interactions were included as fixed terms and Cow ID was fitted as a random term. All analyses were conducted using Genstat 16th Edition (VSN International Ltd). Residual analyses were performed to determine that assumptions of normality were met.

The model for both analyses was as follow:

$$y = \text{constant} + \text{Parity} + \text{SOL} + (\text{Parity*SOL}) + \text{CowID} + \varepsilon$$

where, y is daily milk yield (DY; kg/cow/day) or milking frequency (MF; numbers of milking/day); parity = effect of parity (LacNo 1, …, 5); SOL = effect of stage of lactation (SOL No 1, …, 31); Cow ID = effect of cow and ε = random error.

For both outcome variables DY and MF, predicted means and residual values resulting from the model were used to calculate the relative residual (RR):

Relative residual (%) = residual value / predicted mean x 100

The relative residual was calculated in order to estimate how much a cow produced (for DY), or how many times per 24 h she was milked (for MF) in relation to her fitted or expected value after accounting for the effects of stage of lactation and parity number by the model. For example, a cow presenting a Relative Residual of DY of 10% and a Relative Residual of

MF of -20% indicates that the cow produced 10% more milk above her expected production value with MF 20% below her expected frequency value.

Categorisation and Lactation data analysis

In order to categorise cows, lactation curves were constructed utilising DY, MF and relative residuals for both variables for each cow, excluding lactations <290 and >310 days and/or lactations with less than 90% of the lactation records available. This criterion was adopted in order to enable the comparison of cows with similar volume of data within a given lactation. Thus, only 113 lactations from 85 cows were included in the categorisation from Farm 1 (30% of the total recorded lactations) and 179 lactations from 110 cows from Farm 2 (44% of the total recorded lactations). There were 28 cows in Farm 1 and 62 cows in Farm 2 that were included more than once (up to 3 lactations).

For each cow lactation, averages of relative residual for DY (RRDY) and MF (RRMF) were calculated for the whole lactation and utilised to categorised cows in 4 categories. Cows presenting a positive RRDY and a negative RRMF were categorised as Efficient; cows presenting a negative RRDY and a positive RRMF as Inefficient; cows presenting positive RRDY and RRMF were categorised as High Production and cows with negative RRDY and RRMF were categorised as Low Production. For each category, averages of DY and MF were calculated for three periods: whole lactation, early lactation (30-60 days in milk) and late lactation (180-210 days in milk).

A simple ANOVA was used to determine if the differences between the averages of the 4 categories for each variable were significant (P values lower than $P < 0.05$ were considered significant).

RESULTS

Descriptive statistics

The average daily milk yield was 25.3 ± 9.1 kg/cow per day for Farm 1 and 18.5 ± 6.9 kg/cow per day for Farm 2. Daily milk yield presented a large standard deviation in both farms (Table 1). Average MF was 2.2 events/cow per day for Farm 1 and 2.0 events/cow per day for Farm 2, which are within the range of typical values for a pasture-based AMS. Both DY and MF were greater in Farm 1 (high input system in comparison to Farm 2). The included fixed effects of SOL, Parity and their interaction were all found to be significant ($P<0.001$) for both analysed outcome variables.

Table 1. Descriptive statistics for data set for Farm 1 and Farm 2.

	Item	Variable	Cows (n)	Records (n)	Mean	SD[1]	Data Source
Farm 1	Daily milk yield (kg/cow)	(24hs)	206	100388	25.3	9.1	Collected
	Milking frequency (events/cow)	(24hs)	206	100388	2.2	0.7	Collected
	Daily milk yield (kg/cow)	(7 days)	206	13976	25.2	8.8	Calculated
	Milking frequency (events/cow)	(7 days)	206	13976	2.2	0.5	Calculated
Farm 2	Daily milk yield (kg/cow)	(24hs)	179	105499	18.5	6.9	Collected
	Milking frequency (events/cow)	(24hs)	179	105499	2.0	0.5	Collected
	Daily milk yield (kg/cow)	(7 days)	179	13660	18.7	6.8	Calculated
	Milking frequency (events/cow)	(7 days)	179	13660	2.0	0.4	Calculated

[1]SD: Standard Error

Categorisation

Relative Residuals of DY and of MF for the whole lactation of each cow are shown in Figure 1 for Farm 1 (a) and Farm 2 (b). Each dot represents a lactation of one cow. A strong positive relationship between RRDY and RRMF was observed in both farms. Whilst considerable variation between individual cows existed in both farms, that variation was greater in Farm 2.

On each farm, cows identified on the upper left quadrant were categorised as Efficient, on the lower left as Low Production, on the upper right as High Production and on the lower right as Inefficient. On Farm 1, 9 cows (11 lactations) (10% of total lactations) were categorised as Efficient and 18 cows (19 lactations) (17% of total lactations) were categorised as Inefficient. On Farm 2, 25 cows (29 lactations) (11% of total lactations) were categorised as Efficient and 12 cows (13 lactations) (7% of total lactations) were categorised as Inefficient.

In Farm 1, of the 28 cows that presented two lactations analysed, only 2 were categorised as Efficient in both lactations and one cow was categorised as Inefficient in both lactations. There were no cows categorised Efficient and Inefficient (in different lactations). In Farm 2, 53 cows were included two times and 8 cows three times, of them 4 cows were categorised as Efficient in both lactations and one cow was categorised as Inefficient in both lactations. There were 2 cows that were categorised as Inefficient in the first lactation and Efficient in the second lactation analysed.

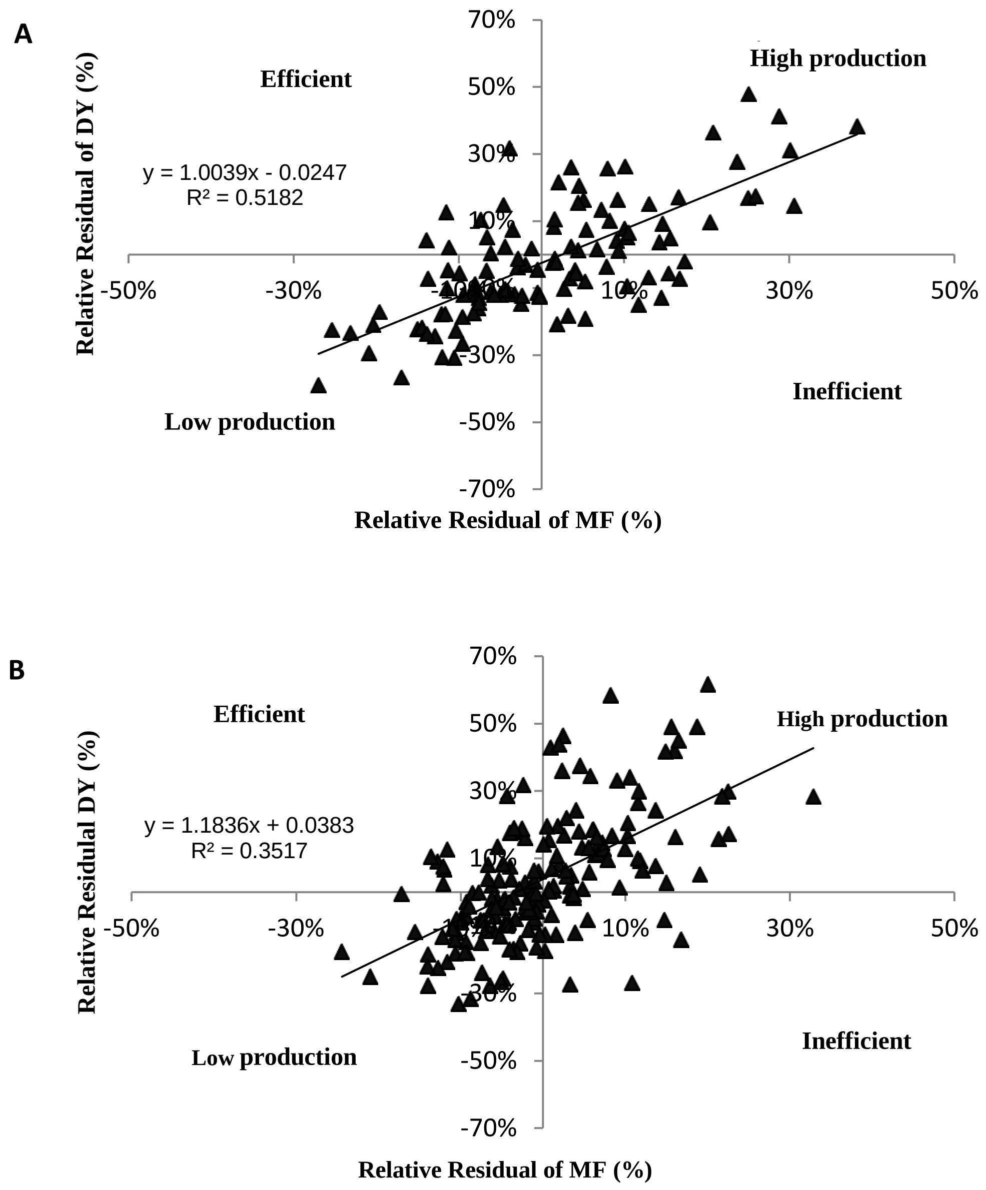

Figure 1. Mean Relative residuals of milking frequency and daily milk yield for Farm 1 (A) and Farm 2 (B).

Lactation data

Lactation characteristics are shown in Table 2. When analysing average relative residual of DY and MF for the whole lactation, on Farm 1, Efficient cows produced 8% more milk in relation to their expected value (predicted mean) with 7% less milkings; Inefficient cows produced 9% less milk with a 7% higher MF. On Farm 2, Efficient cows produced 10% more milk in relation to their expected value with 6% less milkings. Inefficient cows produced 11% less milk with a 5% higher MF.

Table 2. Averages of lactation characteristics for each group for Farm 1 and Farm 2.

	Farm1						
	All lactations	SE[1]	Efficient	Inefficient	High Production	Low Production	*P*-value
Lactations (n)	113		11	19	37	46	
Cows (n)	85		9	18	34	38	
Whole Lactation							
Relative Residual DY (%)	-1	0.02	8^{b}	-9^{c}	17^{a}	-16^{d}	<.0001
Relative Residual MF (%)	1	0.01	-7^{c}	7^{b}	14^{a}	-10^{c}	<.0001
DY (kg/d)	25.2	0.48	29.7^{a}	22.8^{b}	28.7^{a}	21.56^{b}	<.0001
MF (events/d)	2.25	0.03	2.13^{c}	2.33^{b}	2.49^{a}	2.05^{c}	<.0001
Early Lactation							
Relative Residual DY (%)	2	0.01	16^{a}	-3^{b}	15^{a}	-10^{c}	<.0001
Relative Residual MF (%)	4	0.02	-4^{b}	16^{a}	16^{a}	-7^{c}	<.0001
DY (kg/d)	36	0.74	44^{a}	33.15^{b}	40.31^{a}	31.77^{b}	<.0001
MF (events/d)	2.65	0.05	2.52^{b}	2.86^{a}	2.93^{a}	2.37^{b}	<.0001
Late Lactation							
Relative Residual DY (%)	-6	0.03	1^{b}	-12^{c}	12^{a}	-19^{d}	<.0001
Relative Residual MF (%)	0	0.01	-10^{c}	5^{b}	11^{a}	-8^{c}	<.0001
DY (kg/d)	19.7	0.45	22.8^{a}	18.15^{b}	23.1^{a}	16.7^{b}	<.0001
MF (events/d)	2.15	0.04	1.96^{b}	2.24^{a}	2.38^{a}	1.98^{b}	<.0001

	Farm 2						
	All lactations	SE[1]	Efficient	Inefficient	High Production	Low Production	*P*- value
Lactations (n)	179		29	13	66	71	
Cows (n)	110		25	12	47	56	
Whole Lactation							
Relative Residual DY (%)	4	0.01	10^{b}	-11^{c}	20^{a}	-11^{c}	<.0001
Relative Residual MF (%)	0	0.01	-6^{b}	5^{a}	9^{a}	-7^{b}	<.0001
DY (kg/d)	19.2	0.4	21.09^{a}	15.01^{b}	22.4^{a}	16.17^{b}	<.0001
MF (events/d)	2.02	0.02	1.95^{c}	2.08^{b}	2.2^{a}	1.87^{d}	<.0001
Early Lactation							
Relative Residual DY (%)	1	0.01	7^{b}	-20^{d}	16^{a}	-11^{c}	<.0001
Relative Residual MF (%)	-1	0.01	-6^{c}	4^{a}	10^{a}	-11^{b}	<.0001
DY (kg/d)	23.2	0.55	25.54^{a}	16.93^{b}	26.9^{a}	19.93^{b}	<.0001
MF (events/d)	2.08	0.03	2.01^{b}	2.12^{b}	2.33^{a}	1.86^{c}	<.0001
Late Lactation							
Relative Residual DY (%)	7	0.02	12^{b}	-5^{c}	24^{a}	-9^{c}	<.0001
Relative Residual MF (%)	1	0.03	-4^{b}	5^{a}	8^{a}	-5^{b}	<.0001
DY (kg/d)	18.3	0.39	19.74^{a}	15.12^{b}	21.43^{a}	15.36^{b}	<.0001
MF (events/d)	2.01	0.02	1.93^{bc}	2.05^{ab}	2.16^{a}	1.88^{c}	<.0001

[1]SE: Standard Error; Different letters (within row) indicate significant differences (P<0.05) between groups.

In farm 1, average DY for the whole lactation was 30% higher in the Efficient than in the Inefficient group with a 9% lower MF. In farm 2 the difference between Efficient and Inefficient groups for DY and MF were of 40% and 6% respectively.

Efficient and High production cows presented similar and significantly higher average DY values than Inefficient and Low Producer cows in early, late and whole-lactation in both farms (P <0.001).

Milking frequency decreased across lactation in every group in both farms as was expected. Due to lower levels of production and MF in Farm 2, differences between groups were smaller (although still significant) than those observed in Farm 1.

Although the differences in MF observed between the groups were relatively small in both farms (Table 2), they were significant. Table 3 shows an estimation of what could be achievable in Farm 1 and Farm 2 if the milking herd was composed in their totality by cows of the same category, assuming the robot performs around 160 milkings per day (occupation rate of 80%, fixed duration of a milking of 7 minutes, typical values observed on commercial AMS farms under grazing conditions in Australia; K. Kerrisk, pers. comm.).

Table 3. Estimation of number of cows and extra milking production for Farm 1 and Farm 2.

	Category	MF[1]	DY[2]	Cow per robot (n)	MHR[3] (% change compared to average)
Farm 1	Efficient	2.13	29.7	75	2227 (+24%)
	Inefficient	2.33	22.8	69	1573 (-12%)
	High Production	2.49	28.7	64	1837 (+3%)
	Low Production	2.05	21.5	78	1677 (-6%)
	Average herd	2.25	25.2	71	1789
Farm 2	Efficient	1.95	21.0	82	1722 (13%)
	Inefficient	2.08	15.0	77	1155 (-24%)
	High Production	2.20	22.4	72	1613 (+1%)
	Low Production	1.87	16.1	86	1385 (-9%)
	Average herd	2.02	19.2	79	1517

[1]MF= milking frequency (events/d); [2]DY=Daily milk yield (kg/d)
[3]MHR=milk harvested per robot (kg milk/robot/day)

When comparing milking an ‘efficient’ herd against an ‘inefficient’ herd, on average on both farms production per AMS unit increased 18% with a relative increase of only 5 cows per robot. A herd of Efficient cows compared to a herd of High production cows (similar milk production per cow), increased production per AMS unit by 14% - primarily due to milking an additional 9 cows per robot.

Category & Parity

In Farm 1, the majority of cows in the Efficient group were in their 4th or 5th lactation (older cows) and most of the Inefficient cows were primiparous or cows in their second lactation

(Table 4). Conversely in Farm 2 almost half of the efficient lactations were from young cows (1 & 2 lactations). It is important to note that of the total lactations categorised more than 50% in both farms were from cows in their first or second lactations.

Table 4. Proportion of cows (%) in each category of each parity on each category.

		Lactation number		
	Category	1&2	3	4&5
Farm 1	Efficient	18	36	46
	Inefficient	42	32	26
	High Production	54	11	35
	Low Production	59	17	24
Farm 2	Efficient	48	18	34
	Inefficient	85	-	15
	High Production	55	9	36
	Low Production	59	7	34

DISCUSSION

The main objective of this study was to develop a methodology to identify Efficient and Inefficient cows through the analysis of whole lactation datasets from two commercial farms. This was achieved by comparing data from complete lactations of individual cows with the predicted means for each category of parity. Our results showed that on both farms, about 13% (range 10-16%) of the lactations analysed were identified as Efficient and about 12% (range 7-17%) as Inefficient.

