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EDITED BY
Geoffrey E. Dahl,
University of Florida, United States

REVIEWED BY
Giovanni Buonaiuto,
University of Bologna, Italy
Deise Aline Knob,
University of Giessen, Germany

*CORRESPONDENCE
Jake S. Thompson
jake.thompson2@nottingham.ac.uk

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Could living space provision in the first lactation have long term effects on milk production in housed dairy cows?

Jake S. Thompson*, Christopher D. Hudson and Martin J. Green

School of Veterinary Medicine and Science, University of Nottingham, Sutton Bonington, United Kingdom

The productive life of a dairy cow centres milk production, reproduction, and health status. Current management practices, including living space provision, for first lactation animals are highly variable and associated with large impacts on reproduction and milk production. The aim of this investigation was to explore the potential lifetime effects on milk production when primiparous cows are provided with additional living space. This prospective study used two cohorts of cows from a previous randomised controlled trial that used matched pairs of cows, with one in each pair provided with 3m^2 living space ("Control") and the other 6.5m^2 living space ("High"). In terms of lifetime milk production, the high space group consistently performed better; mean milk volume per lifetime day in the control space group was 37.55L versus 38.92L in the high space group. A random effects model was used to account for repeated measures within cow and revealed significant and substantially increased milk production in the high space group at less than 400 days in milk, between 800–1000 days in milk and greater than 1200 days in milk, compared the control space cohort. A Cox-Proportional hazards model was built to investigate time to herd exit, no difference was identified between the groups. This research allows cautious insights into the potential for the impact of increased space allowance for primiparous dairy cows on lifetime milk production. This could have important implications relating to societal perception, health, welfare, economics and environment impact, which could aid more sustainable approaches to managing dairy cows.

KEYWORDS
environment, heifers, space allowance, survival, sustainability

1 Introduction

Dairy cow longevity has been defined as total lifespan or duration of productive life (Schuster et al., 2020; Vredenberg et al., 2021). Societal expectation of livestock life expectancy will influence the demand on acceptable productive lifespan, especially as early culling is most likely to occur due to disease (De Vries and Marcondes, 2020).

Increased longevity has been associated with sustainability of the industry, particularly in the areas of environmental emissions, economics and societal license to produce (Hansen Axelsson, 2013; Barkema et al., 2015; Grandl et al., 2019; Vredenberg et al., 2021; Gambonini et al., 2022). There is a current trend of longevity being shorter in high production systems due to involuntary culling, which is a problem for sustainability and welfare (Dallago et al., 2021). The sustainability link with longevity exists largely through the reduced need for the rearing of future replacements (Buonaiuto et al., 2024; Clasen et al., 2024). Technical change and productivity growth on farms has been associated with improved longevity, indicating adoption of new information has had positive impacts in these areas (Ali, 2021). Production performance efficiency is not directly linearly related to longevity, with cows later than sixth parity having lower production outputs, therefore there is a balance to be struck between efficiency associated with longevity and economic performance (Owusu-Sekyere et al., 2023). It is important to consider how to sustainably improve metrics such as longevity and production using methods that are both seen as positive by society and based on evidence for management of livestock; it is also important to consider that a longer life does not necessarily translate into a better life, especially when accounting for welfare, profitability and production efficiency (Farm Animal Welfare Council, 2009; Schuster et al., 2020).

The productive life of a dairy cow centres around performance in the areas of milk production, reproduction, and health status (Hu et al., 2021). Together these factors can be used to assess the overall resilience of an individual to their environment and farm management practices (Röcklinsberg et al., 2016). Analyses regarding factors which influence longevity have shown that investments into farm buildings are significant contributors to longevity, with a likely synergistic effect with welfare improvements (Owusu-Sekyere et al., 2023). The economics of dairy farming (and the sustainability of a dairy business) relies heavily on the survivability of individuals within a herd (Kerslake et al., 2018; Vredenberg et al., 2021). To be profitable to a business a cow must produce sufficient milk to more than cover input costs during its lifetime on the farm; this links longevity with production efficiency (Boulton et al., 2017).

