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Physical and economic comparison of pasture-based automatic and conventional milking systems

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ABSTRACT

Automatic milking systems (AMS) have the potential to increase dairy farm productivity and profitability; however, adoption rates, particularly in pasture-based systems, have been lower than expected. The objectives of this study were to compare the physical and economic performance of pasture-based AMS with conventional milking systems (CMS) and to identify gaps for improving AMS productivity and profitability. We used data from 14 AMS and 100 CMS located in the main Australian dairy regions and collected over 3 yr (2015–2016, 2016–2017, 2017–2018). Farms within similar regions and herd sizes were compared. Results showed that all the main physical performance indicators evaluated such as milk production per cow, milk production per hectare, pasture grazed per hectare, or milk solids per full-time equivalent were similar between systems. The AMS farms had higher overhead costs such as depreciation and repairs and maintenance; however, no differences in total labor costs were observed between systems. Profitability, measured as earnings before interest and tax, operating profit margin, and return on total assets, was not significantly different between AMS and CMS. Opportunities for improving pasture utilization, labor efficiency, and robot utilization in AMS farms were identified. Improving efficiency in these areas could improve productivity and profitability of these systems, and therefore increase the interest of this technology.

Key words: robotic milking, profitability, productivity, economics, business analysis

INTRODUCTION

Technological advancements allow dairy farmers to increase the efficiency of use of land, labor, and capital to produce milk, counteracting the long-term decline in the terms of trade (Ruttan, 2002; Kompas and Che, 2004; ABARES, 2019). Automatic milking systems (**AMS**) offer the possibility to increase productivity and profitability by potentially improving labor efficiency, milk production, animal welfare, and lifestyle (De Koning, 2002; Hogeveen et al., 2004; Mathijs, 2004; García and Fulkerson, 2005; Jacobs and Siegford, 2012; Wildridge et al., 2018). Adoption of AMS has grown significantly worldwide since the technology was first introduced in the Netherlands in 1992 (De Koning, 2010), with an estimated 50,000 units on 25,000 farms in operation in 2019 (T. Perrotin, DeLaval, Rochester, MN, personal communication). In some European countries, adoption reaches 23% (Barkema et al., 2015) and it is estimated that half of the new dairy installations are AMS (O'Brien et al., 2015).

Research, development, and extension investment in pasture-based AMS was initiated in New Zealand in 2001 (Jago et al., 2002) and continued in Australia in 2004 with the national program FutureDairy (García et al., 2007). Despite the large number of success stories demonstrating the benefits of pasture-based AMS relating to labor and productivity, and that farmers perceive AMS to be within the 5 most adopted precision technologies by 2025 (Gargiulo et al., 2018), adoption remains below 1% (N. A. Lyons, unpublished data). The reasons for the slower than expected adoption of pasture-based AMS are unclear but could be related to the lack of demonstration of the physical and economic performance of this technology in comparison with conventional milking systems (**CMS**; Bijl et al., 2007; Davies et al., 2010; Steeneveld et al., 2012; Salfer et al., 2017).

Most of the research comparing physical and economic performance of AMS and CMS has been conducted for confined housing systems using simulation models (Hyde and Engel, 2002; Rotz et al., 2003; Salfer et al., 2017). Three studies evaluated the profitability of pasture-based AMS (Jago et al., 2006; Davies et al., 2010; Shortall et al., 2016), however, these investigations were also based on modeling and some of the assumptions used (e.g., increased milk production or

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labor savings) might not be accurate. As far as we are aware, only 2 studies (Bijl et al., 2007; Steeneveld et al., 2012) have used commercial farm data; however, these were based on confined housing systems, which are not directly comparable to pasture-based dairy systems.

The objectives of the current study were therefore to compare the physical and economic performance of pasture-based AMS and CMS using data from commercial Australian dairy farms and to identify gaps for improving AMS productivity and profitability.