In this study Efficiency was defined as a relationship between DY and MF; the former as it is the main output of the system and the latter because it represents a ‘cost’ for not only the cow (time and energy, both limited resources) but also the system (power, water consumption, etc.). The most efficient operation of an AMS will be an optimisation of milkings/cow/day to maximise the number of cows that can be milked whilst minimising any reduction in production per cow associated with lower MF. The question becomes; whether it is more effective to milk the existing cows more frequently or to milk additional cows through the system. This second option might be more suitable for pastured-based systems milking larger herds where cows have to walk large distances and the concept of relatively higher per-cow production with a reduced MF would likely be very appealing to farmers. The highest level of productivity would likely be achieved by combining a high ratio of cows/AMS unit with a herd comprised of predominantly Efficient cows.

The variability in cow performance (MF and DY) observed among cows in both datasets was key and enabled the categorisation of the cows based on their performance. These differences may be explained by multiple factors including cow factors (genetic merit, animal behaviour, milking characteristics, feeding efficiency, previous experience) and system factors (cow traffic, herd dynamics, waiting times, walking distances).

Although cows were categorised based on the average RRDY and RRMF for the whole lactation, data from table 2 showed that cows were in the same category in early and late lactation, indicating that a cow could remain efficient / inefficient for the whole lactation. This would suggest that efficient and inefficient cows could be identified in early lactation, which would in turn increase the potential application of these data to improve system performance. However, results of this study also indicate that a cow is unlikely to be 'efficient' for its lifetime as only a low proportion (8%) of cows (which had two or three lactations analysed) were categorised as efficient or inefficient across more than one lactation. This suggests that the factors creating 'efficiency' (high producing cows with relatively less milkings per day, as defined in this study) are generated mostly by management/environmental factors, but further investigation is required.

The strong positive relationship between MF and milk production is well known in conventional (Rémond *et al.*, 2004; Clark *et al.*, 2006) and pasture-based AMS (Lyons *et al.*, 2013a) and it might explain the performance of cows categorised as High and Low production cows. However, our results indicate that there are individual animals that depart from the above-mentioned relationship, suggesting high individual variability (and therefore room for improvement) associated with these factors.

Milking frequency was identified as a key factor that can be manipulated and that affects production efficiency and system utilisation in AMS (Lyons *et al.*, 2014). The aim for every AMS operation will be to develop criteria to optimise MF for cows and to maximise the capacity of the AMS (Koning & Ouweltjes, 2000). The optimum MF for an individual cow should be a result of its production potential and also should consider other factors such as cow welfare (Jacobs & Siegford, 2012).

In a review of MF management in pastured-based AMS, Lyons *et al.* (2014) summarised the key factors affecting MF and the complex interactions between them; including *animal related factors* such as: cow dominance, training and previous experience, cow behaviour; *farm management factors* such as: pasture allocation, supplementary feed and *environmental* *factors* such as climatic conditions. The interaction between all these factors results in a high variability in MF and DY within and between cows and throughout lactation and may provide some opportunity to identify those cows that better suit the system and those individuals that do not perform as expected.

In the same review Lyons *et al.* (2014) reported a reduction in MF of around 40% when comparing data from studies where cows that were managed in a pasture-based AMS (MF of 1.61 ± 0.12 milking events/cow per day, range 1.10-2.30 milking events/cow per day) with studies where cows were managed in indoor-based AMS and allowed to graze for less than 24h/d (MF of 2.64 ± 0.06 milking events/cow per day, range 2.40-2.85milking events/cow per day). This indicates that it may not be possible for cows in pasture-based system to achieve the optimum MF that would be required for them to reach their production potential, due mainly to characteristics associated with this type of system (long walking distances, climatic conditions, limitation in dry matter intake, among others).

In a study conducted in Ireland, Foley *et al.* (2015) reported that there was no reduction in milk production or cow voluntary traffic when MF was reduced in mid or late lactation in a pasture-based AMS. This strategy is only relevant to Split and All year round calving systems, as Seasonal calving systems are limited by the peak lactation period.

Targeting lower milking frequencies gives the AMS operator the possibility to milk more cows per milking unit and may also result in other benefits from the welfare point of view. High producing cows with a lower MF (as per Efficient cow definition) would travel reduced distances/day and might spend less time in yards with hard surfaces, reducing the risk of lameness.

In AMS, although milking interval is the inverse of MF, two cows with same MF will not necessarily have the same milking intervals (MI; example MF = 2, cow A might have MI 18 hours and 6 hours whilst cow B might have two intervals of 12 hours) and it has been reported in several studies that extreme MI's reduce daily milk production (Lyons *et al.*, 2013a; Schmidt, 1960) and increase the risk of mastitis (Hammer *et al.*, 2012). Lyons *et al.* (2013a) reported that milk accumulation rate was greatest at 16 hours and decreased on average 40% in extended MI (MI>16h) in a study in which there was a high prevalence (30%) of extended MI.

Not all cows are affected by milking intervals in the same way, there is an important variability in regards to milking characteristics. Andre *et al.* (2010) showed great variation with regards to the effect of milking interval length on milk yield and Tol *et al.* (2013) reported that some cows are able to handle a longer milking interval without a decrease in milk production. In a review about once-a-day milking production systems, Davis *et al.* (1999) indicated that yield loss presented great variability among and between individual cows. Holmes *et al.* (1992) reported a variable response in milk production losses when changing from twice to once-a-day milking, ranging from less than 10%, to over 50%. This individual variability might be partially explained by several physiological characteristics (cisternal milk storage capacity, ease of alveolar drainage, production of a concentrated milk) (Davis *et al.*, 1999). Such individual variation might be key to explain the difference in performance between Efficient and Inefficient cows.

Given that in pasture-based AMS operating with voluntary traffic cows can decide where to spend their time (within certain limits), it might be possible that some cows spend more time on pasture and grazing than others, potentially resulting in higher dry matter intake and therefore higher milk production. In addition, the variability among dairy cows in grazing behaviour (Phillips & Denne, 1988) and dry matter intake (Garcia et al., 2000) might be also affecting cow performance in grazing systems.

For decades, cow selection was made for twice-a-day milking production systems with relatively regular milking intervals, meaning that the cows currently being managed in AMS operations were not selected for AMS; there may be a significant opportunity to identify, select and breed cows more suitable to AMS conditions and select against those cows which are less suited to AMS. Farmers in New Zealand that have been breeding cows more suitable for once-a-day milking and culling those cows that were underperforming for more than 3 years, have achieved increases in milk yield/cow of about 21% compared to their first season (Holmes, 2011).

Cow dominance might be a factor affecting cow efficiency; Jago *et al.* (2003) showed that in pasture-based AMS social rank influences the frequency of milking. An efficient cow might be a high yielding cow that is located in the lowest part of the social rank with relatively less access to the milking unit and less motivation to traffic to the dairy due to the experience of long waiting times. In the same way an inefficient cow could be a dominant cow that has more direct/prompt access to the milking unit but who is not producing sufficient milk to put her into the high production category. Further research to elucidate this is needed.

Individual milking characteristics like milking speed and time spent in the robot per milking, were not analysed in this study but are both recognised as significant factors affecting milk harvesting efficiency in commercial AMS herds.

The individual milk production response to concentrate fed in the dairy is another important variable to include in a future wider analysis as it might have an impact on cow performance. Although it is recognised that the level of concentrate can directly affect milk production per cow, in this particular study all cows in each farm were fed to production levels following the same criterion, therefore it was expected that that the average response was similar. In relation to cows' traffic, regardless of the known positive effects of feeding concentrate on voluntary cow traffic in AMS (Prescott et al., 1998a; Lyons et al., 2013), recent studies (Shortall et al., 2017; Lessire et al., 2017) showed that there is no significant effect of the level of concentrate on MF on pasture-based AMS. Furthermore, Jago et al. (2007) also demonstrated that cows in a pasture-based AMS can be successfully milked with no concentrate reward in the milking unit.

The objective of the estimation and comparison shown in Table 3, denotes the potential increases in milk harvested per AMS. However, it is important to recognise that a more realistic approach on a commercial farm will likely be to firstly attempt to reduce the proportion of inefficient cows present in herd and at the same time increase the proportion of efficient cows. Another way of generating a significant impact would be by managing the different groups of cows in different ways, and not necessarily eliminating those individuals that are not being efficient.

With current knowledge and the data analysed in this study it could be speculated that efficient cows are more profitable and that they might be also in a better position regarding health and welfare. However there is a lack of both evidence and understanding around these cows and further research would need to be conducted in order to try to explain the causes.

A more complete understanding of the different levels of Efficiency is needed as many questions about these individual cows still remain. Developing an understanding of the causes of the differences will be an important next step which may help to determine the potential to lift inefficient cows into the efficient category. Data from this study suggest that the efficiency is not repeatable, which points towards management/environment and or behavioural factors playing an important role. Once an understanding of the key factors impacting on efficiency is developed the research should focus on how to implement distinct management practices on commercial farms that might impact on productivity by reducing the prevalence of inefficient cows in the herd.

CONCLUSION

This study developed a successful methodology to identify Efficient and Inefficient cows and quantified the differences in milk yield and MF between categories. Cows categorised as Efficient produced 9% more milk with 5% less milkings per day and Inefficient cows producing 10% less milk with a 6% higher MF. There is a potential opportunity to increase productivity by managing cows with different levels of efficiency in different ways, but further research is needed to improve our understanding of reasons behind the different level of efficiency discovered by this present research.

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OVERVIEW OF CHAPTERS 5 AND 6

Chapter 4 demonstrated that contrasting performance efficiencies at individual cow-level co-exist in AMS farms. However, whether these contrasting efficiencies originated from management, genetics or other factors is not known. Filling this gap in knowledge is key to successfully developing new management practices that could capture the benefit/s of contrasting individual animal efficiency. Therefore, a field study was designed (Chapter 6) to investigate the comparative efficiency and behaviour of contrasting (Efficient and Inefficient) animals and to increase our understanding of factors affecting the differences observed in Chapter 4. However, as differences in individual animal efficiency, as defined for pasture-based AMS, are likely to be related to foraging behaviour, animal sensors that can monitor cow activity and rumination behaviour remotely and accurately in grazing systems were needed. Such technologies have become commercially available in recent years. Yet, none had been properly and independently evaluated for accuracy of key components of grazing behaviour under the conditions of pasture-based systems in Australia. Thus, in Chapter 5, the validation of a recently commercially released version of an activity- and rumination-monitoring system was conducted, in order to have a validated methodology for comparing foraging behaviour of ‘efficient’ and ‘inefficient’ cows (Chapter 6).

CHAPTER 5: Evaluation of an activity and rumination monitor in dairy cattle grazing two types of forages

Animal Production Science, 57, 1557-156

ABSTRACT

The aim of the present study was to evaluate the accuracy of a newer version of an activity- and rumination- monitoring system by comparison against direct visual observations, for the following three different types of behaviour: grazing, resting (described as lying or standing idle) and ruminating for cows grazing either annual ryegrass or chicory-based swards (two pasture types commonly used in NSW dairy farms). Eight non-lactating Holstein–Friesian cows were fitted with the sensor tags, and grazed on annual ryegrass pasture for a target consumption of 10 kg DM ryegrass/cow.day for 7 days. The experiment was then repeated with cattle offered a similar allowance of chicory. Observations were conducted by two trained observers in two observation periods each day, to capture the above described behaviours. In each period, electronic behavioural measurements were recorded continuously by the sensors, while visual observations were also continuous (during observation periods), and the two datasets were matched. On average, each cow was visually observed for 87.2 min/day. For each behavioural state (at 1-min intervals, n = 6963), probability of agreement, sensitivity, specificity and positive predicted value were determined for grazing as 98%, 98.3%, 97.3% and 98.9% respectively, for resting as 80%, 77.5%, 99.1% and 92.9% and for ruminating as 87%, 86.9%, 98.4% and 90.68%. Concordance correlation coefficient (CCC) and Pearson correlation (r) were used to investigate the relationships between visual observations and data generated from the tags. Different behaviours were analysed separately. Significant correlations were found for the three behaviours (grazing: CCC = 0.99, r = 0.99; resting: CCC = 0.95, r = 0.97; ruminating: CCC = 0.80, r = 0.80), with no differences detected between the two forages. We conclude that, under the conditions of the present study, the activity- and rumination-monitoring system tag measured grazing, resting and ruminating behaviours with high accuracy on the basis of comparison to visual observations.

Keywords: behaviour, pasture, precision dairy, sensor.

INTRODUCTION

The predominant behavioural activities of dairy cows, such us ruminating, eating or lying, are widely used as indicators related to health, welfare and productivity. Therefore, the ability to measure, monitor and detect changes in the behaviour is the key to improving individual cow health and performance (Bikker et al. 2014). Health and performance are key parameters that have an impact on an individual cow's longevity in the herd, her contribution to the productivity of the operation, and can also be used as indicators of individual animal welfare to some degree. From an industry perspective, these parameters are important at both the cow and the herd level.

Generally, these behaviours can be assessed by visual observations, which is one of the most reliable methods if conducted properly. This could be undertaken either by direct live visual observations or through the analysis of video recordings. However, both methods have some limitations (i.e. are labour intensive, time consuming, require qualified personal, a limit in the amount of cows that can be monitored simultaneously, require expensive equipment that may also influence the behaviour of animals). In addition, visual observations are subjective and, when multiple observers are used, there is a potential disadvantage of inter-observer differences (Martin et al. 1993; Weary et al. 2009). Nevertheless, previous studies have reported that feeding, rumination and activity patterns such us lying, standing and walking, can be assessed accurately by direct visual observations (Rutter et al. 1997; Schirmann et al.2009; Burfeind et al. 2011; Bikker et al. 2014).

Recently, several sensor-based technologies have been developed to automatically monitor and record different types of behaviours for commercial and research applications. Feeding, rumination and activity have been previously monitored with devices such as silicone-tube nosebands recording electrical resistance (Rutter et al. 1997), mercury switches (Delagarde et al. 1999), microphones (Delagarde et al. 1999; Schirmann et al. 2009) and accelerometers (Elischer et al. 2013; Nielsen 2013; Bikker et al. 2014). However, most of these available systems are constrained by either the type or number of behaviours that can be measured or because they are less suitable for a practical use (Bikker et al. 2014), such as automated oestrus detection or early disease detection, creating a limitation in the value for researchers and even more so for commercial dairy operations. Many of these technologies have been already validated for feeding (Beauchemin et al. 1989; Rutter et al. 1997; Kononoff et al. 2002) and rumination (Schirmann et al. 2009; Bikker et al. 2014), resting (Bikker et al. 2014) and for oestrus detection (Walker et al.1996), with strong correlations reported between visual observations and the technology. However, the majority of these studies were conducted in indoor housed systems and results cannot be extrapolated directly to pasture-based systems (Schirmann et al. 2009; Burfeind et al. 2011), mainly due to the differences in cow behaviour and environmental conditions.

An updated new version of a rumination and activity collar- based sensor monitoring system (SCR HR-LDn, SCR Engineers, Netanya, Israel) was recently introduced to the Australian market. A significant change compared with previous models is that rumination is now calculated utilising data from the accelerometer and not from a microphone, as in previously validated versions (Schirmann et al. 2009; Ambriz-Vilchis et al. 2015). The monitoring system categorises the level of activity (low, medium, high) and is also capable of distinguishing between eating and ruminating behaviours.

Although the limits between different levels of activity are not fully clear, the manufacturer indicates that resting refers to a cow idling lying or standing, not ruminating, eating or drinking. Previous versions of the SCR activity monitor have been validated and are recognised as valuable tools for commercial and research application (Schirmann et al. 2009). The current version (SCR HR-LDn) is already used in commercial dairy farms, predominantly for oestrus detection and to generate health alerts by monitoring cow behaviour. There is an opportunity to use this sensor for the development and implementation of advanced management practices such as individualised supplementation of dairy cattle (Hills et al.2015) or to predict the day of calving for cows (Clark et al.2015). However, the activity-specific accuracy of this new version of the sensor has not been evaluated yet.

The objective of the study was to test the accuracy of a newer version of the SCR HR-LDn activity and rumination monitoring system by comparing the electronic data against independent data collected through direct visual observations, for the following three different types of behaviour: grazing, resting (described as idling lying or standing) and ruminating for cows grazing either annual ryegrass (*Lolium multiflorum L.*)- based or chicory (*Cichorium intybus L.*)-based swards. Previous studies have shown that the characteristics of the pasture canopy affect the grazing behaviour of the cow (Sollenberger and Burns 2001), and, therefore, there is a need to test the ability of the device to accurately indicate grazing behaviour in different types of pastures.

MATERIALS AND METHODS

The study was conducted at the University of Sydney Corstorphine dairy farm between 2 April and 15 April 2015. Ethics approval was granted by the Animal Ethics Committee of the University of Sydney (Project number 2014/569) before the commencement of the present research.