The primary reasons reported for replacing dairy cows in a herd are infertility, disease or poor production (Compton et al., 2017; Bugueiro et al., 2019). The way in which primiparous cows are managed around their first calving and lactation is likely to be associated with lifetime performance metrics (Brickell and Wathes, 2011; Sawa and Bogucki, 2017; Puerto et al., 2021) and overall longevity (Dallago et al., 2021). Current common management practices will mean that first lactation animals are often managed within an indoor housed environment (for at least part of a year); the nature of these environments can be highly variable, particularly in terms of total space availability (Thompson et al., 2020). A recent study showed that there was a distinct variation in the housing supplied to dairy cows in Great Britain, with the average total space available per cow being a mean of 8.3m^2 from a range between 5.4 to 12.7m^2 (Thompson et al., 2020). This variation was associated with cubicle stocking density, farm location, farmer attitude and outdoor access (Thompson et al., 2020). This research led to a new definition of an area within dairy cow accommodation: Living space. Living space describes the area within dairy cow accommodation which is greater than that considered a baseline requirement per cow, excluding lying areas (Thompson et al., 2020). The mean living space was 2.5m^2 (range: 0.5m^2 - 6.4m^2). Although total space per cow is a current standard metric within the industry, the novel term "Living Space" provides a more nuanced detail about shed design as it accounts for cubicle dimensions for different breeds and fluctuations in cubicle stocking density. It then standardises the excess passageway or loafing area space above a minimum baseline during housing. Increased living space in high yielding Holstein dairy cows has been shown to lead to increased milk production for primiparous compared to multiparous cows (Thompson et al., 2022). Other research has assessed the impact of primiparous-cow-only groups based on improvements to welfare (Bøe and Færevik, 2003) and production (O'Connell et al., 2008) and reported that variables such as facility design have the potential to impact upon risk of culling and milk production.

A stochastic simulation model was created to further explore the potential economic impacts of these results. The estimated direct financial comparison over cow's lifetime dependent on living space scenario showed a median increase in financial return of +£87.61 per cow per year when provided high living space (Thompson et al., 2024). The associated return on the initial investment was deemed to be dependent on method of providing additional space, interest rates, and the duration of loan repayments (Thompson et al., 2024).

The aim of this research was to provide insight into whether there are long-term effects of providing additional living space to primiparous dairy cow in terms of milk production. Our null and alternative hypotheses were:

- Null: There is no difference in lifetime milk volume production between primiparous dairy cows, dependent on living space allowance provision (9m^2 or 14 m^2 total space per cow) in first lactation.
- Alternative: There is a difference in cumulative lifetime milk volume production between primiparous dairy cows, dependent on living space allowance provision (9m^2 or 14 m^2 total space per cow) in first lactation.

2 Methods

This work follows on from a series of publications linked to the exploration of housed environments for dairy cows. A year-long randomised controlled trial (RCT) to explore the effects of living space on all year-round housed Holstein dairy cows was previously undertaken (Thompson et al., 2022). That RCT explored this question by pairing dairy cows based on parity and calving date, and randomly assigning each individual into a different pen environment for the remainder of the lactation. This was undertaken for primiparous and multiparous animals in the original study. The two scenarios tested were:

- Single control space group: 9m^2 total space per cow including 3m^2 of living space per cow
- Single high space group: 14 m^2 total space per cow including 6.5 m^2 of living space per cow

In the original study there were the same number of cows present in each group (35 of mixed parities at any one point in time); a total of 75 animals entered each trial group over the trial duration, of which 38 were primiparous heifers). Cow entry initially occurred at any day in milk (DIM) during lactation, then only new cow pairs (<14DIM) entered once the trial commenced (Thompson et al., 2022). All other aspects of the environment, management and animal husbandry remained identical between groups. These animals completed one lactation in either the control or high space group and then resumed life back in normal management conditions in the herd.