MATERIALS AND METHODS

Data Collection

A comprehensive whole-farm physical and economic data set collected over 3 financial years (2015–2016, 2016–2017, and 2017–2018) was used for this study. Data from CMS farms were available through the Dairy Farm Monitor Project (**DFMP**), a benchmarking program that monitors physical and economic performance indicators of close to 250 farms across all dairy regions in Australia (~5% of the total dairy farms in the country, with more than 90% pasture-based systems; Dairy Australia, 2018, 2019). Data were collected by trained staff and validated by an expert panel of farm business consultants to ensure reliability and accuracy throughout the process. Farms participating in DFMP represent a distribution of farm and herd sizes and geographical locations within each Australian dairy region. This program uses a whole-farm business analysis methodology adapted from Malcolm et al. (2005) and is shown in Figure 1. Physical performance indicators were considered those that typically relate to production outputs, physical inputs, productivity, and production efficiency measures (e.g., total milk production, farm area, number of cows, milk per hectare, and labor efficiency). Economic performance indicators were those that relate to income, costs, and business profitability measures (e.g., gross farm income, variable and overhead costs, earnings before interest and tax, operating profit margin, and return on total assets). Income and costs were expressed in Australian dollars (A$; average exchange rate for the period of the study: A$1 = US$0.79) per kilogram of milk solids (**MSD**), where MSD is defined as kilograms of fat + kilograms of protein. Operating profit margin (%) was calculated as earnings before interest and tax/gross farm income × 100. Current prices were calculated by adjusting nominal prices to the year 2017–2018 by using the consumer price index (Australian Bureau of Statistics, 2019). Data from AMS farms were collected following the same methodology as DFMP. A total of 14 AMS farms (~30% of the AMS population in Australia) located in New South Wales, South Australia, Tasmania, Victoria, and Western Australia provided their data over the same 3 yr. This represents the dairy regions where 96% of milk in Australia is produced. The final AMS data set included 9 farms in 2015–2016, 12 farms in 2016–2017, and 9 farms in 2017–2018. Half of the farms (n = 7) participated in 2 out of 3 yr of the study, while the others participated in either 3 (n = 4) or 1 yr (n = 3). In addition, data from 203 CMS farms (~3.6% of CMS Australian population) located in New South Wales, South Australia, Tasmania, and Victoria were used for this study. Data from CMS farms in Western Australia (which represents <3% of the dairy farms in Australia) could not be used because some indicators, such as the number of milking cows or the milking area, were not available. The final CMS data set contained 153 farms in 2015–2016, 143 farms in 2016–2017, and 156 in 2017–2018. The majority of the CMS farms participated in 3 yr of the study (n = 98), whereas the rest participated in either 2 (n = 53) or only 1 yr (n = 52).

Statistical Analyses

Given the known effect of herd size on profitability (Hadley et al., 2002; Dairy Australia, 2013) and the smaller sample size of AMS farms, we applied a selection criterion based on herd size to enable a proper comparison between both systems. Each AMS farm was paired with all CMS farms within a similar region (i.e., "North" for farms located in New South Wales or Western Australia and "South" for farms located in Victoria, Tasmania, or South Australia) and with a similar average number of milking cows (i.e., CMS farms with ±10% of the AMS farm). If a given CMS could be paired with more than one AMS, it was allocated to the group of the closest AMS in terms of the number of cows. This selection process resulted in 14 groups (i.e., as many groups as AMS farms) containing 1 AMS and between 2 and 22 CMS each (in total 14 AMS and 100 CMS farms). These 14 groups were used for the first comparison conducted and termed throughout this manuscript as "All Farms" (**AF**). In addition, a second comparison termed "Top 25%" (**T25**) was also conducted. In this comparison, the 14 AMS and 100 CMS farms were ranked in descending order by the average earnings before interest and tax (**EBIT**) and only the top 25% farms within each system were selected. Therefore, this selection process resulted in 4 AMS and 25 CMS being used for this analysis.

A linear mixed model was used for the statistical analysis. The outcomes of interest related to different physical and economic parameters are shown in Figure

1, and the main explanatory variable was milking system (AMS or CMS). For the AF comparison, group, farm, and year were used as random effects. For the T25 farms comparison, farm and year were included as a random effect. Data preparation and statistical analysis were performed with R software, version 3.6.2 (www.r-project.org/). All variables were checked for assumptions of linearity, normality, and homoscedasticity. If the assumptions were invalid, variables were log-transformed. Parameter estimates were calculated using restricted maximum likelihood procedures. Significance was determined if $P < 0.05$, and a trend toward significance was considered if $P > 0.05$ and $P < 0.10$.

RESULTS

General Farm Information

The 14 AMS farms milked between 130 and 360 cows, had between 40 and 151 ha of milking area, and 2 to 4 people (full-time equivalent; **FTE**) working on the farm. On average, the AMS farms had 4 robotic units (ranging from 2–7 units) and 4 yr of experience operating these systems (ranging from 2–8 yr). The 100 CMS farms selected for the analysis milked between 132 and 395 cows, had between 9 and 250 ha of milking area, and between 3 and 5 people working on the farm.