Cows and experimental design

Eight non-lactating multiparous Holstein–Friesian dairy cows were allocated to a paddock and managed as a single herd. Cows grazed on pasture for a target consumption of 10 kg DM/cow.day under a strip-grazing management strategy, with a new strip being made available each day at 0700 hours. Pre-grazing pasture biomass was measured every day (average 2500 kg DM/ha) utilising a pre-calibrated electronic plate meter (Electronic Plate Counter, Farmworks, Fielding, New Zealand) and the area of the strip to be grazed was calculated (average 30x20 m^2) to meet target intakes. For the first seven consecutive days, cows grazed an annual ryegrass (*Lolium multiflorum L.*) pasture, and for the following seven consecutive days, cows grazed a chicory (*Cichorium intybus L.*)-based sward. Data were collected during 5-day measurement periods for each forage type. For both periods (pastures), the first 2 days were considered as adaptation days to allow cows to become accustomed to the forage type, the change in forage and the presence of the observers in the field. Water was available for cows at all times in the paddock.

Activity and rumination monitoring

Seven days prior to the commencement of the study, cows were fitted with a neck-mounted electronic rumination- and activity- monitoring tag (SCR HR-LDn; SCR Engineers). Collars were removed two days after the completion of the study. The tag consisted of an accelerometer, a microprocessor unit, a memory unit and a transponder; all encapsulated in a plastic unit and attached to a collar. On the basis of the continuous data generated by the three-axis accelerometer, the microprocessor calculated activity and rumination (utilising specifically developed algorithms) and stored the data in the memory unit. Each tag used in the present study contained an SD memory card, from which the data were downloaded to a computer, utilising the manufacturer's support software (Data Flow software, SCR Engineers) and collated into 1-min intervals.

Visual observations

Direct visual observations were conducted by two independent observers, in two observation periods each day, for each of the 5- day monitoring periods. One period was conducted in the morning (commencing between 0700 hours and 0800 hours), immediately after the new strip of forage was offered, and a second observation period was conducted in the afternoon (commencing between 1400 hours and 1500 hours). Observers recorded the different behaviours using an electronic application on a laptop computer. Timestamps on observer's computer, electronic tags and the tag software were synchronised before the commencement of the study. The observers were trained before the commencement of the study, to ensure correct and consistent interpretation of cow behaviour, a high level of agreement between the observers and an understanding of the data-recording procedure. Observers stood in the paddock at a distance (~20 m) to minimise any disruption to cow behaviour and routine. Observers did not communicate during the observation period and were unable to see each other's data- recording device. Each observer was designated approximately half of the paddock and observed cows that were located in that area only. Cows were identified using a combination of numbers on ear tags, collars and numbers painted on both sides of the thorax and rump area in a luminescent colour. Visual observations were not based on a fixed amount of time per cow nor the total time spent by a cow on a particular activity within that time, as it was not possible for the two observers to capture all the different behaviours of all cows at all times. Rather, cows were observed for periods of variable duration with the aim of collecting ~1.5 h/day of net total time of captured (observed) behaviour for each cow. On average, each cow was observed for 87.2 min/day. During each period, the time the observed cow spent performing any of the three behaviours (grazing, resting or ruminating) was recorded continuously. Grazing was defined as the behaviour when the cow was actively searching or removing pasture from the canopy, which could also include chewing and manipulation of feed bolus (Phillips 2002). A cow was considered to be resting if lying or standing, not ruminating, eating or drinking with eyes open or closed. Ruminating was defined as the period of time when the cow was actively chewing a regurgitated bolus until swallowed either standing or lying (Ambriz-Vilchis et al. 2015). The start and finish time of each behavioural event was recorded to then match exactly (on 1-min intervals) the activities recorded by visual observation with the activity 'detected' by the sensor. In total, 6963 1-min intervals of visual observations of behaviour were collected.

Statistical analysis

Data from the direct visual observations were collated into 1-min intervals on the basis of the predominant behaviour of the cow during the observed 1-min period, so as to compare with the data generated by the monitoring tags. Data from the direct visual observations and data from the tags were then merged into one file, transitional minutes (minutes when cows demonstrated more than one behaviour) were removed, and accuracy was investigated at the following two levels: at each 1-min interval and at a session level (total time each cow spent performing each behaviour in each of the two observation periods). All analyses were conducted in GENSTAT statistical package (16th edn; VSN International, Hemel Hempstead, UK).

Analysis at 1-min intervals

First, so as to determine the level of agreement between observations and data generated by the tags at 1-min intervals, data were analysed as a binary variable using a generalised linear mixed model (GLMM) with a binomial distribution and a logit- link function. Type of forage and behavioural state were included as fixed effects and cow ID was fitted as a random term. The model was as follows:

y = constant + behavioural state + type of forage + cow ID;

where y expresses the agreement (1 = agreement or 0 = no agreement), behavioural state = observed behavioural state (grazing, resting, ruminating), forage = grazed forage (annual ryegrass or chicory), cow ID = effect of cow.

Second, to measure performance of the tags at 1-min intervals, sensitivity (defined as the ability of the tag to correctly identify the true behaviour), specificity (defined as the ability of the tag to not report a false behaviour) and positive predictive value (defined as the proportion of true behaviours identified by the tag in relation to the total true behaviours observed) were estimated for each behavioural state by combining true and false recordings (Table 1).

Table 1. Criteria for evaluation of the system performance

Criteria	Formula[1]
Sensitivity	(TP/(TP+FN)) x 100
Specificity	(TN/(TN+FP)) x 100
Positive predictive value	(TP/(TP+FP)) x 100

[1]TP= true positive; FN= false negative;
FP = false positive, TN = true negative.

For example, for grazing behaviour: true positives (TP) equalled the number of observed grazing behaviours detected by the tags as grazing behaviour; false positives (FP) equalled the number of non-grazing behaviours (i.e. either ruminating or resting) reported by the system as grazing behaviour; false negatives (FN) equalled the number of grazing behaviours classified by the tag as being non-grazing behaviour (i.e. ruminating or resting), and true negatives (TN) equalled the number of non-grazing behaviours (i.e. ruminating or resting) detected by the tag as non-grazing behaviour.

Analysis at a session level

A Pearson correlation analysis and concordance correlation coefficient (CCC) analysis (Lin 1989) were performed to evaluate the relationship between the data recorded via direct visual observations and data generated by the tags, for each of the behavioural states ($P < 0.05$ was considered significant). Bias correction factor and confidence intervals were also calculated.

Outlier removal

Two rumination data points (i.e. 'sessions') for the same cow were reported by the electronic data to have zero rumination when the visual observers recorded rumination for 23 and 43 min. The cause of this discrepancy is unknown and may be indicative of a faulty or inaccurate tag. However, the same tag recorded six rumination periods that accurately reflected the visual observations and, in relation to the total number of sessions, the two data points represent only 7% of the average number of observation sessions per cow, or 0.9% of the total number of sessions.

RESULTS

Analysis at 1-min intervals

The probability of agreement between visual observations and tags for each behavioural state were 98%, 80% and 87% for grazing, resting and rumination respectively. The model also provided the probability of agreement on observations conducted on each type of forage, being 90% for annual ryegrass and 94% for chicory.

Sensitivity, specificity and positive predicted value were determined for each behavioural state at 1-min intervals, and these were 98%, 97% and 99% respectively, for grazing, 77%, 99% and 93% for resting and 87%, 98% and 91% for ruminating.

Analysis at a session level

A total of 201 sessions (2.6 sessions per cow per day on average) were included in the analysis. Strong and significant correlations were observed between direct visual observations and tags in all three behaviours analysed (Table 2, Fig. 1). The strongest correlations were generated for grazing and resting behaviours. Although the correlation for ruminating was somewhat lower than for the other behaviours, it was still significant at the $P = 0.05$ level.

Table 2. Pearson correlation coefficient (r), bias correction factor (Cb), concordance correlation coefficient (CCC) and confidence intervals (CI) values between direct visual (Actual time) observations and electronic tag recorded time (Tag time).

	r	C_b	CCC	CI (95%)	Actual time Mean ± SD (min)	Tag time Mean ± SD (min)
Grazing	0.99	0.99	0.99	(0.99-0.99)	49 ± 20	49 ±20
Resting	0.97	0.98	0.95	(0.92-0.97)	18 ± 18	14± 17
Ruminating	0.80	0.99	0.80	(0.66-0.87)	20± 12	18± 11

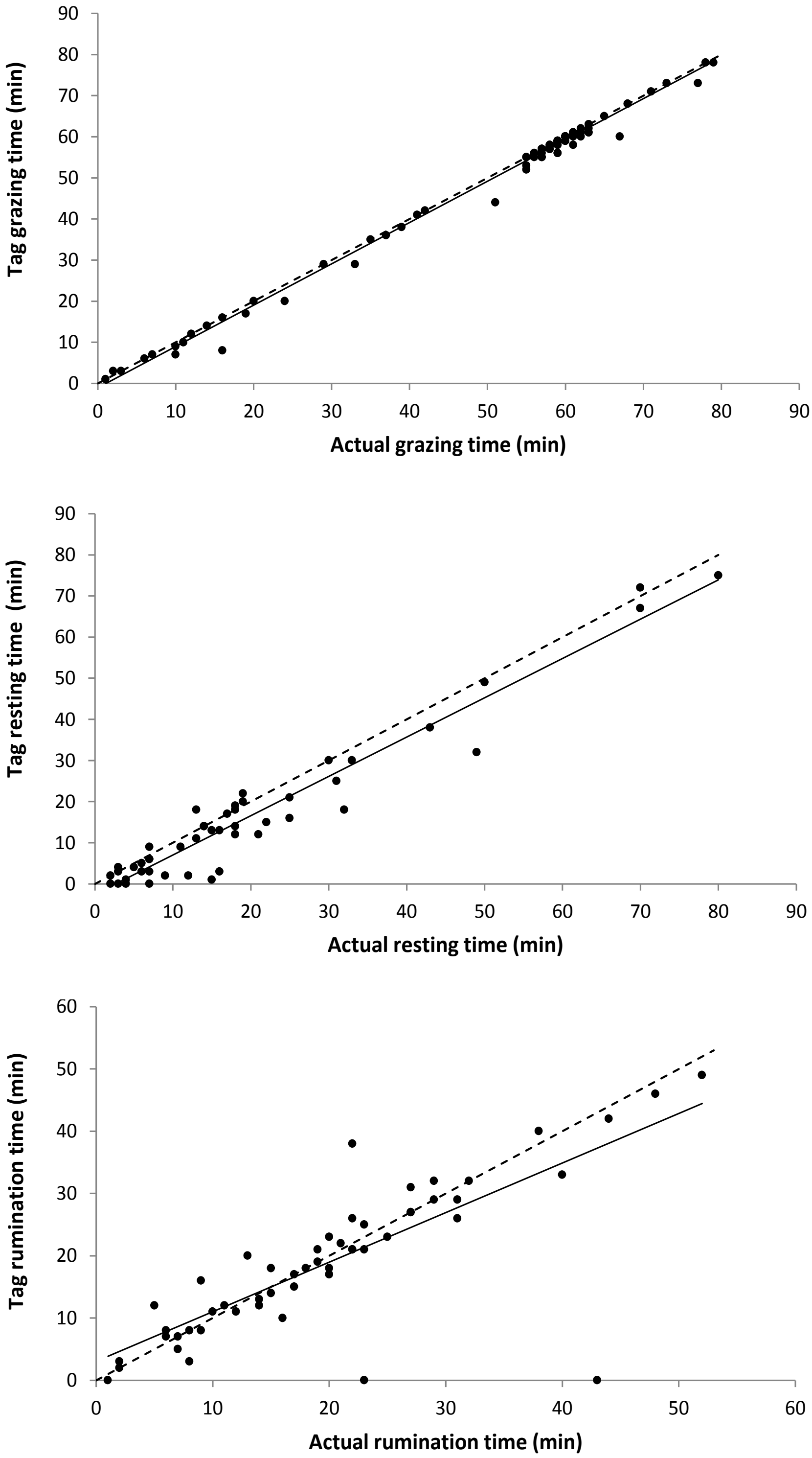

Figure 1. Relationship between total time (min/session) measured by observers and time measured by the tag for grazing (top), resting (mid) and rumination (bottom). Each point represents the amount of time a particular cow was involved in a measured behavioural activity, as observed by the observer (X axis) and the tags (Y axis). The broken line represents the line of equality and the solid line the equation line.

DISCUSSION

Accurate measurement of different cow behaviour patterns, such as eating, lying and ruminating, are now recognised as key indicators in the assessment of health status, cow comfort and cow performance (Mattachini et al. 2013; Bikker et al. 2014) of cattle at a farm level. Having a device capable of measuring, recording and reporting changes in multiple behaviours will aid producers in the effective, timely and individualised management of cows. However, it is recognised that the greatest value (on farm) will be realised if interpretive software generates accurate and reliable alerts. The majority of technologies evaluated for cattle have the capability to monitor only one behaviour at a time. Only one study (Bikker et al. 2014) evaluated a technology capable of measuring multiple behaviours and concluded that the device was accurate when measuring rumination and resting behaviour, and presented slightly lower accuracy levels for eating behaviour (Pearson correlation coefficients of 0.93, 0.98 and 0.88 respectively). However, that study was conducted with freestall-housed dairy cattle and the SCR HR-LDn has not been evaluated under grazing conditions.

To our knowledge, the present study is the first to evaluate the SCR HR-LDn tag or any similar technology (that measures grazing, resting and ruminating time) for grazing cattle. This technology accurately quantified grazing, resting and rumination times under the conditions of the study. Strong correlations between device-generated data and visual observations were established (probabilities of agreement, Pearson correlations and CCC all being greater than 0.8).

Grazing

The SCR HR-LDn recorded grazing behaviour with a high level of accuracy, at 1-min level intervals. The probabilities of agreement between direct visual observations and data recoded by the tag were high for both forage types, despite the anecdotal difference in sward height, plant architecture and grazing behaviour (cows grazing chicory displayed more active and selective grazing behaviour) between the two species. An accurate and practical way of measuring daily grazing patterns and total grazing times at both an individual and herd level could lead to an improved understanding of the nutrition of herds in pasture-based systems, some indication of DM intake and improved efficiency for management of pastures. While it is recognised that several technologies have been developed to measure grazing behaviour, the majority of them are either expensive, labour intensive (Nielsen 2013), not practical for commercial use, and/or specific for that function only. As an example, Delagarde and Lamberton (2015) validated the Lifecorder Plus (LCP, Suzuken Co., Nagoya, Japan), a device that measured grazing time with high accuracy, but was limited in that it was not able to detect other behaviours (based on a mono-axial accelerometer), which limited the scope of the data generated by the device and, therefore, the potential value in a commercial farm application. Such a device can likely be coupled with other devices, such as, for example, a pedometer (assuming there is no interference) on individual cows for research purposes, to generate additional data.

Resting

In a previous study, Elischer et al. (2013) evaluated a three- axial accelerometer device (Qwes-HR, Lely) and found only moderate correlations for standing-idle and lying behaviours (Pearson correlation r = 0.46 and r = –0.57 respectively) in a study were cows had access to pasture 24 h a day. To the best of our knowledge, only one study (Bikker et al. 2014) has reported a validation for 'resting' behaviour with high levels of accuracy (r = 0.98, CCC = 0.97); however, that study was conducted with cows housed indoors (using a three-dimensional accelerometer attached to the ear identification tag). Our results, in accordance to Bikker et al. (2014), reported high levels of accuracy when measuring 'resting' under grazing conditions. Postural behaviours, such as lying, are now recognised as valuable indicators of cattle comfort and welfare (Elischer et al. 2013). The present study is the first study that has reported high levels of accuracy for an electronic-sensor measuring 'resting' behaviour under grazing conditions.

Rumination

The majority of rumination-monitoring devices previously tested have been based on activity meters with incorporated microphones. Unfortunately, these have been somewhat prone to other audible disturbance. Ambriz-Vilchis et al. (2015) reported a poor performance when tested with grazing cattle, potentially due to the background noises typical of outdoor environments and by noises caused by activities such as self-grooming and/or drinking. In contrast, high levels of accuracy have been reported with accelerometer technology for the indication of rumination when tested on cows housed indoors (Borchers et al. 2016). In the present study, the accelerometer technology was shown to give accurate indications of rumination activity (in accordance with Borchers et al. 2016) when cows were grazing outdoors. This suggests that the limitations of the microphone technology can be addressed by converting to accelerator-based devices for cows grazing forages.

The device evaluated in the present study can monitor multiple behaviours with high levels of accuracy under grazing conditions, giving confidence that it could be a valuable tool for use in both research and commercial settings. While Bikker et al. (2014) successfully validated a similar device (measuring multiple behaviours) for indoor cows, the present study is the first successful evaluation (with high levels of accuracy) of such a device in outdoor grazing settings. Combining data provided by the sensor evaluated in the present study, together with additional automated data, such as individual cow milk production, milk quality and bodyweight or body condition score, creates the opportunity to understand, monitor and manage individual cows with low labour inputs (Elischer et al. 2013).This is even more crucial in large herds under extensive pasture-based conditions where it is difficult to visually observe individual animals. The combination of data from multiple devices may allow for the generation of computer-guided management strategies, whereby setting parameters such as feed allowances, milking permission, breeding and lactation windows could be automatically adjusted (on the basis of user-defined limits) to improve productivity of the whole farm system.