2.1 Trial design

This research was undertaken following ethical review, granted by the Home Office and the University of Nottingham ethical review committee; license number MG_P07992717. The data collection for this project occurred at the University of Nottingham's (UK) freestall dairy cow housing facility.

A cohort study design was used to follow a population of primiparous cows through their lifetime following allocation to different living space allowances during their first lactation. The aim was to assess the impact that the different housing conditions in first lactation had on lifetime milk production. Dairy cows that entered the RCT during their first lactation were subsequently followed until herd exit or 26th January 2025 (2022 days after the end of the initial trial). Therefore, a total of 76 primiparous cows were used to evaluate lifetime milk production (n = 38 matched pairs per group).

The study herd comprised of 350 pedigree Holstein cows, in an all year round housed automatic milking system. Lactating cows were housed in deep sand bedded cubicles in early lactation and in a sawdust-based mattress cubicle system pen in late lactation. They had continual access to the same partial mixed ration, with additional concentrate feed being provided according to yield in the robotic milker. Milking was performed in a robot system with 7 Lely A4 robots (1x per group (with a maximum stocking rate of 55 cows per robot). All management routines were identical for all cows across both treatment groups throughout their lives.

2.2 Data analysis

Data were collected from the on-farm management Uniform-Agri software (calving and exit dates) and Lely Horizon system (daily milk production data) (Uniform-agri, 2023; Lely, 2025). Data analysis was conducted using R statistical software (R Core Team, 2025), version 4.4.2 using the tidyverse package (Wickham, 2019) and minpack.lm (Elzhov et al., 2016).

2.2.1 Individual cow descriptive analysis

Individual cow daily milk recording data were collected and anomalous results removed. These data were aggregated such that total milk production and survival times were calculated for each cow and treatment group. These outputs were used to describe the mean daily production by cohort. Distributions of milk volume production per day between trial group were compared visually using summary statistics (range, IQR, mean, median) and graphically.

2.2.2 Individual cow milk production model

The primary outcome milk production per day of life (repeated measures per cow) was evaluated using a mixed effects model. To assess the impact of group membership on daily yield over time, an outcome variable was defined as individual cow daily yield and the inferential predictor variables were group (high or control space in parity one), days in milk (DIM), used as a categorical indicator with 200-day intervals), and the interaction between group and DIM, as shown in Equation 1. Different categorical DIM intervals were explored to identify the model of best fit. The model took the following form:

$$Y_{ij} = \beta_0 + \beta_1 X1_j + \beta_2 X2_j + \beta_3 X1_j * X2_j + u_j + e_{ij} \quad (1)$$

where Y_{ij} denoted the ith daily milk yield for cow j, β_0 the model intercept, $X1_j$ an indicator variable for space allowance group for jth cow, $X2_j$ a covariate for days in milk category for the jth cow, $X1_j$ * $X1_j$ represents an interaction term between group and DIM category, β were the coefficients for respective covariates, and u_j and ε_{ij} represented model error terms at cow and milk reading level respectively, assumed to have a mean of 0 and variances σ_u and σ_e respectively. Model fit was evaluated using conventional residual analysis.

To visualise the data, mean daily milk yields were calculated for cowsin the two living space groups (n=38 per cohort) and displayed graphically, as shown in Equation 2.

$$\textit{Mean daily milk per cow} = \frac{\textit{Cumulative milk yield from first calving per cohort}}{(\textit{no days post first calving event} * 38 \textit{ eligible cows})} \quad (2)$$

2.2.3 Survival analysis

Cow survival in the herd was described for each cohort using summary statistics (range, IQR, mean, median). These data, based on matched pairs of cows between the two space allocation groups, was not normally distributed: a Mann-Whitney U test was performed to test for a difference in survival between the two groups.