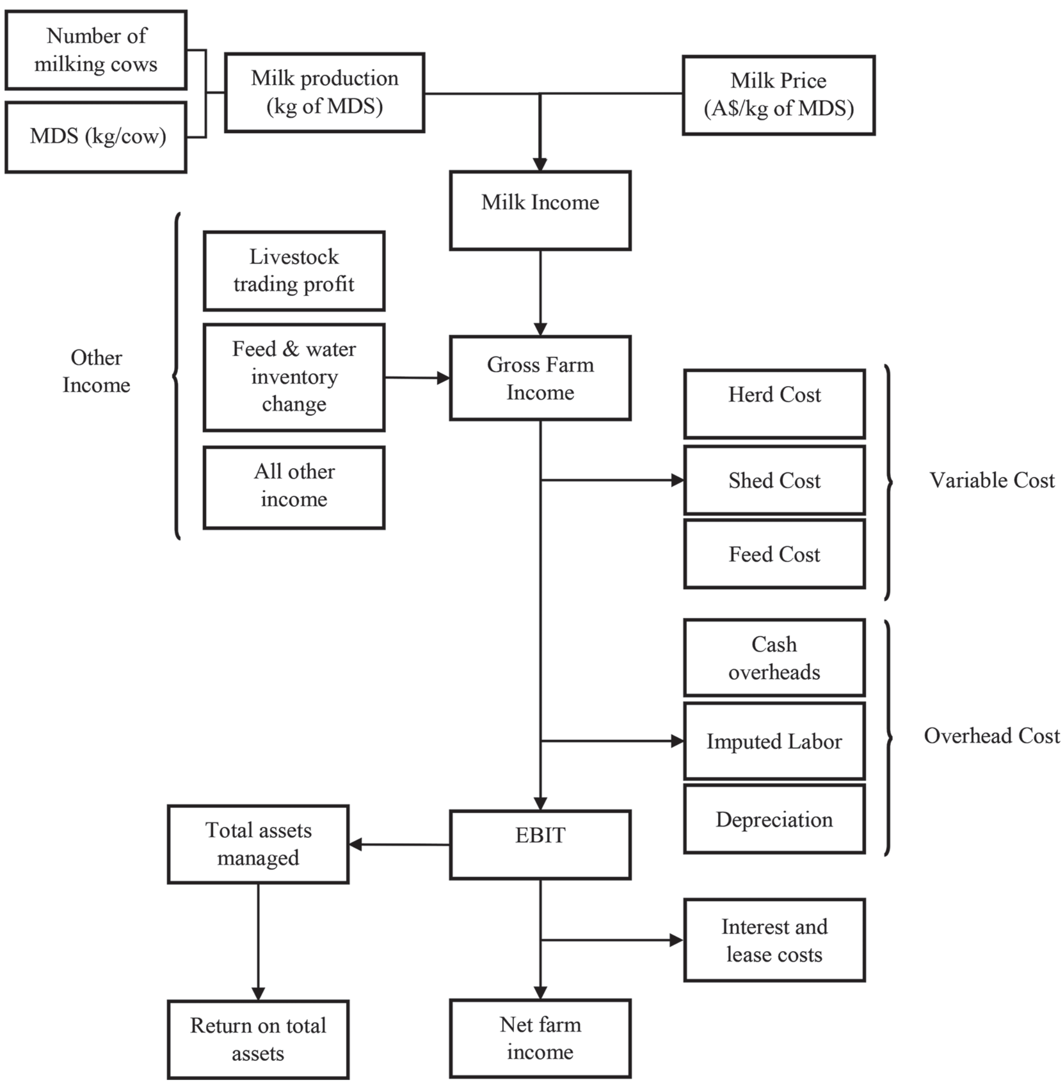

Figure 1. Business analysis methodology adapted from the Dairy Farm Monitor Project. MDS = milk solids; EBIT = earnings before interest and tax.