CONCLUSIONS

The present study is the first study that has evaluated the SCR HR-LDn tag, which operates without a microphone and with all measures conducted by an accelerometer. In the present study, in relation to the net time that individual cows were observed on a particular activity, the SCR HR-LDn tag quantified time spent grazing, resting and ruminating with high to very high level of accuracy in dairy cows grazing two different forage swards. Further work should focus on the use of the data to generate meaningful management guidelines, so as to ensure that real value (of the technology) can be captured on commercial farms.

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OVERVIEW OF CHAPTER 6

As described in the Overview of Chapters 5 and 6 (page 82), increasing our understanding of factors affecting efficiency or determining why some individual animals are more ‘efficient’ (as defined for pasture-based AMS) than others, was considered imperative for developing (outside the scope of this thesis) new tools to tailor management strategies to the proportion of cows in a herd that are categorised in each efficiency class. Chapter 6 therefore summarises the results of a field study aimed at understanding behavioural aspects of the individual cows (Efficient and Inefficient).

CHAPTER 6: Performance and behaviour of Efficient and Inefficient cows in a pastured-based automatic milking system

ABSTRACT

In automatic milking systems (AMS) operating with voluntary traffic, dairy cows have some freedom to 'set' (within management and operator set software limits) their own milking frequency across each 24-h period. As a consequence a wide range of milking intervals and milking frequencies are typically observed within and between cows and throughout lactation in pasture-based AMS, resulting in different levels of efficiency. A field study was conducted to compare performance and behaviour of Efficient (EFF) and Inefficient (INEF) cows in a pastured-based automatic milking system. It was hypothesised that Efficient cows would spend more time in the paddock grazing pasture which might result in higher levels of rumination and higher milk production than Inefficient cows in the same herd. Twenty-eight Holstein-Friesian cows were selected and classified based on the level of efficiency (as defined for pasture-based AMS) regarding cow performance using the methodology developed in Chapter 4 (17 cows were identified as Efficient and 11 cows as Inefficient). Behaviour and performance were recorded for 7 consecutive days. Efficient cows produced more (P < 0.001) milk (EFF = 30.25 kg milk/day versus INEF = 21.63 kg milk/day), with similar (P > 0.05) milking frequency (1.9 milkings/day) to their Inefficient counterparts. Efficient cows spent 40 min more per day grazing (P = 0.04), 42 min more per day ruminating (P < 0.001) and 55 min less resting (P = 0.004) in comparison to Inefficient cows. There was no significant difference between Efficient and Inefficient cows for time spent in laneways, time spent in dairy and time spent in paddocks. It was concluded that the difference in cow performance might be partially explained by cow behaviour, as Efficient cows were recorded to have longer grazing and rumination times and shorter resting times. Further research should be conducted to elucidate the proportion of increased daily milk yield/greater efficiency that could not be explained by changes in grazing and feeding behaviour.

INTRODUCTION

In automatic milking systems (AMS) operating with voluntary traffic, dairy cows have some freedom to 'set' (within management and operator set software limits) their own milking frequency across each 24-h period. This is in contrast with conventional milking systems (CMS) where cows are milked in defined sessions with milking frequency determined by the herd manager.

Several factors related to pasture-based AMS, such as proportion of pasture in the diet, pasture allowance and distance between pasture and dairy facility have an effect on voluntary traffic (Lyons et al., 2013a). As a consequence, a wide range of milking intervals and milking frequencies are typically observed within and between cows and throughout lactation in pasture-based AMS. In addition, there is a significant impact of social synchronisation regarding individual cow behaviours such as, lying and feeding (Ketelaar-De Lauwere et al., 1996, Uetake et al., 1997). This might result in a greater individual cow variability regarding cow behaviour, cow performance and how cows distribute time spent in different areas of the farm in comparison to CMS. Typically, in pasture-base systems cows spend the majority of their time on pasture as they attempt to meet their daily energy requirements by foraging which is known to be a time-consuming activity. Grazing typically occurs in bouts which are alternated with periods of ruminating and idling (Gibb et al., 1997).

In a study where 30 cows were monitored over a 16-week period, Melin et al. (2005) suggested that each individual cow develops a unique feeding and drinking pattern and that the pattern is relatively consistent over time. Previous studies showed a positive relationship between dry matter intake (DMI) and milk production (Garcia et al., 2000, Hristov et al., 2004) and also between rumination time and milk yield (Soriani et al., 2013, Kaufman et al., 2018). Given that voluntary traffic allows cows to decide where to spend their time, it might be possible that in pasture-based AMS some cows spend considerable more time on pasture and grazing than others, potentially resulting in greater intake of pasture and consequently, greater milk production.

In Chapter 4, whole lactation datasets from two commercial AMS farms were used to assess the magnitude of the variability in cow performance (milking frequency and milk yield) and to successfully develop a methodology to classify cows with different levels of 'efficiency'. According to this specific definition of efficiency, 'Efficient' cows (which produced more milk from relatively less milkings in relation to their expected values); and 'Inefficient' cows (which produced less milk from relatively more milkings in relation to their expected values), were identified. The findings in Chapter 4 showed relatively little repeatability between lactations for the efficiency categorisation, which suggests that genetics was probably not a key factor determining the categorisation. Since factors such as stage of lactation and parity were adjusted for in the methodology developed in Chapter 4, it is likely that differences in cow behaviour could explain, at least in part, the differences observed between levels of efficiency in cow performance.

Therefore, the aim of this experimental study was to investigate the behaviour and performance of two groups of cows with different levels of efficiency in a pasture-based automatic milking system. It was hypothesised that Efficient cows would spend more time in the paddock grazing pasture which might result in higher levels of rumination and higher milk production than Inefficient cows in the same herd. The development of a more complete understanding of the different levels of efficiency between cows may allow AMS farmers to implement distinct management practices with the objective of reducing the prevalence of inefficient cows in the herd, and therefore increase whole herd/system efficiency.

MATERIALS AND METHODS

General farm management

The study was conducted at the University of Sydney Corstorphine dairy farm in Camden, New South Wales, Australia, between 1 October and 17 October 2016. Ethics approval was granted by the Animal Ethics Committee of the University of Sydney (Project number 2014/569). The milking herd consisted of 298 Holstein Frisians cows (31% first-lactation cows, 26% second-lactation cows and 42% more than two lactations; herd average 2.5 ± 0.3). At the commencement of the study, the seven-day average (mean ± SD) daily milking frequency was 2.03 ± 0.3 milkings/cow/day and the seven-day average daily milk yield was 26.66 ± 5.95 kg milk/cow/day and the average days in milk (DIM) of the milking herd was 141 ± 23 days.

Cows were milked in a 24-bail internal herringbone robotic rotary (RR; Automatic Milking Rotary - AMR^{TM}, DeLaval International AB, Tumba, Sweden) and were managed with a '3-way grazing system' (3WG; (Lyons et al., 2013b)). Cows were allowed to voluntary traffic from pasture to the milk harvesting facility to be milked at any time during the day and night, through 6 automatic drafting gates (DeLaval Smart Selection Gate, Tumba, Sweden) located within the dairy. All cows were fitted with an electronic identification transponder attached to a collar, to allow them to traffic through the automatic drafting gates to access different areas. This transponder also generated an electronic record of all trafficking events, which were captured in the support software. Using these individual trafficking records, the amount of time each cow spent in each area of the dairy and in each of the grazing areas was calculated. Cows exiting the dairy after being milked or when denied milking permission, had access to one of the 3 daily pasture allocations, depending on the time of the day (Table 1). Cows were granted milking permission based on a minimum milking interval of 4 hours or an expected yield greater than 6 kg/milking (as calculated by the management software, DelPro, DeLaval, Tumba, Sweden). Incomplete milkings (milkings in which the harvested milk yield was less than 50% of the expected yield) were automatically drafted back to the AMR for a second attempt at milking. Cows that had not returned to the dairy from the pasture allocation were fetched by the operator to minimise milking intervals extending beyond 24 h, by ensuring that the maximum time any cow could spend in a given pasture allocation did not exceed 21 hours (Table 1). The furthest paddock was 1.6 km from the dairy and the closest was 0.7 km.

Table 1. Pasture allocations, time each allocation was open to cows, fetching times and targeted DM/cow allocation per paddock.

Allocation	Available	Fetching time	Total hours of access	Kg of DM/cow
A	10:00-17:00	06:30	20.5	5
B	17:00-23:00	10:00	17.0	5
C	23:00-10:00	17:30	20.5	5

Average daily dry matter intake targets (DMI) were 23 kg DM/cow, and feed was offered as a combination of grazable pasture (targeting 15 kg DM/cow/day across three allocations) and grain based concentrate (GBC). Pastures were comprised of annual ryegrass (*Lolium multiflorum*), white clover (*Trifolium repens*) and oats (*Avena sativa*). Cows had access to GBC feed after milking in 14 automated out-of-parlour feeders (FSC400, DeLaval International AB, Tumba, Sweden) located in an adjacent area. Individualised GBC allocation was calculated automatically based on days in milk (DMI). At the commencement of the study cows averaged 5.95 ± 2.3 kg DM/cow/day of GBC.

All cows were fitted with a neck-mounted electronic rumination-and activity monitoring device (SCR HR-LDn, SCR Engineers, Netanya, Israel). The tag consisted of an accelerometer, a microprocessor unit, a memory unit and a transponder; all encapsulated in a plastic casing which was attached to a collar. On the basis of the continuous data generated by a three-axis accelerometer, the microprocessor calculated activity and rumination (utilising specifically developed algorithms) and stored the data in the memory unit to then automatically transfer the data to a computer located in the dairy. The tag continuously recorded time cows spend ruminating, grazing and resting within 24 hours in 2h intervals. The SCR HR-LDn tag was validated by Molfino et al. (2017) (Chapter 5) for grazing, resting and ruminating behaviours with a high level of accuracy in pasture-based systems.

Treatment and experimental design

The study was conducted over a 7-day data collection period. One week prior to the commencement of the experimental period, raw electronic data from the previous 8 weeks was extracted from the herd management software. That data included cow number, parity, days in milk, daily milk yield (DY; defined as accumulated milk production of all individual milking events within each given 24-hour period, kg milk/cow/day) and daily milking frequency (MF; defined as sum of all individual milking events per cow within each given 24-hour period) for all cows of the milking herd.

Following the methodology developed in Chapter 4, all cows managed in the main milking herd (n=289) were classified based on their relative residuals for DY (kg milk/cow/day) and MF (milkings/cow/day). Relative residuals (RR) estimate how much a cow produced (for DY), or how many times per 24 h she got milked (for MF) in relation to her fitted or expected value after accounting for the effects of stage of lactation and parity number. Cows presenting a positive residual for DY and a negative residual for MF were categorised as Efficient (EFF); cows presenting a negative residual for DY and a positive residual for MF as Inefficient (INEF). See Chapter 4 for more details.

It is important to note that in Chapter 4 cows were classified based on the *whole lactation performance* and for this study they were classified based on an *8 week period* of data leading up to the trial period. In Chapter 4 it was shown that cows that were classified as Efficient or Inefficient on the whole lactation, were also in the same category in early and late lactation, giving us the confidence that selecting cows based on a fragment of the lactation in this study was a viable option.

Three days before the commencement of the experimental period, selected cows were fitted with commercially produced CatLog^{TM} GPS units (17 x 25 x 5 mm) (Catnip Technologies Ltd, US), which were encased in a waterproof plastic box, and secured with polystyrene foam together with a battery pack (17 x 20 x 49 mm). The plastic box was mounted on a collar on the upper left side of the neck of each cow, to ensure the GPS unit antenna was unobstructed from satellite signals. GPS units were programmed to record the position of the cow every 3 min using CatlLog™ software. Collars were removed one day after the completion of the experiment.

Data analysis

Cow performance and cow traffic data

All individual cow traffic events and milking events during the experimental period were recorded electronically and then manually downloaded from the herd management software (DelPro, DeLaval, Tumba, Sweden). Data included daily milk yield (DY; kg milk/cow/day), milk yield per milking (MY; kg milk/cow/milking), milking interval (MI; hours, defined as total time between two consecutive milking events), milking duration (MD; min/cow; from the beginning of milk flow until the end of milk flow); incomplete milkings (INC; %, defined as the proportion of milking events whereby one or more individual quarters were either not milked or yielded less than 50% of the calculated expected yield); and daily milking frequency (MF; milkings/cow/day). In addition, concentrate consumption (CC; total amount of GBC consumed; kg DM/cow/day) and percentage of concentrate consumed (%CC; %, defined as the proportion of allocated concentrate that was actually consumed/cow/day) were also included.

Waiting area time (WT) was calculated as the total time the cow spent in the pre-milking waiting yard before a milking event. Return time (RT) was calculated as the total time cows spent outside the dairy between milkings, and was calculated as the time between the cow exiting the dairy after a milking event and the subsequent entry to the pre-milking waiting yard. Feeding area time (FT) was calculated as the total time the cows spent in the post-milking yard in the vicinity of the out-of-parlour feeders.

Cow behaviour data

Daily ruminating, grazing and resting time data were collected from the computer utilising the manufacturer's support software (Data Flow software, SCR Engineers) and summarised for each cow by 2-h interval, and day.

Data from GPS units were downloaded using CatlLog™ software and exported into ArcGIS 10.3.1. software for further analysis. Positional fixes (location of the cow) that were located outside the predefined areas (paddock, laneways and dairy), which included a 30 m buffer to account for potential location errors, were removed (17 % of data points). Location information was utilised to calculate the total time spent in paddocks, laneways and the dairy (for each cow each day).

Statistical analysis

Outcome variables analysed statistically included five related to cow performance (DY, MY, MD, INC, CC and %CC); five related to cow traffic (MI, MF, WT, RT and FT); and six related to cow behaviour (time spent in paddocks, time spent in laneways and time spent in dairy and time spent ruminating, grazing and resting (h/day)).

All variables were analysed using multivariable linear mixed models with parameter estimates calculated using residual maximum likelihood (REML). All analyses were conducted using Genstat 16th Edition (VSN International Ltd). Residual analyses were performed to ensure that the assumptions of normality were met. Data from two variables (WT and FT) required log-transformation prior to analysis. Predicted means, effects and standard errors generated form the fitted model were back-transformed.

All models included the explanatory effects of t*reatment* (EFF and INEF), *stage of lactation* (SOL, as early = ≤ 100 DIM; mid = 101 - 200 DIM and late = ≥ 201 DIM), *parity* (as lactation number 1=1, lactation number 2=2, lactation number 3=3, lactation number 4=4, lactation number ≥5 = 5). *Cow ID* and *Trial day* were included as random effects in all models. Model for RT included additional effects of *Area* (the grazing area the cow visited before returning to the dairy, as ‘Area A’, ‘Area B’ or ‘Area C’). Model for MY also included CC as a fixed effect and *Fetched* (whether the cow was fetched from pasture to the yard, as ‘yes’ or ‘no’). The interactions between effects were tested, and removed if not significant. Significance was determined if $P < 0.05$. Least significant differences were used to determine significant differences between predicted means.

RESULTS

Cow selection

After classifying the whole herd, a total of 28 cows were selected; 17 cows were identified as EFF and 11 cows as INEF. Means from the 8 week pre-trial period are shown in Table 2. During this 8 week period cows categorised as EFF produced 28% more milk with 4% less milkings per day and INEF cows produced 8% less milk with 5% more milkings per day in relation to their expected values (predicted means). It is important to note that cows were classified based on the relative residuals for DY and MF (as per methodology developed in

Chapter 4). The relative residual estimates how much a cow produced (for DY), or how many times per 24 h she was milked (for MF) in relation to her fitted or expected value after accounting for the effects of stage of lactation and parity number by the model. In both groups, the majority of the cows were in mid and late lactation (Table 2). In regards to parity, 18% of the cows in EFF (n=3) and the INEF cows (n=2) were primiparous and 82% were multiparous.

Table 2. Cow performance measures (daily milk yield, milking frequency, relative residual for daily milk yield (RRDY) and milking frequency (RRMF) from the 8-week pre-experimental period for selected Efficient and Inefficient cows milked in a pasture-based automatic milking system.