In addition, conventional survival analysis was conducted to assess the difference in longevity between space allocation groups. The outcome was days to removal from the herd, control versus high space. The initial randomised pairing of cows on entry to the

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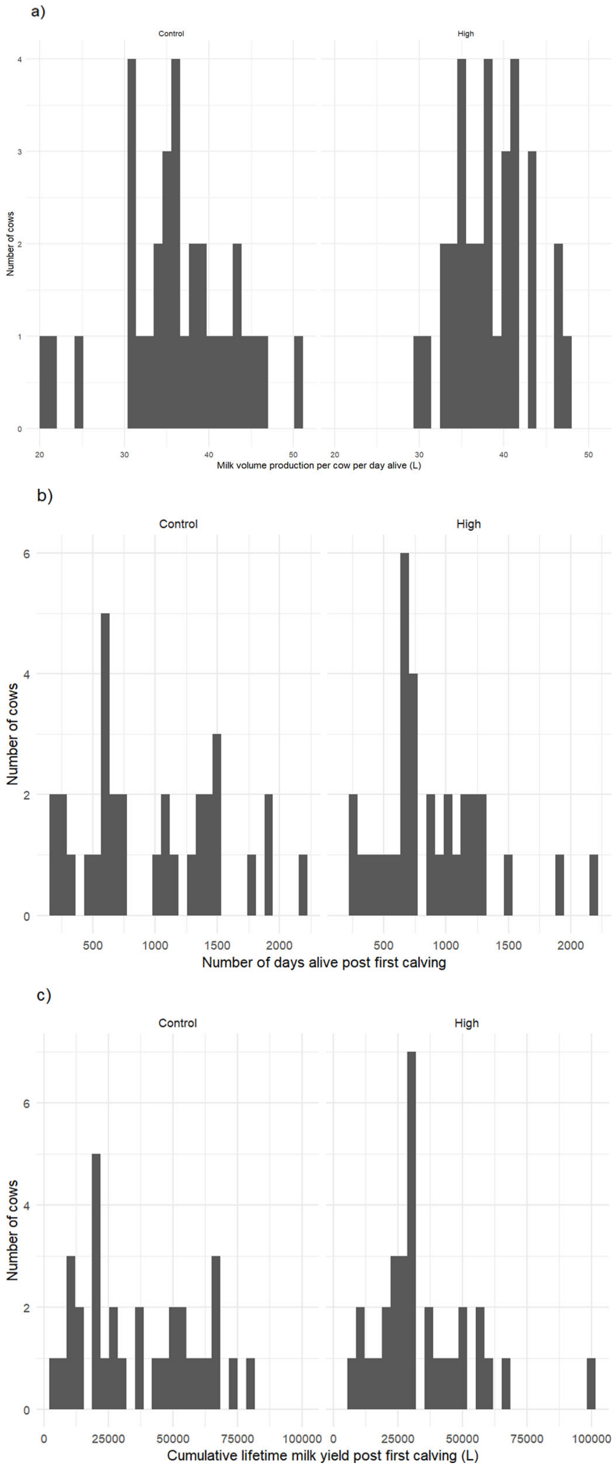

FIGURE 1
(a) A graph to show the variation in average daily lifetime yield between the two cohort of dairy cows post first calving event once entered the original living space trial. **(b)** A graph to show the variation in days alive post calving between the two cohorts of dairy cows having entered the original living space trial. **(c)** A graph to show the variation in cumulative yield between the two cohorts of dairy cows post first calving event once entered the original living space trial.

trial provided control of initial group characteristics (e.g. days in milk at trial entry and calving month).

A Kaplan–Meier plot was used to visualise survival curves and a Cox proportional hazards models built to estimate the impact of cohort. The Cox proportional model equation can be described as (Equation 3):

$$h(t) = h_0(t)x \;\; \exp(\beta_1 x_1) \tag{3}$$

where t was the time alive post first calving, $h(t)$ the hazard function which was dependent on a baseline hazard $h_0(t)$, and the x_1 covariate of cohort group was tested with coefficient $\beta 1$.

3 Results

3.1 Individual cow descriptive results

A control space cow produced a mean of 37.6L milk volume per day during her lifetime (total= 1, 253, 960L in 33390 total days) compared to a high space cow that produced a mean 38.9L milk volume per day (total = 1, 260, 017L in 32371 total days). With Figure 1c illustrating the distribution of lifetime yield for each cow dependent of cohort.