Table 1. Comparison of the main physical indicators (all farms)

Item	Milking system[1] AMS	Milking system[1] CMS	SED[2]	*P*-value
Log total usable area[3] (ha)	2.24	2.23	0.06	0.957
Retransformed total usable area (ha)	172	171		
Milking area (ha)	90	108	11	0.108
Number of milking cows	222	224	11	0.593
Stocking rate (cows/usable area)	1.36	1.55	0.20	0.362
Log milk production[3] (kg of milk solids/yr)	4.99	5.03	0.03	0.117
Retransformed milk production (kg of milk solids/yr)	98,166	106,503		
Milk solids (kg/ha)	628	745	90	0.214
Milk solids (kg/cow)	466	497	22	0.178
Fat (%)	4.02	4.20	0.10	0.090
Protein (%)	3.28	3.40	0.05	0.018
Pasture grazed (t of DM/ha)	6.2	6.5	0.7	0.724
Purchased feed per cow (t of DM/cow)	2.2	2.4	0.3	0.354
Homegrown feed (%)	66	61	4	0.118
Cows/FTE[4]	109	93	9	0.069
Milk solids/FTE	50,754	45,343	3,820	0.141
Total labor (FTE)	2.3	2.7	0.2	0.087
Employed labor (FTE)	0.8	1.1	0.2	0.105
Imputed labor (FTE)	1.5	1.5	0.2	0.939
Imputed labor (%)	67	62	7	0.451

[1]AMS = automatic milking system; CMS = conventional milking system.

[2]SED = average standard error of the difference.

[3]Total usable area and milk production were log-transformed, given that they did not meet the assumption of normality.

[4]FTE = full-time equivalent (2,400 h/yr, calculated as 48 h/wk for 50 wk).

Physical and Economic Comparison–All Farms

In general, most of the physical variables analyzed (total usable area, milk production, MSD/hectare, MSD/cow, and total labor used) were similar between AMS and CMS (Table 1). Only protein content (%) was lower ($P = 0.018$) for AMS than CMS. Milk income per kilogram of MSD was 3.9% higher for AMS ($P = 0.047$), however gross farm income was similar between systems (A$7.07/kg of MSD on average) ($P > 0.05$). No difference in total variable costs was observed between systems ($P > 0.05$). However, AMS farms had approximately double the amount of total shed costs (shed power and dairy supplies) than CMS farms ($P < 0.001$), a trend to lower total herd cost ($P = 0.070$), and no difference in total feed costs ($P > 0.05$). Alternatively, total overhead costs were 23% higher for AMS ($P = 0.001$), explained by a greater depreciation and repairs and maintenance ($P < 0.05$). Total labor costs, including employed and imputed labor costs (here defined as the allocated allowance for the cost of owner or operator, family, and sharefarmer time in the business), were similar for both systems ($P > 0.05$). Overall profitability measured as EBIT, operating profit margin, or return on total assets (**ROTA**) did not differ between systems ($P > 0.05$), with an average of A$0.49/kg of MSD, 6.17%, and 1.67%, respectively (Table 2). Net farm income was negative and A$0.82/kg of MSD lower for AMS ($P = 0.002$), driven by almost double interest and lease costs for AMS farms ($P < 0.001$).

Physical and Economic Comparison–Top 25% Farms

When comparing top-performing farms, most of the physical indicators such as MSD per hectare, MSD per cow, and MSD per FTE were similar between AMS and CMS ($P > 0.05$) (Table 3). However, the AMS farms milked 75 cows less on average than the CMS farms ($P = 0.014$), had lower total labor (FTE) per farm ($P = 0.017$), and a trend to lower milk production per farm ($P = 0.055$). For most of the economic performance indicators, no differences were observed between the T25 farms in either system (Table 4). Gross farm income and milk income were similar on average between systems (7.08 and 6.23 A$/kg of MSD, respectively; $P > 0.05$). Despite no difference in total variable costs between systems ($P > 0.05$), total shed costs (including shed power and dairy supplies) were about double for AMS farms ($P < 0.001$). The T25 AMS farms had higher depreciation ($P = 0.044$), but similar repairs and maintenance, total labor costs, and total overhead costs ($P > 0.05$). Profitability measured in EBIT and ROTA did not differ between T25 AMS and T25 CMS ($P > 0.05$), with averages of A$1.49/kg of MSD and 4.63% for each system, respectively. However, when profitability was measured as operating profit margin, T25

Table 2. Comparison of the main economic indicators (in A$/kg of milk solids; all farms; average exchange rate for the period of the study: A$1 = US$0.79)