	Efficient	Inefficient
Number of cows	17	11
Daily milk yield (kg milk/day)	30.3	20.63
Milking frequency (milkings/day)	1.9	1.9
RRDY (%)	28	-8
RRMF (%)	-4	5
Parity (mean, range)	3.3 (1-8)	3.5 (1-6)
Days in milk (mean, range)	166 (86-254)	178 (90-265)
Stage of Lactation (n)		
Early (≤ 100 DIM)	1	1
Mid (101 – 200 DIM)	6	5
Late (≥ 201 DIM)	10	5

Cow performance

There was a significant effect of *SOL* ($P < 0.001$), *Parity* ($P < 0.001$), *CC* ($P < 0.001$) and t*reatment* (P<0.001) on daily milk yield, although there was no interaction between effects. During the experimental period EFF cows produced 39% more milk in comparison to INEF cows and had greater (P = <0.01) milk yield per milking (Table 3). *Parity* had an effect on MY ($P = 0.024$) and *stage of lactation* had a significant effect ($P = 0.002$) on CC. In all models there was no interaction between *SOL*, *Parity* and t*reatment*. There was no difference ($P > 0.05$) between EFF and INEF cows with regard to MD, CC and % CC.

Table 3. Predicted means for daily milk yield, milk yield, milking duration, percentage of concentrate consumption, concentrate consumption and incomplete milkings for Efficient and Inefficient cows milked in a pasture-based automatic milking system.

	Treatment			
	Efficient	Inefficient	SED[1]	*P* -value
Daily Milk yield (kg milk/cow/day)	30.25[a]	21.63[b]	1.41	<0.001
Milk yield (kg milk/cow/milking)	18.71[a]	12.65[b]	1.96	0.002
Milking duration (mm:ss/cow)	07:08	07:11	1:03	0.921
% Concentrate consumption (%)	69.26	75.73	3.77	0.103
Concentrate consumption (kgDM/day)	7.03	6.94	0.35	0.683
Incomplete milkings (%)	6	4	0.02	0.598

[1] Average standard error of the difference
[a-b] Different lowercase superscripts within row indicate significant differences ($P < 0.05$)

Cow traffic

Return time was affect by *Area* ($P < 0.001$) and *Fetched* ($P < 0.001$), although no significant difference was observed between t*reatments* (Table 4) and there was no interaction between effects. Cows returning from 'Area A' had a shorter average RT than cows returning from 'Area B' and 'Area C' (10:42 ± 0:04 hh:mm, 13:14 ± 0:15hh:mm, 11:13 ± 0:08 hh:mm, respectively). Cows that had been fetched presented a significantly higher RT than cows not fetched (14:56 ± 0:05 hh:mm and 10:48 ± 0:15 hh:mm, respectively) although there was no interaction with *treatments* ($P > 0.05$). Exploratory descriptive statistics showed that EFF and INEF cows were fetched 36% and 38% of their recorded milking events, respectively.

Treatments, *stage of lactation* and *parity* did not affect any of the analysed cow traffic variables ($P > 0.05$). There was no significant difference between EFF and INEF cow for FT, WT and MF. Figure 1 shows frequency distribution of MI for each *treatment*.

Table 4. Predicted means for return time, feeding area time, waiting area time, milking frequency and milking interval for Efficient and Inefficient cows milked in a pasture-based automatic milking system.

	Treatment			
	Efficient	Inefficient	SED[1]	*P* -value
Return time (hh:mm)	11:49	11:37	0:09	0.830
Feeding area time/visit (hh:mm)[2]	00:23	00:24	0.15	0.749
Waiting area time/visit (hh:mm)[2]	01:05	01:20	0.04	0.697
Milking frequency (milkings/day)	1.80	1.84	0.1	0.887
Milking interval (hh:mm)	13:24	13:06	0:15	0.762

[1] Average standard error of the difference
[2] Feeding area time and Waiting area time were retransformed from LOG

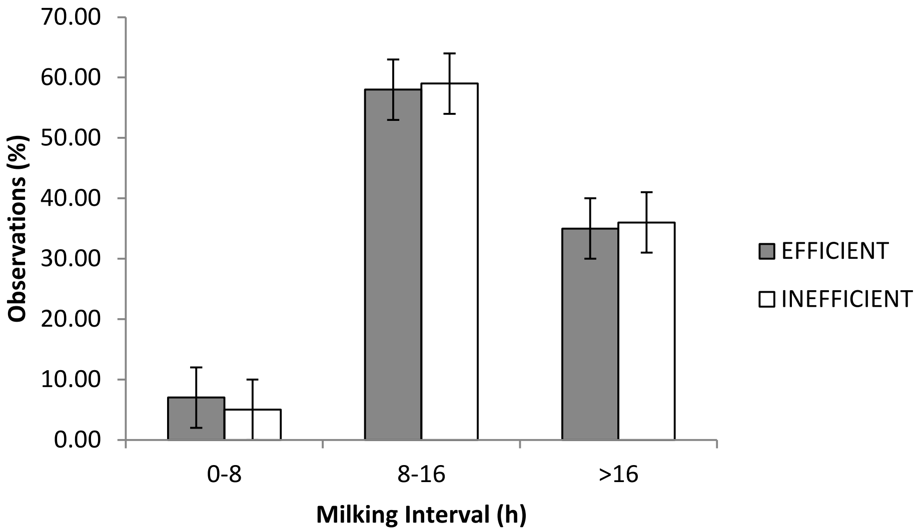

Figure 1. Frequency distribution of milking intervals for Efficient and Inefficient cows milked in a pasture-based automatic milking system. Vertical bars indicate SEM (standard error of the mean).

Cow behaviour

Efficient cows spent 40 min more per day grazing (P = 0.04), 42 min more per day ruminating (P < 0.001) and 55 min less resting (P = 0.004) in comparison to INEF cows (Table 5). There was no significant difference (P > 0.05) between EFF and INEF cows for time spent in laneways, time spent in dairy and time spent in paddocks. Only RT was affected (P < 0.01) by *parity*, but there was no effect of *SOL* and there was no interaction between effects in in any of the models (P > 0.05). Rumination and grazing diurnal patterns (Figure 2) are presented in Figure 2.

Table 5. Predicted means for grazing time, ruminating time, resting time, time spent in paddocks, time spent in laneways and time spent in the dairy for Efficient and Inefficient cows milked in a pasture-based automatic milking system.

	Treatment			
	Efficient	Inefficient	SED[1]	P -value
Grazing time (min/day)	467.2[a]	427.2[b]	19.34	0.04
Ruminating time (min/day)	490.6[a]	448.5[b]	14.24	<0.001
Resting time (min/day)	296.9[a]	349.3[b]	17.96	0.004
Time spent in paddocks (h/day)	17.2	16.9	0:20	0.156
Time spent in laneways (h/day)	2.2	2.5	0:08	0.504
Time spent in dairy (h/day)	2.9	2.8	0:06	0.698

[1] Average standard error of the difference
[a-b] Different lowercase superscripts within row indicate significant differences (P < 0.05)

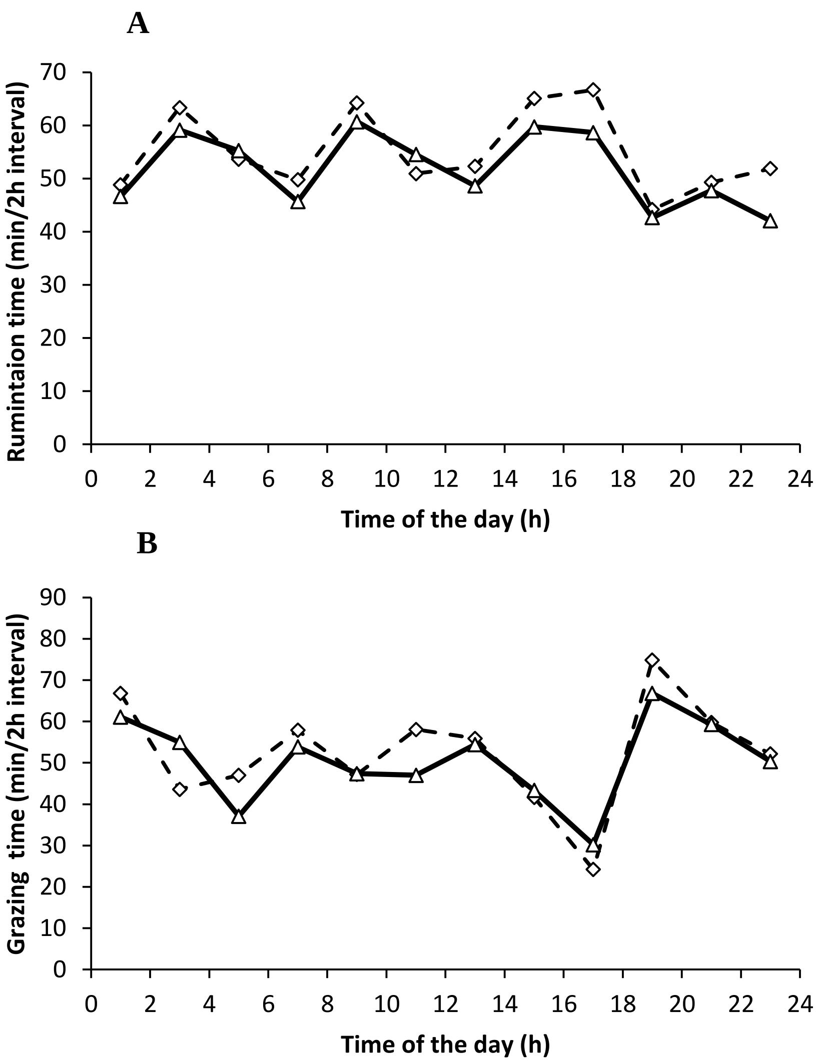

Figure 2. Diurnal pattern of rumination time (A) and grazing time (B) for Efficient (broken line) and Inefficient (solid line) cows milked in a pastured-based automatic milking system.

DISCUSSION

The aim of this study was to investigate the behaviour and performance of two groups of cows with different levels of efficiency in a pasture-based automatic milking system. Results showed that EFF cows produced more milk, with similar MF to their INEF counterparts. Whilst there was no difference in variables associated with cow traffic, EFF cows spent more time displaying grazing and rumination behaviour in comparison to INEF cows.

The proportion of EFF and INEF cows identified in this study (5% EFF; 3% INEF) was lower in comparison to those reported in Chapter 4 (10% EFF; 12% INEF). Aside from being a chance occurrence or specific to the herds in each study, the only plausible explanation for this could be in relation to the length of the period analysed to select the cows in each study (8 weeks in the present study and whole lactation data sets in Chapter 4). Although the number of EFF and INEF cows identified in the present study was relatively smaller than in Chapter 4, it was still deemed relevant to understand their behaviour and performance of individual animals with contrasting levels of 'efficiency'. Regardless of the proportion of the herd falling into each of these categories, EFF and INEF cows still have a significant impact on the system performance and might also influence the behaviour of herdmates.

As expected, there was a significant difference ($P < 0.05$) in DY between INEF and EFF cows, with the latter group producing on average 8.62 litres/cow/day more. Although SOL, Parity, CC had significant effect ($P < 0.001$) on DY, there was almost no difference in regards to these variables between treatments. Milking frequency and milking interval results were in agreement with previous studies conducted in pasture-based AMS (Lyons et al., 2013b, Shortall et al., 2017) and did not differ significantly between treatments. This finding supports the suggestion that the core differences in DY between EFF and INEF cows might be due to behaviour and time spent on different behaviours rather than being a direct reflection of MF.

Further analysis of raw data showed that there was no difference in regards to MI distribution (Figure 1), with both groups presenting similar proportions (~ 35%) of extended MI (over 16h). This value is similar to the 30% reported by Lyons et al. (2013a) previously for pasture-based AMS. Together with the relatively low MF (in comparison to frequencies typically reported for more intensive indoor systems for example), this factor (extended MI) might be at least partially responsible for the low number of incomplete milkings observed for both treatments. Longer MI's typically result in fuller and more distended udders that would likely increase the ease and success rate for any automatic cup attachment technology (Kolbach et al., 2012). Furthermore, data from pasture-based AMS does indicate that on average, when MF increases over 2 milking/cow/day (i.e. when MI is decreased), the percentage of incomplete milkings also tends to increase (N. Lyons, personal communication).

The lack of effect between treatments in regards to cow traffic variables (MF, WT, RT, FT) might be the result of the high level of behaviour synchrony among cows of the milking herd. Grazing cows typically exhibit a high level of synchronisation in behaviour (Uetake et al., 1997, Thorne et al., 2003) particularly with activities like grazing (Rook and Huckle, 1995, Ketelaar-de Lauwere et al., 1999). The similarity in the diurnal pattern of rumination and grazing time between EFF and INEF cows (Figure1) also supports this concept of synchronisation. Furthermore, there was no difference across the treatments with regards to time spent in the different areas of the farm (paddocks, laneways and dairy facility). It is recognised that during the trial period the system was not operating in full capacity (RR can perform between 60-90 milking per hour (García et al., 2007, Kolbach et al., 2012) with only 298 milking cows). The low cow:robot ratio would have increased the possibility for cows to move through the system in groups.

It has been previously reported that in pasture-based AMS, early lactation cows typically traffic around the system with higher levels of motivation with higher MF, shorter MI (Jago, 2006, Lyons et al., 2013a); and less likelihood of requiring to be fetched (Ipema and Benders, 1992, Jago, 2006) than cows in late lactation. In the current study, DIM did not have an effect on any of the traffic variables measured. However this was not surprising as the majority of the EFF and INEF cows were in mid and late lactation.

Cow returning from ‘Area B’ had a longer average RT than cows returning from ‘Area A’ and ‘Area C’. This longer RT may have been due to this area becoming available to the cows in the late afternoon-early evening, when cows are more likely to be actively seeking a fresh pasture allocation. During the night cows tend to be less active (John 2018) and prefer to be at pasture, (Legrand et al., 2009). Therefore, it is plausible that after accessing ‘Area B’ (available 17:00-23:00), and after a period of time grazing fresh pasture, cows were less motivated to leave the allocation and stayed in the pasture during the night, resulting in longer RT. The peak in grazing behaviour (Figure 2) observed after 18:00 h supports this idea. In a recently published study John et al. (2017) demonstrated the diurnal feeding pattern of cows, under outdoor conditions, when feed quality was held consistent. Moreover, when the timing of feeding was restricted (feed access between 1800 and 0600 h), cows consumed more feed (74% on the total DMI) in the first 6 h period, maximising lying time between 2400 and 0600, even with an *ad libitum* feed regimen.

The average time that cows spent grazing and ruminating was in agreement with values previously reported in the literature (Rook et al., 1994, Bargo et al., 2002, Krause et al., 2002, Kennedy et al., 2009). Although there was no difference between treatments with regard to time spent at pasture, EFF cows spent more time grazing and ruminating and less time resting than INEF cows. What is not known is whether EFF cows grazed and ruminated more because they were producing more milk or whether they were higher producers which resulted in an increased appetite and increased 'drive' to graze and ruminate.

Dry matter intake is a function of total grazing time (min/day), biting rate (bites/min) and bite mass (gDM/bite) (Phillips and Denne, 1988). Several studies have shown a strong relationship between grazing behaviour, pasture intake and milk production with Holstein-Friesian cows (Pulido and Leaver, 2001, Bargo et al., 2002, McCarthy et al., 2007). Pulido and Leaver (2001) reported an increase in grazing time and pasture intake rate with cows producing between 16.9 and 35.5 kg/milk/cow/day when grazing ryegrass pasture. In that study, cows with a high DY (35.5 kg milk/cow/day) grazed for 552 min/day and cows with lower DY (16.9 kg milk/cow/day) grazed for 480 min/day over two experiments. In addition, Bargo et al. (2002) and McCarthy et al. (2007) reported a positive relationship between DY and total bites/cow/day, indicating increments of 5 kg and 4.2 kg of milk per 10,000 bites, with average biting rates of 55 and 60 bites/min, respectively. When comparing different strains of Holstein Friesian dairy cows with regard to grazing behaviour, McCarthy et al. (2007) reported that almost half of the observed variation in milk production (R2=0.42) within a strain was explained by grazing behaviour. Grazing time (min/day), biting rate (bites/min) and bite mass (gDM/bite) were the main grazing behaviour variables associated with milk production.

A reduction in grazing time caused by concentrate supplementation has been reported previously (Pulido and Leaver, 2001, McCarthy et al., 2007) and could explain differences in grazing time among cows. However in our study there was no difference in concentrate consumption between EFF and INEF cows. Given that cows from both treatments had similar diurnal grazing patterns (Figure 2), it is thus highly likely that the observed longer time spent grazing for EFF cows in the present study would have resulted in greater pasture and total (given similar concentrate intake between treatments) DMI.