In their lifetimes the distributions of individual milk production volume production per day per group were as follows (Figure 1a):

Control space cows: 1st Quartile = 29.0L, Median = 34.0L, Mean = 33.3L, 3rd Quartile = 38.1L. High space cows: 1st Quartile = 31.6L, Median = 34.8L, Mean =34.4L 3rd Quartile = 38.5L.

3.2 Group level production

3.2.1 Model results

The full results of the random effects model are presented in Table 1. The model showed significant and substantially increased milk production in high space cows at less than 400-DIM, between 800–1000 DIM and greater than 1200-DIM, compared the control space cohort (Figure 2). Residual analysis indicated good model fit with normally distributed residuals at both milk yield reading and cow levels.

3.2.2 Group level data visualisation

To aid visualisation of these patterns further the mean daily yield per cow per total days post calving was compared for each cohort (Figure 3). This shows that expected daily production was consistently greater in the high space group (until day 1400 after first calving, which was when sample size is reduced).

TABLE 1 Results of model 1 outputs for predicting daily milk production dependent on cohort group and days post first calving categories.

Predictors	Estimates	Confidence intervals	P-value
(Intercept)	40.13	37.70 – 42.56	
trial group [High]	1.97	-1.47 – 5.41	0.261
days group [d200400]	-5	-5.40 – -4.59	**<0.001**
days group [d400600]	5.49	5.08 – 5.89	**<0.001**
days group [d600800]	-2.73	-3.19 – -2.27	**<0.001**
days group [d8001000]	4.23	3.76 – 4.69	**<0.001**
days group [d10001200]	-0.84	-1.37 – -0.30	**0.002**
days group [d12001400]	0.03	-0.52 – 0.58	0.921
days group [d1400p]	-3.03	-3.61 – -2.45	**<0.001**
trial group [High] × days group [d200400]	-0.27	-0.84 – 0.29	0.343
trial group [High] × days group [d400600]	-1.67	-2.25 – -1.10	**<0.001**
trial group [High] × days group [d600800]	-1.71	-2.35 – -1.07	**<0.001**
trial group [High] × days group [d8001000]	-0.03	-0.71 – 0.64	0.921
trial group [High] × days group [d10001200]	-5.82	-6.59 – -5.06	**<0.001**
trial group [High] × days group [d12001400]	1.52	0.62 – 2.41	**0.001**
trial group [High] × days group [d1400p]	1.29	0.45 – 2.13	**0.003**
Random Effects			
σ^2	100.53		
$\tau_{00\ EarTag}$	57.69		
ICC	0.36		
N_{EarTag}	76		
Observations	58814		
Marginal R^2/Conditional R^2	0.087/0.420		

Bold: indicates a significant estimate for a predictor at less than P = 0.05.

3.3 Survival results

The summary statistics for lifetime days spent in herd following first calving for the 38 eligible pairs were as follows (Figure 1b):

- Control group cohort were observed to have had a mean lifetime period after first calving of 945.6 days with a median of 837 days (1st Qu.: 584.0, 3rd Qu.: 1384.2).
- High space cohort had a mean lifetime period after first calving of 918.8 days with a median of 815.5 days (1st Qu.: 652.5, 3rd Qu.: 1190.2).

The Kaplan-Meier plot of time alive post first calving is shown in Figure 4. The results of the Mann-Whitney test (P-value = 0.82) did not indicate a significant difference in survival times between