Item	Milking system[1] AMS	CMS	SED[2]	P-value
Gross farm income	7.18	6.95	0.28	0.278
Milk income	6.39	6.15	0.21	0.047
Total variable costs	3.53	3.62	0.24	0.650
Total herd costs	0.25	0.31	0.03	0.070
AI and herd test	0.06	0.12	0.02	0.000
Animal health	0.16	0.15	0.02	0.593
Calf rearing	0.04	0.04	0.01	0.865
Total shed costs	0.46	0.22	0.02	<0.001
Shed power	0.23	0.12	0.01	<0.001
Dairy supplies	0.23	0.11	0.02	<0.001
Total feed costs	2.81	3.07	0.22	0.159
Fertilizer	0.38	0.38	0.05	0.985
Irrigation	0.08	0.20	0.08	0.142
Hay and silage making	0.17	0.18	0.04	0.872
Fuel and oil	0.17	0.11	0.02	0.001
Pasture improvement and cropping	0.11	0.20	0.03	0.005
Other feed costs	0.02	0.06	0.02	0.074
Fodder, grain, and concentrates purchases	1.85	1.89	0.18	0.769
Agistment costs	0.02	0.10	0.04	0.038
Total overhead costs	3.31	2.69	0.19	0.001
Cash overheads	1.31	1.35	0.15	0.787
Registration and insurance	0.12	0.12	0.02	0.556
Repairs and maintenance	0.52	0.38	0.05	0.005
Other overheads	0.24	0.23	0.03	0.627
Employed labor	0.43	0.61	0.12	0.132
Imputed labor[3]	1.18	1.03	0.13	0.262
Total labor costs	1.58	1.61	0.12	0.751
Depreciation	0.82	0.28	0.05	<0.001
Interest and lease costs	1.19	0.62	0.12	0.000
Earnings before interest and tax	0.38	0.59	0.24	0.378
Operating profit margin (%)	4.44	7.94	3.67	0.324
Net farm income	−0.83	0.01	0.26	0.002
Return on total assets (%)	1.41	1.67	0.76	0.716
Cost of production[4]	6.82	6.35	0.32	0.069

[1]AMS = automatic milking system; CMS = conventional milking system.

[2]SED = average standard error of the difference.

[3]Imputed owner or operator and family labor.

[4]Total variable costs plus total overhead costs.

CMS had 6.27% more profit than T25 AMS farms ($P = 0.042$). Net farm income was almost zero for AMS and A$1.09/kg of MSD for CMS ($P = 0.001$), a result associated with the more than double interest and lease costs for AMS farms ($P < 0.001$).

DISCUSSION

The aim of this study was to assess the current physical and economic situation of pasture-based AMS in comparison to CMS, and identify opportunities for improving productivity and profitability of AMS. Our results show that, for pasture-based farms with herd sizes between 130 and 395 cows, AMS and CMS farms can achieve relatively similar physical and economic performance.

Overall profitability, measured as EBIT, operating profit margin, and ROTA, were similar for AMS and CMS despite some differences in specific costs. However, the average profitability across systems was lower than the Australian average since 2006–2007 (EBIT, A$1.32/kg of MSD; operating profit margin, 17%; and ROTA, 4.38%; Dairy Australia, 2018). This could be explained by a combination of lower farmgate milk prices and higher feed costs (driven by dry conditions in some regions), which also reduced the total milk produced (Dairy Australia, 2019). It is important to mention that despite the similarities of EBIT, operating profit margin, and ROTA across systems, net farm income was negative and significantly lower for AMS (Table 2), which was largely associated with increased interest and lease costs for AMS farms.

Our commercial farm-based results contrast with previous modeling-based research for pasture-based and confined housing systems that showed that AMS was less profitable than CMS. In New Zealand, Jago et al. (2006) concluded that the profitability of an established AMS was lower than that of a CMS rotary system, mainly due to the higher interest, depreciation, and repairs and maintenance. In Ireland, Shortall et al. (2016) reported that CMS farms with a medium level of automation achieved higher profit than AMS at 2 different herd sizes (70 and 140 cows), whereas in the Netherlands, Bijl et al. (2007) showed that profitability was lower for AMS mainly due to larger overhead costs. On the contrary, Steeneveld et al. (2012), also in the Netherlands, concluded that both systems achieved similar profitability, and Salfer et al. (2017) showed that in the United States for herd sizes of 120 and 240 cows, AMS were more profitable. However, Salfer et al. (2017) also showed that at larger herd sizes (1,500 cows), CMS achieved better results mainly because they tend to run at full capacity for almost 24 h/d, reducing the required investment. The differences in research results between the current and previous studies is indicative of the number of factors influencing profitability, and how these vary between regions and feeding systems. Nevertheless, in comparison with previous research, our study is based on robust data systematically collected on commercial farms from different regions and a range of herd sizes.