In our study EFF cows presented a longer grazing time in comparison to INEF (467.2 min/day and 427.2 min/day, respectively). If we assume an average bite rate of 60 bites/min and a bite size of 0.63 g DM/bite (Bargo et al., 2002, McCarthy et al., 2007), this difference in time spent grazing would account for approximately an additional 1.5 kg DM/day for the EFF cows. However, it is recognised that the difference in daily DMI may in fact have been even greater. If the EFF cows were more motivated to graze then it is also possible that they were more aggressive with their grazing behaviour and may have had both a higher bite rate and/or a higher bite size. Considering a typical feed conversion efficiency in pasture-based systems of 1-1.5 L milk/kg DM, it follows that the observed differences in grazing behaviour (and potentially in pasture intake) might explain only a proportion of the observed difference in DY. The lower rumination time measured for the INEFF also supports the association with the (potentially) lower DMI by INEFF cows, as less rumination time may indicate less material in the rumen to digest (Kennedy et al. 2009).

A proportion of the variability observed in grazing behaviour in ruminants is genetically inherited (Launchbaugh et al., 1999, Snowder et al., 2001), creating the opportunity to select for individual cows based on behavioural traits that are more suitable to our pasture-based production systems. The development of new and more accurate technologies that can monitor various animal behaviours (sometimes even in real time) and generate reliable data, such as activity and rumination monitors, opens up the possibility for selection. In addition, AMS provides the opportunity to easily capture data from individual animals. For example, Carlstrom et al. (2013) proved the feasibility of using data from commercial AMS for genetic analysis of '*milkability'* traits.

Another factor to consider is the order in which cows gain access to a fresh pasture allocation (not recorded in the present study), as the quality and nutritive value of pasture decreases, it is accessed by herd mates and the sward is gradually depleted (Clark, 2013). In pasture-based AMS operating with voluntary traffic (3WG), cows might access the same allocation up to 8 hours apart. Cows accessing pasture at an early stage are offered an *ad libitum* allowance and better quality pasture in comparison to cows accessing later (Scott et al., 2014). This will impact on not only milk production of the cow (due to differences in intake and quality), but also cow behaviour, as cows accessing the pasture later will have to graze for longer to meet their requirements, potentially spending more time and energy. It is possible that EFF cows may have been able to harvest more pasture and of higher quality, which would help to explain the higher DY observed for those cows compared to INEFF cows. Unfortunately, due to equipment malfunction, the specific GPS data, which would have added light into this speculation, were not captured.

It is important to mention that there are several other factors/variables affecting whole cow performance in dairy systems, such as milking characteristics (e.g. milking duration, average milk flow), milk solids production, fertility, feed conversion efficiency, longevity and temperament that need to be considered when defining whether a cow is efficient or not. This study was focused on variables regarding cow performance (including traffic) and behaviour of two groups of pre-selected cows aiming to increase the understanding of how productivity can be improved in pasture-based AMS. It is noted that the definition of E and I used in this study applies only for the purpose of the present investigations.

CONCLUSION

Optimising cow performance from grazed pasture is key for pasture-based AMS operating with voluntary traffic. This study has shown that Efficient cows produced more milk, with no difference in MF and cow traffic variables in comparison to Inefficient cows. The difference in cow performance might be partially explained by cow behaviour, as Efficient cows were recorded to have longer grazing and rumination times and shorter resting times. Further research should be conducted to elucidate the proportion of increased daily milk yield/greater efficiency that could not be explained by changes in grazing and feeding behaviour.

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OVERVIEW OF CHAPTER 7

It was shown in previous Chapters that contrasting levels of individual animal efficiency, as defined specifically for the purpose of these investigations, can be identified and quantified in pasture-based AMS. The next question becomes one of how individual animal efficiency (or aspects of behaviour associated with it), could be used to capture benefits at the whole herd or whole system level.

One opportunity to capture such benefits is provided by pasture-based AMS that operate a voluntary traffic system, with either seasonal or split calving systems. These systems will typically have a period of the year with a low cow:robot ratio, resulting in an underutilisation of the robotic equipment, with a high labour input and high energy costs on a per litre of milk basis. As a result, productivity and efficiency of the system is reduced. Traffic system type is generally very consistent within farm, due to the facility infrastructure and also the lack of knowledge regarding how cows adapt to short changes in the traffic management system. Chapter 7 summarises the results of a field study conducted with the aim of addressing this issue by implementing a short period of voluntary-batch milking.

CHAPTER 7: Increase Automatic Milking Systems efficiency: effect of a short-period of voluntary-batch milking on cow performance

ABSTRACT

Pasture-based automatic milking systems operating with voluntary cow traffic, with either seasonal or split calving systems are likely to have a period of equipment underutilisation due to reduced herd size and subsequent low cow:robot ratios. During these periods it is expected that operating costs are increased and labour efficiency is reduced. Operating a voluntary-batch traffic system during this period could address these issues; however, the ability of experienced cows to shift from voluntary-batch milking back to voluntary milking without significant negative impacts on cow performance has not been investigated to date. Acquiring this knowledge is important before new strategies to capture benefits arising from different levels of 'efficiency' are developed in the future. Cow performance data were collected over a 24-week period from a farm in Tasmania, where 156 cows were milked by an automatic milking robotic rotary. For the first 8 weeks cows were allowed to traffic voluntarily with a 3 way grazing system (VOL-PRE), followed by 8 weeks where cows were milked twice-a-day and managed under a voluntary-batch trafficking systems (VB) before reverting back to 3 way grazing (with voluntary cow traffic) (VOL-POST) for the last 8 weeks. Milking cows twice-a-day in the VB period resulted in a reduction in daily milk yield (VOL-PRE = 35.3 kg/cow/day and VB = 34.44 kg/cow/day) and milking frequency (VOL-PRE = 2.14 milkings/cow/day and VB = 1.97 milkings/cow/day). During VOL-POST period, milking frequency increased ($P < 0.001$) (2.31 milkings/cow/day), together with a slight but also significant increase ($P < 0.001$) in daily milk yield (35.5 kg milk/cow/day). Results indicate that experienced cows can be transitioned from voluntary-batch milking and back to voluntary milking without significant negative impacts on cow performance. This is a management strategy that can be employed during periods of underutilisation to improve both milk harvesting and labour efficiencies.

INTRODUCTION

Cow traffic has been recognised as one of the key factors affecting the feasibility and operational efficiency of automatic milking systems (AMS) (Lyons et al., 2014; Utsumi, 2011; Prescott et al., 1998; Halachmi et al., 2009). In Australia the majority of pasture-based AMS use controlled voluntary cow traffic, where cows can move from the paddock and through the dairy (with pre-selection for milking if milking permission is granted) to the next feed allocation with relative freedom of choice. At certain times of the year, AMS farms that operate a voluntary traffic system with either seasonal or split calving systems are likely to have some months where the number of cows per robot is particularly low. This can present some challenges such as difficulty to achieve and maintain good voluntary cow movement with reduced herd size (due in part to very small feed/pasture allocations), reduced labour use efficiency, underutilisation of the milk harvesting equipment, higher operating costs (per litre of milk) (Shortall et al., 2017), and maintaining high milk quality (due to the small volumes harvested per hour).

With 'box-robot' systems some of these challenges can be addressed by operating with a reduced number of boxes (i.e. with some boxes turned off for certain periods of time) to maintain a relatively consistent cow:box ratio. With the high-throughput robotic rotary (RR; Automatic Milking Rotary - AMR™, DeLaval International AB, Tumba, Sweden), the operator can deactivate some of the bails (Kolbach et al., 2013) on the platform, which might address some (but not all) of the above-mentioned challenges. However, additional benefits could be captured if the operator were able to switch to a voluntary-batch milking mode for the months of underutilisation, allowing cows to walk to the dairy by themselves after an automatic gate releaser opens the paddock gate at designated times during the day or night. In the 'voluntary-batch' system, offering supplementary feed in a feeding area located before milking, could encourage cows to voluntarily move to the dairy 2.5 hours before each "milking session" starts. A management strategy such as this would give the operator the opportunity to turn on the milk harvesting equipment for defined hours, saving electricity, controlling milking frequency of the cows and increasing labour efficiency (it would negate the need for on-call staff during the night hours if the dairy was shut down). In addition, having the dairy shut down for a period of time creates the opportunity to do major services to the equipment before the commencement of the next calving season without negatively impacting cow traffic.

However, such benefits would be eroded if cows, particularly those with increased 'AMS-efficiency (higher milk yield relative to milking frequency) did not re-adapt to full voluntary traffic soon after the voluntary-batch period is finished. Whilst it is known that it can take some time for naïve cows to fully adapt to voluntary cow traffic (depending on herd size, machine capacity, pre-training and other factors) (Donohue et al., 2010; Jacobs & Siegford, 2012)) there are currently no published studies that demonstrate the ability of experienced cows to shift from voluntary-batch milking to voluntary milking within the same lactation and the effect that this might have on individual cow traffic and cow performance.

In regards to cow performance, it was expected that daily milk yield (DY, defined here as accumulated milk production of all individual milking events in a given 24-hour period) would respond to the change of milking frequency (MF, defined here as sum of all individual milking events per cow in a given 24-hour period). Several studies conducted in conventional milking systems have measured the effect of MF on DY, showing that production increases 20-40% between once and twice-a-day milking and another ~15 % when cows are milk three times a day (Rémond et al., 2004; Clark et al., 2006). In these studies there was very limited variation in milking intervals (MI, defined here as total time between two consecutive milking events) and no variation in MF within cows and from day to day. In an AMS, as cows walk voluntary to the dairy through the day and night, there is a degree of variation in MI and MF between cows within the herd and within cows from day to day (Hogeveen et al., 2001; Lyons et al., 2013a). In a study conducted over 2 years under pasture-based AMS, Lyons et al. (2013a) showed a relatively high proportion (30% of total milking intervals) of extended milking intervals (MI greater than 16 hours), in which the milk accumulation rate decreased on average by 40%, negatively affecting milk yield per milking. In the same study it was determined that DY increases of 33%, 13% and 6% where associated with MF's in the ranges of 1 to 2, 2 to 3 and 3 to 4 milkings per day, respectively. Based on these studies it is expected that when cows transition from voluntary traffic to batch milking, MY could be negatively affected in those cows for which the MF is reduced (e.g. from 2.5 to 2 milkings per day; and positively affected in those cows for which the MF is increased (e.g. from 1.5 to 2 milkings per day). However, a study conducted by Foley et al. (2015) demonstrated that in a pasture based AMS milking frequency can be reduced, without any significant negative effect on DY or cow traffic in cows in mid lactation. This was done by comparing two different groups of cows, which were allowed to be milked a maximum of 2 and 3 times per day by adjusting milking permission. Although there was a significant difference between groups in MF (1.5 and 1.8 milkings per day) and also in many cow performance variables (MI, kg milk yield/cow/visit , milking duration/cow/visit (min), milking duration/cow/day (min), return time/cow/visit (h) and waiting time/cow/day (h)) there was no significant differences in MY.

A field study was therefore conducted to investigate the effects of implementing voluntary-batch milking (cows were transitioned from a voluntary trafficking system to a voluntary-batch system and back to voluntary) on the subsequent performance and voluntary traffic of individual cows.

MATERIALS AND METHODS

General information

The study was conducted in a commercial split-calving herd located in Deloraine, Tasmania, Australia, between April 27 and October 9 2015, where all milkings were performed on a 24-bail internal herringbone RR (DeLaval Automatic Milking Rotary, AMR™). The farm had operated as a pasture-based system with voluntary cow traffic and 3-way grazing (3WG) (Lyons et al., 2013b; Kerrisk, 2009) since 2012. The experimental period was based on historical data collection which extended over a 24-week period and was divided into 3 'treatments' based on the type of cow traffic: 'voluntary pre voluntary-batch period' (VOL-PRE; weeks 1 to 8), 'voluntary-batch' (VB; weeks 9 to 16) and 'voluntary post voluntary-batch period' (VOL-POST; weeks 17 to 24).

During VOL-PRE and VOL-POST cows were managed with 3WG and were allowed to voluntary traffic from pasture to the milk harvesting facility to be milked at any time during the day and night. Cows exiting the dairy after being milked or when denied milking permission, had access to one of the 3 daily pasture allocations, depending on the time of the day. Under VOL-PRE, allocations opened at 0600 h, 1400 h, and 2200 h and under VOL-POST at 0500 h, 1300 h, and 2100 h. Cows were granted milking permission based on a minimum milking interval of 6 hours or an expected yield greater than 7 kg/milking (as calculated by the support software, DelPro, DeLaval™). Cows that had not returned to the dairy facility from the pasture allocation were fetched by the operator to minimise milking intervals extending beyond 24 h.

During the VB period cows were milked in two defined sessions/day commencing at 0500 h and at 1400 h. Cows were held in the paddock (gate closed) until 2.5 hours prior to the beginning of each milking session when an automatic gate releaser was activated opening the paddock's gate. This meant that cows could traffic voluntarily (thus the name VB) to the dairy via the feedpad area from 0230 h and 1130 h with milking commencing at 0500 h and 1400 h respectively. Any cow not walking voluntarily to the feedpad area was fetched to the dairy before the milking session was finished. Cows were also encouraged by the operator to walk from the feedpad area and through the waiting yard as required to ensure that the milking sessions were generally completed by 0800 h in the morning and 1700 h in the evening. After being milked, cows were allowed to voluntarily walk to the new allocation of pasture and were locked into the paddock after the milking session was complete and the last cow had entered the paddock. During this period there was a significantly high level of manual attachment of cups conducted by the operator, with the aim of reducing total milking sessions time and also as a strategy to prevent incomplete milkings.

For all periods, target daily dry matter intakes were 22.5 kg DM/cow/day, and feed was offered as a combination of grazable pasture (perennial ryegrass, *Lolium perenne L.*), partial mixed ration (PMR) and grain-based concentrate (GBC). The percentage of each feed in the daily allocation varied depending on the availability of pasture. At all times cows were managed as a single herd. In all 3 periods cows had access to GBC feed after milking in 20 automated out-of-parlour feeders (FSC400, DeLaval International AB, Tumba, Sweden) located in an area immediately post-milking. Individualised GBC was calculated automatically based on days in milk. All cows were fitted with an electronic identification transponder attached to a collar, to allow them to traffic through the automatic drafting gates (DeLaval Smart Selection Gate, Tumba, Sweden) and to the out-of-parlour feeders.

The autumn calving herd consisted of 199 Holstein-Friesian primiparous (n=43) and multiparous (n=156, parity range 2 – 8) cows. Only multiparous cows were included in the study, all of which had previous experience with 3WG as a management system. At the beginning of the experiment (week 1) the herd was comprised of 86 cows and by week 6 all 156 cows had calved.

The spring calving herd, comprised of 391 Holstein-Friesians cows (parity range 1 – 8), were dried-off during the VOL-PRE period however, they were managed together with the autumn calving herd before they were dried off. Two weeks prior to the end of VB, week 14, the spring herd started calving and fresh cows joined the autumn milking herd, with almost 50 % of them calved within 4 weeks. Data from the spring calving herd was excluded from the analysis. This study was intended to simulate a commercial situation whereby herd numbers reduced for a period of time, and although data generated by the spring herd was excluded from the analysis, animals that were dried off and calved back into the herd could have influenced herd dynamics, and it was not the intention of this study to remove their influence.

Data collection

Data were collected electronically by the herd management software, including daily milking frequency (MF; milkings/cow/day), daily milk yield (DY; kg milk/cow/day), milk yield per visit (MY; kg milk/cow/milking), milking interval per visit (MI; h), milking duration per visit (MD, min), concentrate consumption (CC; kgDM/cow/day), percentage of concentrate consumed (%CC; %, defined as the proportion of allocated concentrate that was actually consumed/day); incomplete milkings (INC; %, defined as the proportion of milking events whereby one or more teats were either not milked or yielded less than 50% of the calculated expected yield); parity number, and days in milk (DIM). Due to the variability (between days) typically observed in AMS, seven-day averages were calculated prior to statistical analysis.

Statistical analysis

Outcome variables

The outcome variables analysed at cow level were milking frequency, milk yield per day, milk yield per visit, milking interval, milking duration, concentrate consumption, percentage of concentrate consumption and incomplete milkings.

Explanatory variables

The main explanatory variables included in the analysis were: days in milk, lactation number, traffic system (VOL-PRE, VB, VOL-POST), concentrate consumption and cow ID.

Statistical models

Linear mixed models (REML) were used to analyse data. All models included the fixed effects of days in milk, lactation number and traffic system. The interactions between days in milk and lactation number with traffic system were tested, and removed if not significant. For the analysis of DY, concentrate consumption was included in the model as an interaction with traffic system. Cow ID was included as a random effect in all models. Residual analysis was performed to check for normality. All analyses were conducted in Genstat 16th Edition (VSN International Ltd.) and *P* values lower than 0.05 were considered significant. Least significant differences were used to determine significant differences in variables between the different traffic systems.

RESULTS

For all models there were no interactions between DIM, lactation number and traffic system (all $P > 0.05$). Days in Milk (DIM) had a significant effect on all outcome variables ($P < 0.001$) except for INC. Traffic system had a significant effect on all variables except CC, and lactation number had a significant effect on MF, DY and MI. Concentrate consumption has a significant effect on DY ($P < 0.001$).