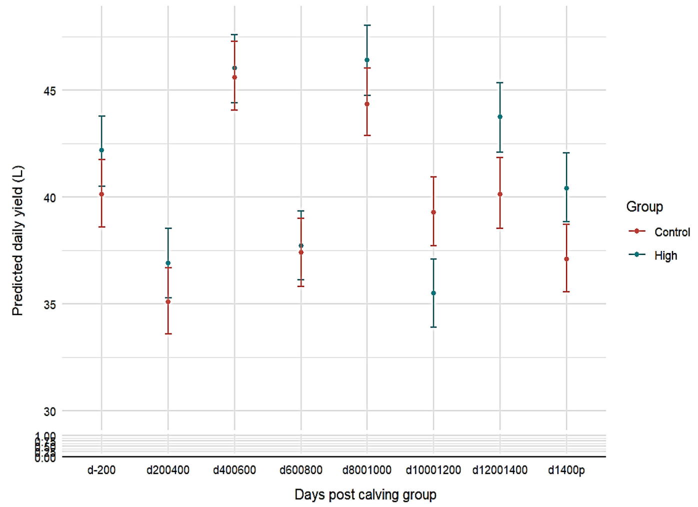

FIGURE 2
A graph to show model 1 output of predicted daily milk production dependent on cohort and days post first calving category.

space allocation groups. The associated results of the Cox-Proportional model for the hazard of herd removal indicated no difference could be identified between the high space and control space groups (hazard ratio = 1.07, SE:0.233, $P = 0.76$) with a median time alive post first calving of 816 days for cows in the high space group (95% CL; 687-1128) and 837 days for cows in control group (95% CL; 634-1278).

4 Discussion

This research provides the first preliminary evidence that there are associations between space allowance within the housed environment for primiparous dairy cows and lifetime milk production. It appears housing conditions of primiparous cows has potential to lead to increases in milk production for a period longer than during the first lactation. This has implications for cow productivity as well as welfare, which could help to facilitate more sustainable approaches to managing dairy cows and improving dairy businesses.

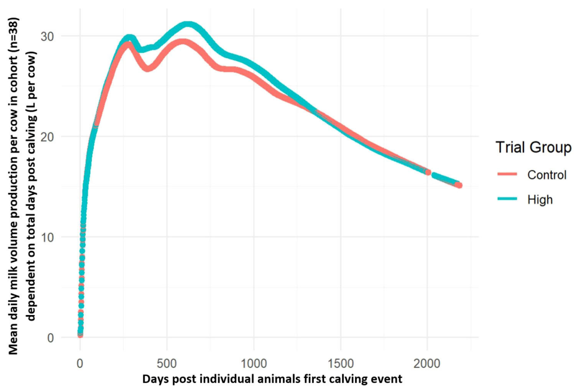

FIGURE 3
A graph to show the group level mean daily milk production pattern dependent on cumulative performance over lifetime days for each cohort post entry into trial conditions.

The difference in first lactation milk yield for individual cows, described in Thompson et al., 2022, showed important yield differences during the time of exposure to different space allocations. The findings in this research indicate that differences in milk yield continued beyond the initial study of the first lactation. Lifetime performance traits have been previously associated with high first lactation yields but poorer reproductive performance (Fahim et al., 2025). This study identified a similar outcome but used randomised matched pairs that reduced the impact of potential confounding factors.

There are a number of plausible biological reasons for our results, although there is limited evidence to support a causal pathway. Reasons for a prolonged impact of additional living space beyond the time the additional space was provided include; epigenetic changes (Ratan et al., 2023), behavioural changes (feeding patterns or lying time differences as shown in the original study), or long-term metabolic changes. It is unclear which, if any, of these factors played a role in the alteration of lifetime milk yield. Epigenetics have been shown to be associated with diet (Lesta et al., 2023), and since the first parity animals in this study produced more milk, it is possible they consumed more food which led to epigenetic change. Similarly, mammary gene expression has been related to behaviours such as milking frequency and milk yield in short term trials (Wall et al., 2013), therefore another potential carry over effect to enhance future milk yields could be associated with such mammary gene expression. The exact biological mechanism of the effect identified in this