Previous studies (Wagner-Storch and Palmer, 2003; Wade et al., 2004; De Koning, 2010), have suggested a potential of 2 to 10% increase in milk production on AMS farms mainly driven by an increase in milking frequency and better overall management, which is linked to improved animal comfort, health, and reproduction. Yet, in the current study, we found no difference in milk production between systems on either AF or T25 farms (Tables 1 and 3, respectively). However, previous research was mostly conducted in confinement housing where cows consumed a TMR and typically achieved higher DMI than in grazing conditions (Kolver and Muller, 1998). In addition, pasture-based AMS milking frequency is usually lower than AMS in confinement housing (Lyons et al., 2014), mainly due to longer walking distances. It is possible that the lack of difference in milk production for pasture-based AMS is explained by a combination of lower DMI and lower milking frequency, which is not much greater on average than that of CMS farms (Lyons and Kerrisk, 2017).

The main focus in pasture-based systems such as those in Australia is usually placed on optimizing pasture utilization to reduce variable costs, rather than only increasing individual cow production by achieving high DMI (Dairy Australia, 2013). The perceived adverse effects of AMS on pasture utilization was one of the initial concerns of the technology (van Dooren et al., 2004). Such perceptions had already been shown to be unfounded under controlled experiments (Dickeson,

Table 3. Comparison of the main physical indicators (top 25% of farms)

	Milking system[1]			
Item	AMS	CMS	SED[2]	*P*-value
Total usable area[3] (ha)	174	264	79	0.286
Milking area (ha)	100	123	26	0.382
Number of milking cows	209	284	28	0.014
Stocking rate (cows/usable area)	1.53	1.54	0.49	0.977
Milk production[3] (kg of milk solids/yr)	108,232	146,819	18,727	0.055
Milk solids (kg/ha)	786	740	199	0.825
Milk solids (kg/cow)	523	519	48	0.945
Fat (%)	3.89	4.18	0.21	0.188
Protein (%)	3.31	3.39	0.09	0.405
Pasture grazed (t of DM/ha)	6.0	7.1	1.6	0.532
Purchased feed per cow (t of DM/cow)	2.7	2.3	0.5	0.465
Homegrown feed (%)	57	65	5	0.160
Cows/FTE[4]	120	104	18	0.379
Milk solids/FTE	62,692	51,636	6,593	0.104
Total labor (FTE)	1.8	2.9	0.4	0.017
Employed labor (FTE)	0.7	1.6	0.5	0.109
Imputed labor (FTE)	1.1	1.3	0.3	0.460
Imputed labor (%)	59	49	13	0.475

[1]AMS = automatic milking system; CMS = conventional milking system.

[2]SED = average standard error of the difference.

[3]Total usable area and milk production were log-transformed, given that they did not meet the assumption of normality.

[4]FTE = full-time equivalent (2,400 h/yr, calculated as 48 h/wk for 50 wk).

2010; Clark et al., 2016) and were again confirmed in this study using commercial farm data. Yet, despite AMS and CMS farms achieving on average 6.2 t of DM/ha of pasture grazed (ranging from 2.9–9.7 t of DM/ha), this is still much lower than the 13.5 t of DM/ha reported by Clark et al. (2016) under experimental conditions, and the ~22 and ~12 t of DM/ha reported by the same research group under full (Fariña et al., 2011a) and partial irrigation (Fariña et al., 2011b) for a CMS research farm. Pasture harvested has been previously linked to farm profitability (Ramsbottom et al., 2015). In this data set, the bottom 25% farms (ranked by pasture grazed/ha) used only 3.3 t/ha of pasture and achieved A$0.32/kg of MSD of EBIT, whereas the T25 farms used 10.9 t/ha and achieved A$1.24/kg of MSD of EBIT. Although profitability is multifactorial, this clearly shows the importance of optimizing pasture utilization on-farm.