Milking cows twice-a-day during the VB period resulted in a significant reduction of MF, DY, and INC while MY, MI, MD, CC and % CC increased during the VB period (Table 1). Interestingly, when cows switched back to voluntary traffic (VOL-POST) MF increased significantly (17%), together with a slight but also significant increase in DY (3%). During the VOL-Post period, MF reached the highest value in the first week of the treatment (Figure 1) while DY presented the lowest value. Frequency distribution of milking intervals is presented in Figure 2.

Table 1. Predicted means for milking frequency per day, milk yield per day, milk yield per visit, milking interval per visit, milking duration per visit (min), incomplete milkings, concentrate consumption and % concentrate consumption for each of the treatments voluntary pre voluntary-batch period (VOL-PRE), voluntary-batch (VB) , voluntary post voluntary-batch period (VOL-POST) traffic systems.

	Traffic system			
	VOL-PRE	VB	VOL-POST	SED
Milking frequency (milkings/cow/day)	2.14^{b}	1.97^{c}	2.31^{a}	0.04
Milk yield per day (kg milk/cow/day)	35.3^{a}	34.44^{b}	35.5^{a}	0.3
Milk yield per visit (kg milk/cow/visit)	16.51^{b}	17.26^{a}	15.57^{c}	0.17
Milking interval per visit (hours)	11.44	11.98	10.74	0.004
Milking duration per visit (minutes)	6.11^{c}	6.51^{ab}	6.21^{bc}	0.06
Concentrate consumption (kgDM/day)	8.40^{c}	8.62^{a}	8.53^{b}	0.11
% Concentrate consumption (%)	95.14	95.59	96.06	0.3
Incomplete milkings (%)	5^{b}	3^{c}	9^{a}	0.01

SED: Standard error of the difference; Different letters (within row) indicate significant differences (P<0.001) between groups.VOL-PRE is the 8 week period of voluntary cow traffic prior to the voluntary-batching period, VB is the 8 week period of voluntary-batching whereby cows were restricted to the paddock between designated milking times but were allowed to voluntarily traffic to the pre-milking feedpad prior to voluntarily trafficking through the dairy and out to the subsequent pasture allocation, VOL-POST is the the 8 week period of voluntary cow traffic after to the voluntary-batching period.

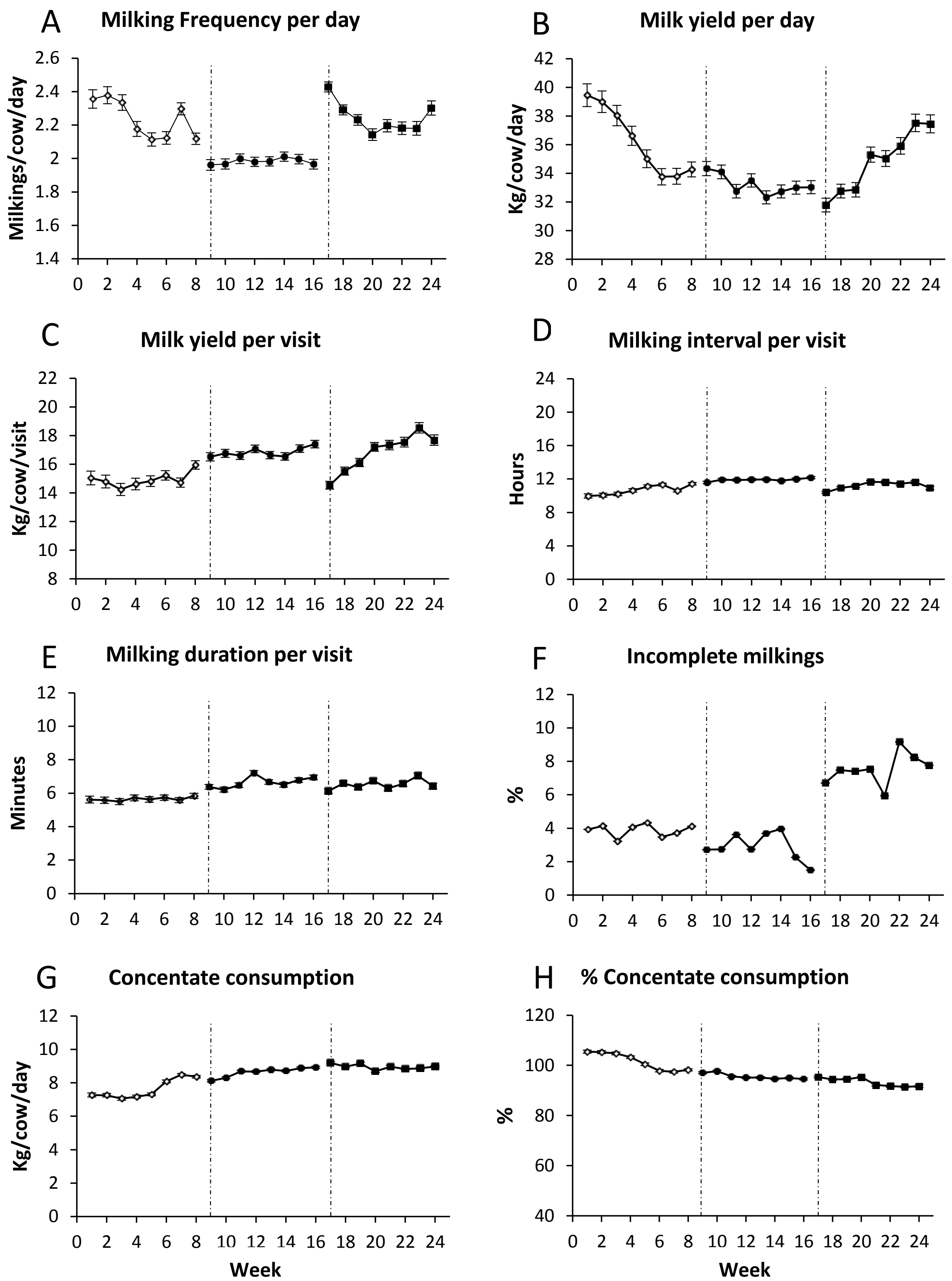

Figure 1. Effect of traffic systems: voluntary pre voluntary-batch period (VOL-PRE, ◊); voluntary-batch (VB, ●); voluntary post voluntary-batch period (VOL-POST ■) on a) milking frequency per day (milkings/cow/day), (b) milk yield per day (kg milk/cow/day), (c) milk yield per visit (kg milk/cow/visit), (d) milking interval per visit (hs), (e) milking duration per visit (min), (f) Incomplete milking (%), (g) concentrate consumption (kg/cow/day), (h) % concentrate consumption (%). Predicted means and standard error are

presented. Break in the data lines indicates when VB started (week 9) and when VOL-POST commenced (week 17).

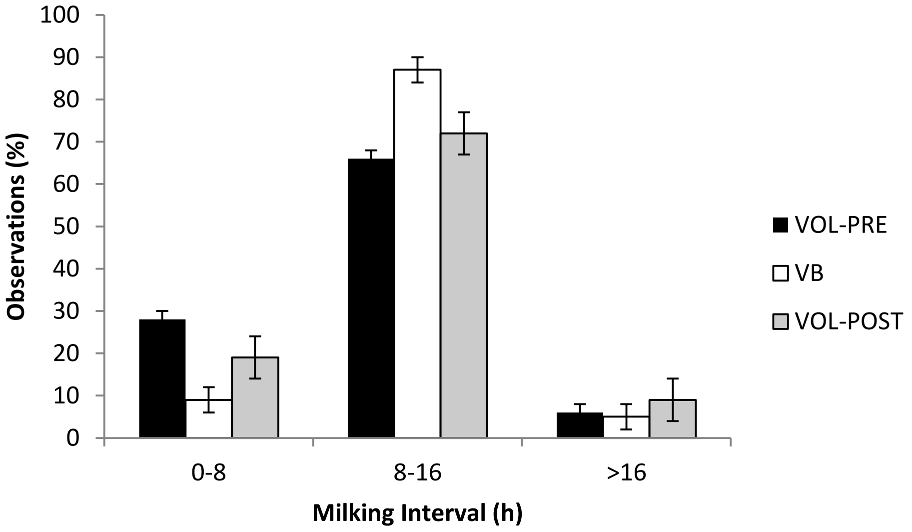

Figure 2. Frequency distribution of milking interval (h) resulting from voluntary pre voluntary-batch period (VOL-PRE; ■), voluntary-batch (VB; □) , voluntary post voluntary-batch period (VOL-POST; ▫) traffic systems. Vertical bars indicate SEM (standard error of the mean).

DISCUSSION

The aim of this study was to investigate the effect on cow performance and cow traffic when cows were transitioned from a voluntary trafficking system to a voluntary-batch system and back to voluntary. The concern with such an approach related to whether or not the cows would resume voluntary cow traffic (without significant negative impacts on milking frequency and milk production) when herd size increased (with fresh calved cows re-entering the herd) after a relatively prolonged period of voluntary-batch milking.

Milking frequency dropped from 2.14 milkings/cow/day to 1.97 milkings/cow/day when cows were shifted from VOL-PRE to VB system. This was expected as they were restricted to two defined milking session times. Interestingly, when the management strategy was reverted to VOL-POST (after the 8 week period of VB) the milking frequency increased to 2.30 milkings/cow/day, indicating that cows responded positively to the change of management. This immediate, significant and rapid increase in MF (Figure 1a), was particularly interesting given that the study cows were in mid-lactation as they moved into the VOL-POST treatment, and it is well known that MF decreases with stage of lactation (Lyons *et al.*, 2013b). Two weeks prior to the end of VB (week 15), the spring herd started calving and fresh cows joined the autumn milking herd, this most likely impacted the motivation levels of the autumn calvers being studied and could explain, at least in part, the observed increase in MF in VOL-POST. This would have also been the case if the autumn-calving cows had been managed with voluntary cow traffic throughout the full 8 week winter period and it is possible that the autumn-calving cows would have responded with an increase in MF even earlier (as the spring calving cows started to join the herd) if they had not been restricted with the VB strategy. Further research is needed to elucidate this.

Daily milk yield decreased slightly albeit significantly by 0.86 litres/cow/day when cows were restricted to the VB milking strategy. This was likely due to the slight reduction in mean MF. However, because MF commonly achieved in AMS pasture-based system are not much greater than 2 milkings/day (Lyons *et al.*, 2013b; Lyons & Kerrisk, 2017), the losses in milk production might be compensated by the long-term benefits of reducing milking intervals that extended beyond 16 hours. Further long-term benefits might have been generated by the near elimination of extended milkings (at a quarter level) resulting from incomplete milkings. Interestingly MY was greater for the VB period, resulting in a higher milk harvesting efficiency, and was lower for the VOL-POST period since the increase in milking frequency did not result in a proportionately higher MY. Still, the increase in DY achieved in VOL-POST was encouraging, particularly in light of the fact that cows were beyond the first 100 days of lactation.

Although the level of incomplete milkings (5%) was acceptably low at the beginning of the study, a significant decrease in the incidence of INC was reported during the VB period, this was expected as the level of manual cup attachment conducted by farm staff increased during that period, in an attempt to reduce inefficiencies associates with cows requiring a second or even third attempt at milking. In addition, the fact that the system was only operating over limited number of hours per day could have resulted in a greater level of hygiene on the external surfaces of the equipment with a reduced opportunity for manure to dry on the camera lenses, milk tubes and robotic arms. As a result of the controlled and regular milking frequency during the VB period, a relatively higher proportion of milking intervals between 8-16 hours was observed (87%, Figure 2), resulting in a fuller and more distended udder that would likely increase the ease for any automatic cup attachment device to locate the teats

(Kolbach *et al.*, 2012). This could explain, at least partly, the low number of incomplete milkings.

Whilst the shift to VB reduced the incidence of incomplete milkings, it is concerning that the prevalence of incomplete milkings increased during the VOL-POST period (even to levels significantly higher than those in VOL-PRE). The explanation for this is likely multi-factorial but could include factors such as the automatic cup attachment, the lower milk yield/milking, some disturbance created by the fresh spring calving cows and/or an increase in the variation of intervals between successive milkings.

Having the robotic system operating for discrete sessions/limited hours per day provides the possibility to implement strategies, such us performing manual cup attachment, to reduce the number of incomplete milkings substantially, which might have a positive impact on milk production, udder health, and cow traffic. Such strategies are almost impossible to apply in a practical manner when operating with voluntary traffic.

Contrary to expectations, there was no significant difference between periods in the percentage of concentrate consumption (%CC). With defined milking sessions and manual cup attachment it was expected that a higher number of cows (relative to VOL-PRE) could be present in the feeding area at the same time, creating an increased level of congestion and competition for the feeding stations. This does not appear to have been the case in this study and is likely to be directly related to the number of feeding stations available (20 parlour feeders) and the rate (cows/hour) of cows exiting the dairy. As dairy cows in conventional milking systems have been shown to maintain a relatively similar order of milking (Scott et al., 2014) it is possible that the VB management strategy resulted in cows accessing the feeding stations in more of a hierarchical order. This in turn may have reduced the likelihood that some cows were not able to access their concentrate allocation without being disturbed by more dominant herdmates. Concentrate consumption increased significantly (but only by 2.6%) when the study cows shifted from VOL-PRE to VB. This was somewhat surprising given the reduced visitation frequency and the reduced milk yield but it also could be explained by the programmed increment in allowance during early lactation stage. Although MF increased in VOL-POST period, CC decreased significantly in comparison to VB, more than likely due to the fact that allocation levels automatically decreased as cows progressed through mid-lactation.

Knowing that cows can quickly adapt to changes in traffic systems within the same lactation without a significant negative effect on their performance, provides the opportunity to use this as a strategic management option, not only for periods of underutilisation but also perhaps to address other challenges in pasture-based AMS. A similar strategy used in this study might be applicable for example, on farms where cows are exposed to periods with high environmental temperature humidity index (THI) resulting in heat stress. In pasture-based AMS with large herds, where a high proportion of the diet is comprised of pasture, the combination of long walking distances and high temperatures result in a decrease in cow voluntary movement (Wildridge et al., 2018), reducing milking frequency, potentially affecting production and also increasing labour associated with increased fetching. A period of time in which cows can be batch milked or voluntary-batch-milked could have a positive impact on cow production and welfare. It is however, important to understand the impact of the freshly calved cows on the herd dynamics before broad adoption of voluntary-batch milking under various scenarios can be recommended.

In order to avoid having a negative impact in cow performance and welfare, other factors such as: type of robots, farm layout, size of the waiting yards and herd size, need to be consider before applying changes in traffic systems.

CONCLUSION

The findings presented in this study indicate that experienced cows can be transitioned from voluntary-batch milking and back to voluntary milking without significant negative impacts on cow performance and cow traffic. This enhances the potential future application (outside the scope of this thesis) of previous findings in relation to variability in individual animal 'efficiency' for pasture-based AMS. Results from this present study suggest that 'voluntary-batch' milking could be a feasible management option for pasture-based AMS to address periods of underutilisation of the equipment. Care should be taken to monitor and manage the level of incomplete milkings as cows transition back to voluntary milking to ensure that udder health and production are not inadvertently compromised.

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CHAPTER 8: General discussion and conclusion

GENERAL DISCUSSION

This research has explored key aspects of efficiency at animal and system levels as the basis to develop strategies on how to improve system performance in pasture-based AMS operating with voluntary traffic. To achieve this, a research approach that combined innovative uses of data from commercial farms with controlled field investigation, was used to characterise the current situation, identify gaps in knowledge, validate a newly available research tool, and identify and quantify the extent to which different levels of animal efficiency (as defined for pasture-based AMS) could be used to advance pasture-based AMS in the future. The primary purpose of this final Chapter is therefore to integrate the knowledge generated through each of the individual pieces of research, highlight those areas that require further research, and outline the key conclusions of these investigations.

Pasture-based AMS

The exploration of strategies to improve whole farm productivity will continue to play a role in improving the uptake and success of farms operating with Automatic Milking Systems (AMS). In particular, optimising robot performance, a key objective for the vast majority of farmers operating with AMS (Sonck and Donkers, 1995), is deemed critical to increasing farm profitability.

In countries like Australia, New Zealand and Ireland, the majority of commercial dairy farms are pastured-based, i.e. grazed pasture is the main individual component of the total annual dry matter intake consumed by cows. In a world where the demand for high quality dairy products is increasing and consumers are becoming more informed about how their food is produced (Cembalo et al., 2016), pastured-based dairy systems are well positioned to meet that demand.