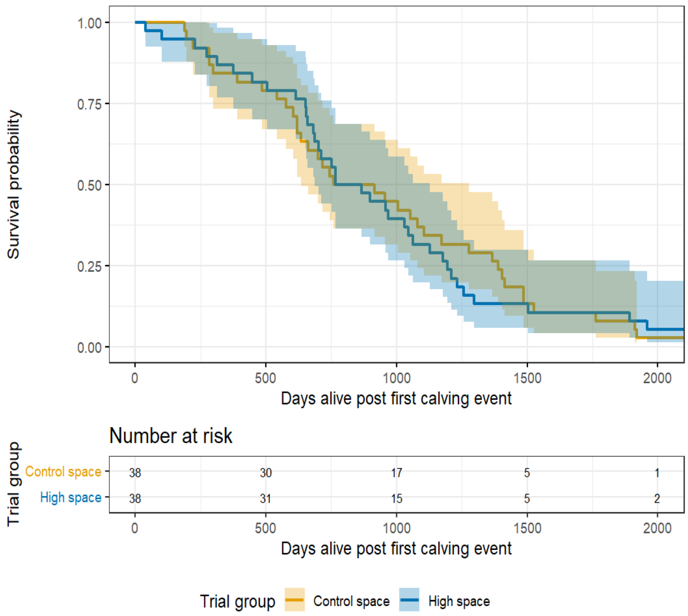

FIGURE 4
Results of time to herd exit post first calving analysis using a Kaplan–Meier plot of survival for the high space (blue) and control space (yellow) cohorts. Respective colour shading represents the 95% confidence interval. Risk table showing the associated number of cows alive at specified timepoints.

research remains unknown however and would benefit from further research.

When assessing the productive days alongside production data to calculate total lifetime yields, at group-level data the combined lifetime milk production in the high space group was 6057 L more than the control space group, produced over 1, 019 fewer lifetime days. This does not account for the potential yield gain that would be achieved when replacing these lost days with a replacement primiparous cow. Based on an average daily production for the high space cohort in this study (38.92L), additional replacement heifers would potentially produce 39, 659 litres over the additional 1, 019 days. However, the payback from this opportunity would also need account for additional replacements costs to rear heifers in the high space group.

There appeared to be no difference between the survival of the two cohorts as no clear patterns emerged in survival times between space allocation groups. However, the small sample size means this could be due to a lack of power in the analysis and more work is needed in this area for further understanding. A study which assessed survival, comparing whether primiparous animals were housed separately from the main milking herd or not within the first month after calving, showed little difference between the groups within the first 580 days after calving, before a divergence in the survival of the two groups (Østergaard et al., 2010).

Due to the complexity of the original trial a limited sample size was available for the current study, which limited the analytic power; there is a risk of type-1 errors within this analysis. However, these were a valuable cohort of cows, given the control placed around their original recruitment and housing conditions. A further limitation was the potential for variation in future living conditions post-trial due to non-standardisation of cow groups without the control of trial conditions, for example cows moved in and out of groups continuously meaning stocking density for each resource would change continuously throughout lactations. However, this variability was the same for both living space groups and since cows were managed with no knowledge of first lactation circumstances, any differences were at random and should not produce a systematic bias. Another limitation was that the data were from a single farm using Holstein cows that were housed year-round, thus the generalisability of the results is unknown.

In conclusion, results from this research provide provisional evidence that there may be long term effects on dairy cows dependent on their living space environments in first lactation. Thus, optimisation of the housed environment at this time could impact future outcomes in terms of lifetime milk production. Future work should be centred around whether there is an equivalent effect of living space allowance in different farm types and management systems. Additionally, more work should be done to evaluate whether a variety of different living space allowances provide additional benefits for milk yield and longevity. It is also unknown how living space provision for older cows compares to outcomes from primiparous only groups; again, this warrants future research.

Data availability statement

The data analysed in this study is subject to the following licenses/restrictions: not available due to commercial sensitivity. Requests to access these datasets should be directed to JT, jake.thompson2@nottingham.ac.uk.

Ethics statement

The animal study was approved by School of Veterinary Medicine and Science, University of Nottingham. The study was conducted in accordance with the local legislation and institutional requirements.

Author contributions

JT: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft. CH: Funding acquisition, Methodology, Supervision, Writing – review & editing. MG: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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