The possibility of reducing labor requirements on-farm has also been mentioned by farmers as a major reason to invest in AMS (Hogeveen et al., 2004; Mathijs, 2004). This opportunity should be particularly attractive to Australian farmers, given that the country has the largest minimum wage within all the main dairy exporting countries (Australian Government, 2019; Eurostat, 2019; Gobierno Argentino, 2019; INE, 2019; NZ Government, 2019). However, our results showed that on average both systems had similar total labor use (employed, imputed, and total in FTE), labor efficiency (cows/FTE or MSD/FTE), and labor costs (total, imputed, and employed labor costs in A$/kg of MSD). This contrasts with the study conducted in Europe by

Table 4. Comparison of the main economic indicators (in A$/kg of milk solids; top 25% of farms; average exchange rate for the period of the study: A$1 = US$0.79)

Item	Milking system[1]			
	AMS	CMS	SED[2]	*P*-value
Gross farm income	7.07	7.09	0.57	0.977
Milk income	6.37	6.09	0.42	0.513
Total variable costs	3.53	3.13	0.33	0.243
Total herd costs	0.25	0.29	0.05	0.462
AI and herd test	0.07	0.11	0.03	0.141
Animal health	0.13	0.13	0.03	0.929
Calf rearing	0.05	0.05	0.03	0.991
Total shed costs	0.43	0.20	0.04	0.000
Shed power	0.20	0.11	0.01	<0.001
Dairy supplies	0.24	0.09	0.03	0.000
Total feed costs	2.85	2.64	0.30	0.505
Fertilizer	0.29	0.36	0.06	0.359
Irrigation	0.06	0.08	0.05	0.781
Hay and silage making	0.13	0.17	0.07	0.570
Fuel and oil	0.10	0.10	0.03	0.976
Pasture improvement and cropping	0.08	0.16	0.05	0.174
Log other feed costs	−1.40	−1.18	0.01	0.596
Retransformed other feed costs	0.04	0.07		
Fodder, grain, and concentrates purchases	2.13	1.59	0.27	0.064
Agistment costs	0.02	0.11	0.07	0.293
Total overhead costs	2.24	2.25	0.32	0.970
Cash overheads	1.06	1.28	0.25	0.395
Registration and insurance	0.10	0.10	0.03	0.968
Repairs and maintenance	0.36	0.31	0.07	0.471
Other overheads	0.16	0.19	0.04	0.525
Employed labor	0.43	0.68	0.19	0.223
Imputed labor[3]	0.74	0.70	0.21	0.845
Total labor costs	1.15	1.36	0.17	0.241
Depreciation	0.45	0.27	0.09	0.044
Interest and lease costs	1.33	0.60	0.18	0.000
Earnings before interest and tax	1.28	1.70	0.22	0.073
Operating profit margin (%)	17.96	24.23	4.22	0.042
Net farm income	−0.03	1.09	0.29	0.001
Return on total assets (%)	4.09	5.18	0.77	0.180
Cost of production[4]	5.77	5.39	0.53	0.484

[1]AMS = automatic milking system; CMS = conventional milking system.

[2]SED = average standard error of the difference.

[3]Imputed owner or operator and family labor.

[4]Total variable costs plus total overhead costs.

Bijl et al. (2007), who reported that AMS had 22% lower total FTE (mainly given by lower owner labor) and 28 and 25% higher labor efficiency (measured in milk/FTE and cows/FTE, respectively). However, our results are in line with Steeneveld et al. (2012), who reported no differences between AMS and CMS in total FTE, cows/FTE, milk/FTE, and labor costs (€/100 kg of milk). Steeneveld et al. (2012) hypothesized that the AMS farms could have been planning to expand the herd instead of reducing labor, or that in reality, net labor savings could not be as large as expected in AMS (some tasks disappear, but new tasks appear once the robots are installed). Anecdotal evidence from a survey by the authors of the current study of 19 farmers from Australia, Ireland, and New Zealand indicated that they primarily invested in this technology to acquire more flexibility in time management, to reduce the physical effects on the body from repetitive manual tasks, and because of labor availability. Only a minor proportion mentioned that they adopted AMS to reduce total labor costs (J. Gargiulo, unpublished data).

A large variability in total labor, labor efficiency, and labor costs between AMS farms was found in the present study. The farm with the lowest labor efficiency (ranked by MSD/FTE) produced 19,000 kg of MSD/FTE, managed 55 cows/FTE, and spent the equivalent of 56% of the milk income in total labor costs. In contrast, the farm with the highest labor efficiency produced 97,792 kg of MSD/FTE, managed 181 cows/FTE, and spent 15% of the income in total labor costs. Previous studies conducted in the United States on 33 AMS farms in confinement housing reported an average of 90 cows/FTE with a standard deviation of 34 cows/FTE (Siewert et al., 2018). A study in Australia conducted by Molfino et al. (2014), in which 5 pasture-based AMS were monitored monthly for a whole year, showed that AMS farms managed on average 181 cows/FTE (ranging from 100–273 cows/FTE). This represents a 54% increase in labor efficiency in comparison to the average AMS in our study. Combined, these findings indicate that greater labor efficiency can be achievable on some AMS farms, and that this could have a potential effect on farm profitability.