When AMS commenced to be adopted in countries like Australia and New Zealand, the predominant perception was that they would not be compatible with pasture-based systems (Garcia and Fulkerson, 2005). This was perhaps influenced by the reported reduction in grazing (hours/days/months) which is associated with AMS adoption in many European countries (de Koning, 2011); a concern when consumer opinion is increasingly influencing farming practices. Despite this, research studies conducted in various countries have demonstrated that AMS can be successfully integrated into grazing systems and that cows adapt very well to voluntary cow traffic when feed is used as the primary incentive (Jago et al., 2002, Davis, 2006). A review of current and relevant literature (Chapter 2) showed that the nature of voluntary traffic and the management systems implemented in pasture-based AMS are associated with significant levels of variability in milking frequency (MF) and milking interval (MI), not only among individual cows but also over time. Interestingly, the impact of MI on milk yield varies significantly between cows (Lyons et al., 2013a). The feasibility of, and opportunity for, using data from commercial herds to determine individual performance through in-depth analysis of factors including MF, MI, and milking time (among others) was also highlighted in the literature review. Thus, Chapter 2 proposed that there was a significant opportunity to explore the individual cow variability in order to identify, select and in the future potentially breed cows more suitable to AMS, and even more specifically for pasture-based AMS. It was also shown that current levels of robot utilisation and milk harvested per robot (MHR) in pasture-based AMS are relatively low (Lyons and Kerrisk, 2017; Chapter 2) in comparison to indoor systems, indicating that there was an opportunity to improve system performance.

In a comprehensive review on the impact of AMS on dairy cow management, behaviour, health, and welfare, Jacobs and Siegford (2012) suggested that completely different AMS optimisation strategies might be needed to successfully operate pasture-based AMS. It is evident that factors specific to, or more exacerbated by, grazing systems (such as greater walking distances, periods of hot weather, diurnal grazing behaviour and greater social synchronisation of cow behaviour) add and element of complexity to the system when the aim is to optimise robot performance (John et al., 2016).

Farmers operating with AMS typically have two main strategies to increase robot performance, namely increasing MF or increasing the number of cows in the herd whilst maintaining MF (Woolford et al., 2004; Chapter 2). The need for a better understanding of the relationship between robot performance, cows per robot (CR) and MF in pasture-based AMS was also highlighted in Chapter 2.

In Chapter 3, the relationship between MF, CR and MHR was analysed using data from a 2-year period from 17 commercial pasture-based AMS farms. As expected, it was demonstrated that, on average, commercial pastured-based AMS are achieving lower levels of robot performance (measured as robot utilisation and MHR), together with lower level of MF in comparison with those commonly reported in indoor systems. Interestingly though, the average number of CR was fairly similar to those reported for indoor based systems. From this finding alone it would seem apparent that farmers operating pasture-based AMS are targeting an increase in MF rather than an increase in CR, or a combination of both, as a strategy to optimise MHR, although they are not achieving it. This is in alignment with the work by Lyons and Kerrisk (2017), who estimated that milkings per robot per day, CR, MHR and milking time could be increased (potentially) by up to 60%. The most likely reasons for farmers opting for this strategy (i.e. increasing only MF as a mean to increase MHR) probably include the realisation that operating with high CR creates additional pressure on the system (including cows, labour and equipment), and that an increment in MF is easier and cheaper to target in the short term. The relatively lower levels of MF and milk yield achieved in pasture-based AMS compared to indoor AMS might be explained predominantly by factors associated with feeding system (i.e. walking distances, limitation in dry matter intake), calving system (whereby peak herd size and annual average herd size are significantly different) and possibly even genetic potential.

It was clearly demonstrated (Chapter 3) that the number of CR had a greater positive effect on MHR than MF. From a robot performance aspect, it would therefore be more beneficial for farmers to increase CR, rather than targeting higher MF levels. However, the potential benefits of such strategy have not been determined at either research or commercial farm level. Although studies conducted in New Zealand by Davis et al. (2005) and Jago and Burke (2010) reported high CR (75 and 92 cows per robot respectively), the average MF in both studies was not greater than 1.5 milkings/cow/day, therefore achieving low levels of MHR. These lower levels of MF, together with a different type of cow (lower yielding cows New Zealand Holstein strains, Jerseys and Crossbreds) make it difficult to extrapolate the results to current commercial operations. Further research would be required to elucidate this. Moreover, achieving high levels of MF in pasture-based AMS is somewhat challenging with current management practices. In spite of several studies (John et al., 2013, Lyons et al., 2013b, Scott et al., 2014) that have successfully focused on manipulating feed (timing, placement and distribution) to encourage cows to move frequently around a pasture-based AMS, it is evident that the majority of the farmers are not achieving relatively high and consistent levels of MF, and therefore high MHR. In addition, many farmers are starting to operate with 4 feed allocations per day (4WG) (N. Lyons personal communication), and although anecdotal evidence suggest that cows traffic is improved, no research has been conducted in this specific area.

Together, the above discussion highlights the importance of investigating opportunities to increase performance through better exploiting individual cow efficiencies in AMS, which was a core objective of this research.

Milk harvested per robot and individual animal efficiency in AMS

The vast majority of commercial farms in Australia operate with robot utilisation levels which are well below the technical capability of the equipment. This indicates that key factors limiting performance of the dairy are a combination of animal, management and feed factors. Modifying animal, management and feed factors will come at a cost (financial, labour, stress, operating) that may well be greater than the performance benefits that are sought to be optimised. The optimum number of CR would be the one that will allow the system to achieve a high MHR, with a high individual cow production (not necessarily maximised).

Another key finding from Chapter 3 was that with current management practices, traffic systems and cow types, the probability of achieving high MHR (greater than 1,600 kg milk/day/robot) with Low (<2) and Mid (<2.5) levels of MF in commercial pasture-based AMS, is low.

These findings, together with the known variability in MF and MY between individual cows and over time (Chapter 2) highlighted an opportunity to explore strategies to increase AMS performance and prompted the question: can we identify those cows that are most suited to pasture-based AMS? This question then constituted the central objective of the novel research reported in Chapter 4, which extracted additional benefits from data that are automatically captured in an AMS. If the most ‘efficient’ cows could be identified, that would then open a whole spectrum of opportunities around increasing the proportion of ‘efficient’ cows in the herd either through selection or through management, i.e. potentially shifting cows from a category of ‘inefficient cows’ to another one of ‘efficient cows’.

The search for improved animal efficiency is not new. However, previous studies have focussed on traits different from those this present research has focussed on. As milk flow rate (kg/min) has been shown to be one of the most important variables influencing MHR (Castro et al., 2012), the majority of published studies have focussed on milkability traits, including milk flow rate, milking time, box (usage) time and milking interval (Carlstrom et al., 2013, Carlstrom et al., 2014). Large variation and moderate to high repeatability were found for average flow milk rate and box time traits, meaning that is possible to improve those traits by breeding. 'Habituation of heifers', referring to the period of time a heifer needs to get familiar with the AMS, is another example of an index proposed by a Dutch breeding company to improve efficiency in AMS (Vosman, 2014). However no published studies have validated this index.

In this present research, a novel concept of 'efficiency' at a cow level was developed for AMS in relation to cow performance (MF and MY). The concept was aligned with the strategy of increasing the volume of MHR by increasing the number of cows in the herd, whilst maintaining a relatively low MF, which would in turn allow for further increase in CR. This was following from findings from Chapter 3, which suggested that increasing the number of cows in the herd is the most suitable strategy to increase productivity in pasture-based AMS. Thus, an 'efficient' cow was defined as a cow that produced more milk from relatively less milkings, and an 'inefficient' cow was defined as one that produced less milk from relatively more milkings. With this novel and AMS-specific approach, MF was considered as a 'cost' to the cow (as each milking event costs the cow time and energy, both limited resources) and a cost to the system (as each milking consumes power, water, and uses space and resources that could be used by other cows). In addition, targeting lower MF gives the AMS operator the possibility to milk more cows per unit, which in turn can be of greater economic benefit as CR have a positive effect on MHR. In addition, it may also result in other benefits from an animal welfare point of view. This is because high producing cows with a lower MF (as per Efficient cow definition) would travel reduced distances/day and might spend less time on yards with hard surfaces and more time at pasture, thus reducing the risk of lameness.

The analysis of cow performance at whole lactation level from two large datasets (2 commercial AMS farms) proved that cows could be categorised in relation to their efficiency. On both farms, about 13% (range 10-16%) of the lactations analysed were identified as Efficient and about 12% (range 7-17%) as Inefficient. Cows categorised as Efficient produced 9% more milk with 5% less milkings per day and Inefficient cows produced 10% less milk with 6% more milkings in relation to their expected values. Results also suggested that a cow could remain efficient/inefficient for the whole lactation. However, only a low proportion of cows (8%) appeared to be 'efficient' or 'inefficient' across more than one lactation. Perhaps this was due to the fact that although MF is a repeatable trait, it only has an intermediate repeatability ~ 0.40 (Lovendahl and Chagunda, 2011). Logically, there are many factors affecting MF in pastured-based AMS, and it is likely that those factors also present complex interactions. The fact that only a low proportion of cows carried over the 'efficiency' to the following lactation suggested that factors other than genetics were responsible, limiting the potentially applicability of breeding 'efficient' cows for AMS. However, it is recognised that a relative low numbers of lactation were analysed in the present study (n=292). In addition, there is very limited research in AMS looking over multiple lactations of individual cows (none in pasture-based AMS) making it very difficult to relate this finding with previous literature. It is evident that more research is needed in this area, particularly considering that one of the main advantages of AMS is the enormous amount of data recorded by the system. Whilst extensive data editing is necessary, the captured data are valuable and accurate enough to conduct research (Carlstrom et al., 2013). In this regard, the present thesis makes a significant contribution to AMS research, by providing novel approaches for better exploiting data generated by these systems. However, the difficulty to access large datasets from commercial AMS farms is a reality, which in turn may limit research possibilities.

Proving that cows can be categorised as efficient or inefficient was a key outcome of this research. However, understanding what creates these levels of efficiency was also key if the proportion of the herd falling into each category is to be manipulated in future systems (a potential practical application of this present research). Given that voluntary cow traffic allows cows to decide where to spend their time, it might be possible that some cows in pasture-based AMS spend considerable more time on pasture and grazing than others. It was also suggested that each individual cow develops a unique feeding and drinking pattern and that such pattern is relatively consistent over time (Melin et al., 2005). The theory that Efficient cows might spend more time in the paddock grazing pasture, which might in turn result in higher levels of rumination and higher milk production than Inefficient cows in the same herd, was tested in Chapter 5. Using the methodology developed in Chapter 4, two groups of cows (Efficient and Inefficient) were selected and compared.

To be able to accurately assess differences in cow behaviour between cows, a device capable of monitoring multiple behaviours with high levels of accuracy under grazing conditions was needed. While many devices have been already validated, the majority of the studies were conducted in indoor housed systems and results cannot be extrapolated directly to pasture-based systems (Schirmann et al., 2009, Burfeind et al., 2011), mainly due to the differences in cow behaviour and environmental conditions. In addition, most of the devices validated are constrained by either the type or number of behaviours that can be measured or because they are less suitable for a practical use. Thus, an evaluation of the accuracy of a newer version of an activity- and rumination- monitoring system (SCR HR-LDn, SCR Engineers, Netanya, Israel) was conducted (Chapter 5). This study was the first to show that the monitoring-activity system quantified time spent grazing, resting and ruminating with high to very high level of accuracy in dairy cows grazing two different forage swards. Whilst the technology was already being adopted on commercial farms, this was the first published evaluation study (with high levels of accuracy) of the SCR HR-LDn in outdoor grazing settings.

The proposed hypothesis regarding differences in cow behaviour between Efficient and Inefficient cows was confirmed with a field trial (Chapter 6). In Chapter 6 it was concluded that the difference in cow performance might be partially explained by cow behaviour, as Efficient cows were recorded to have longer grazing and rumination times and shorter resting times, likely explaining at least in part the difference in milk production. However, the investigation also showed that a relatively important proportion of the difference in milk between 'efficient' and 'inefficient' cows, could not be quantified by changes in grazing or feeding behaviour only. Further investigations would be warranted to identify and quantify the different factors involved.

Potential application of the concept of 'efficiency' in AMS

Demonstrating that cows can be categorised (and quantified) as Efficient and Inefficient with regard to cow performance, and that they behave differently, opens new possibilities and options to manipulate cows and move them from an Inefficient category to an Efficient category. In this regard, there may be potential to control or manage cows with different levels of efficiency in different ways. One management option could be to control the MF of Inefficient cows by batch-milking them (i.e. defined milking sessions) through the system which could ensure that their MF was restricted and that their time at pasture could be maximised. The lack of information relating to batch milking in pasture-based AMS prompted the need to investigate this possibility further in this thesis.

In pasture-based AMS operating with either seasonal or split calving systems, higher levels of system utilisation are typically observed in spring-summer (a time at which robot capacity could actually be the limiting factor on some farms). During the remainder of the year these systems will run at lower than potential utilisation levels. In our study, Season (as time of the year) had a significant effect on robot performance (Chapter 3). This was in agreement with

Lyons and Kerrisk (2017). To overcome this period or underutilisation, a study was conducted (Chapter 7) to investigate the effects of implementing a novel management strategy to potentially improve both milk harvesting and labour efficiencies in the system. The introduction of a short period of voluntary-batch milking on the subsequent performance and voluntary traffic of individual cows was investigated. Results from the study indicated that experienced cows can be transitioned from voluntary-batch milking and back to voluntary milking without adversely affecting cow performance and cow traffic. This is the first study to report how cows adapt to large changes in traffic management system within the same lactation. It is recognised that this strategy might be only suitable for farms operating with large herds and robotic equipment with a high-throughput capacity, as the AMR (60-90 milking per hour). It is important to consider that with voluntary-batch traffic systems, individual cow production might be limited as MF is being restricted (i.e. to twice-a-day). However, losses in milk production might be compensated by the long-term benefits of reducing MI that extended beyond 16 hours and also by the lower levels of incomplete milkings. Importantly, the magnitude of the limitation is likely to change depending on the level of MF achieved with voluntary traffic (specific to individual farms) and the stage of lactation of the cows.

Having the robotic system operating for discrete milking sessions (i.e. limited hours per day) has a significant impact on labour. It negates the need for on-call staff during the hours that the dairy is not operating and provides the opportunity to have periods of zero alarms, potentially improving quality of life for farmers. Operating an AMS with voluntary traffic is very demanding from the labour and management point of view, as the 24-hour operation comes with a level of risk of alarms and breakdowns during the night. As the main motivations for farmers to adopt AMS are related to social reasons (i.e. increased labour flexibility, improved lifestyle, reduced labour) (Mathijs, 2004, Molfino et al., 2014), strategies that improve system productivity but also positively impact on labour, like the one proposed in this study, will contribute to make the technology even more attractive. Discrete milking sessions also creates the opportunity to do major services to the equipment before the commencement of the next calving season without negatively impacting cow traffic.

The real value of voluntary-batch milking (as investigated in Chapter 7) might not be realised until further research is conducted to determine the impact on cows at different stages of lactation and cows in different categories of ‘efficiency’. It could be possible that dramatic improvements in whole farm performance could be achieved if sub-herds of milking cows are managed in different ways. For example, perhaps the cows categorised as Inefficient could be voluntary-batched to restrict their MF, freeing vital robot capacity allowing for an increased number of cows to be milked (thereby dramatically increasing robot performance).

CONCLUSION

The central aim of this thesis was to identify strategies on how to improve production efficiency in pasture-based AMS operating with voluntary traffic, which are determined by complex interactions of animal, management, feed and environment factors. Through this thesis, inefficiencies at both system and cow performance levels were identified and analysed with the ultimate aim of finding alternatives to increase AMS productivity. The novel research presented in this thesis has contributed with new, unique and original knowledge to pasture-based AMS, as follow:

Overall, this research was the first to demonstrate that the number of CR had a greater positive effect on robot performance than MF, clearly suggesting that farmers operating pasture-based AMS should focus, when possible, on increasing herd size. This research also showed how existing data from commercial farms can be better exploited to contribute to new knowledge.

In this thesis, a new and innovative approach to 'efficiency' in pasture-based AMS at animal level was developed. As such, this study is the first to develop a new methodology to identify cows with different levels of 'efficiency'; to quantify differences in performance between them; and to apply the novel concept into an independent field research study.

The research also contributes with the first published study on validation of the SCR HR-LDn SCR tags in grazing systems. The key outcomes of this investigation, which showed a high to very high level of accuracy of the tested tool, gives strong confidence in the application of this technology for its use in both, research and commercial settings. Combining data provided by this sensor together with additional automated data, creates the opportunity to understand, monitor and manage individual cows in the future.

This research was also the first to compare aspects of efficiency of voluntary and batch-traffic systems in AMS. The work demonstrated how, not only system efficiency could be improved in period of low utilisation, but also key outcomes of the present research, namely the concept of 'efficient' cows in AMS, could be managed to lift inefficient cows into more productive categories.

As the adoption of AMS and its integration with grazing systems continues to increase, findings from this thesis will help farmers, researchers and consultants to make more informed decisions when working towards more efficient and productive pasture-based AMS systems.

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