Overhead costs (such as repairs and maintenance and depreciation), as well as interest and lease costs, were higher for AMS farms and accounted for the second largest costs after feed. These findings are similar to those reported in previous research (Steeneveld et al., 2012; Shortall et al., 2016; Salfer et al., 2017). The fact that an AMS operates constantly without direct human intervention, and that many of the major components are electronics and moving parts, might explain the need for more frequent repairs and maintenance. Additionally, most AMS farms have to commit to scheduled preventive services as a warranty requirement from the robot manufacturer (Lely, 2019). It is possible that not all CMS farms do regular maintenance, and therefore have a lower cost in comparison to AMS. In addition, some of the robot components, such as cameras, lasers, or arms, could be more expensive than the average equipment on a conventional dairy. The higher depreciation for AMS was expected given the higher initial capital investment of the technology. In this study, depreciation was calculated by applying a fixed rate of 10% to the market value of all owned plant and equipment assets on the farm (Dairy Australia, 2016), and a 7.14% rate for the AMS equipment. Interest and lease costs were higher for AMS, presumably due to higher interest paid for borrowed funds associated with the robot equipment. It is also worth mentioning that, in general, most of the finance for the robotic units is on relatively short-term equipment loans that require principal to be repaid in a short period. Alternatives such as secondhand robots or robot leasing plans are available in the market and might represent an option to reduce these initial costs.

Given the abovementioned factors, optimizing how efficiently the capital invested is used should have a significant effect on profitability. One key performance indicator usually suggested for measuring this is the robot utilization, or kilograms of milk harvested per robot per day (Castro et al., 2012; Tremblay et al., 2016; Salfer et al., 2017). In the current study, the average robot utilization per farm was 1,073 kg/robot per day, ranging between 597 and 1,367 kg/robot per day (data not shown). The T25 farms achieved on average 1,222 kg/robot per day, which is 14% higher than the average for AF. This variability might be explained by factors such as the number of cows managed per robot, the milking frequency per cow, and the milk production per cow. Previous studies on Australian pasture-based AMS report an average of 1,263 kg/robot per day and speculate that there is a potential to achieve at least 1,955 kg/robot per day (Lyons and Kerrisk, 2017). Data from 635 North American AMS farms in confinement housing collected over 4 yr averaged 1,626 kg/robot per day and had a standard deviation of 397 (Tremblay et al., 2016). Castro et al. (2012), using information from 34 Spanish AMS farms, reported an average of 1,506 kg/robot per day with a maximum of 2,182 and a minimum of 650 kg/robot per day. It is clear that despite the higher milk harvested per robot in AMS in confinement housing, there is also room for improving robot utilization within pasture-based AMS. If we assume an average milk price of A$0.46/L, a value of A$690,000 for 4 AMS (plant and equipment), 7.14% of the AMS price for depreciation, 6% for interest, and 6% for repairs and maintenance, the most inefficient farm in our study produces an average of 597 kg/robot per day and spends 33% of the milk income on depreciation, interest, and repairs and maintenance. On the other hand, the most efficient farm produces 1,367 kg/robot per day and spends only 14% on these costs. Changes in variables such as milk price, AMS value, lifespan, and interest rates have an effect on profitability, but are in general out of the farmer's influence. However, robot utilization is a factor that the farmer can control, and the current gap in efficiency could be addressed to increase profitability.

CONCLUSIONS

This study provides a robust analysis of the current level of profitability of pasture-based AMS, taking into consideration differences in herd sizes and regions. The study also identifies key differences with CMS, which are important for farmers who are assessing investment in this technology. Our results showed that despite relatively minor differences in performance and farm economics, pasture-based AMS farms can achieve similar levels of productivity and profitability than pasture-based CMS farms. Opportunities for improving pasture utilization, labor efficiency, and robot utilization on AMS farms have been identified. Improving efficiency in these areas could have a significant effect on the profitability of these systems, making them more attractive and therefore potentially increasing uptake of the technology.

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