Author(s): Mikael Dahlvik, Gökçe Koç, Elina Paakala

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The effects of hoof health and hoof trimming on farm profitability

Mikael Dahlvik [a], Gökçe Koç [b,*], Elina Paakala [c]

[a] Natural Resources Institute Finland (LUKE), Kampusranta 9C, 60320 Seinäjoki, Finland
[b] Natural Resources Institute Finland (LUKE), Latokartanonkaari 9, 00790 Helsinki, Finland
[c] Faba Co-op, Urheilutie 6D, 01370 Vantaa, Finland

HIGHLIGHTS

- Incidence of both infectious and non-infectious hoof diseases are notable on dairy farms in Finland.
- Hoof trimming frequency is affected by hoof health, farm characteristics, and management choices.
- Inverse probability weighting enhances covariate balance, boosting causal inference validity.
- Hoof trimming affects farm profitability ensuing a U-shaped trend increasing after a 97 % trimming frequency.
- Systematic and regular hoof trimming reinforce farm profitability.

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ABSTRACT

Animal diseases pose a significant threat to the global livestock industry, with severe economic consequences. To minimize this impact, farmers employ various preventative measures, with hoof trimming being the most common method for addressing hoof disorders. This study analysed the economic effects of hoof trimming on dairy farms, using a panel dataset containing three years of hoof health data across Finland. This was an observational study that also addressed the issue with unavoidable confounders. To reduce bias, inverse propensity score weighting (IPW) was used, which assigned weights based on the probability density function of treatment frequency. By reweighting the data, this study improved the validity of the causal inference in the presence of confounding unobserved variables. The results of the study indicated that both infectious and non-infectious hoof disorders were notable on dairy farms in Finland. Furthermore, frequency of hoof trimming was influenced by several factors, including hoof health, farm characteristics, and management decisions. The analysis suggested a U-shaped relationship between hoof trimming and farms' profitability. Although the profitability ratio initially decreased, it increased after reaching a hoof trimming level of 97 %. The study highlighted how important systematic and regular hoof trimming is to maintain profitability.

1. Introduction

Animal diseases pose a significant threat to the worldwide livestock industry, with substantial economic implications. The effects of livestock diseases can be divided into two groups, visible and hidden, with two levels, farmers, and society. Diseases may have an impact on farm performance in relation to milk quality and quantity, animal welfare, and productivity. Moreover, they can lead to modifications in the animal population structures, delayed animal sales, and generate additional farm costs (Dijkhuizen et al., 1997; Galligan, 2006; Cainzos et al., 2022). Measures taken to reduce the risk of disease, such as investment in infrastructure, treatment and other medical costs, and additional labour, are important cost variables for farms (Rich and Perry, 2011; Liang, 2013). Even worse, if the disease increases the mortality rate and leads to the death of cattle, this represents a serious loss of productive assets for farms (FAO, 2016). Moreover, society may also face a reduction in food supply and quality, higher costs for animal products, new zoonotic diseases, increased demand for natural resources, additional greenhouse gas emissions and environmental degradation (Chen et al., 2016; Rushton and Bruce, 2017; World Organisation for Animal Health, 2022).

These impacts are multifaceted and are affected by a variety of circumstances. Factors specific to cows, such as their age, breed, lactation

* Corresponding author.
E-mail address: gokce.koc@luke.fi (G. Koç).

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stage or pregnancy status, previous yield, duration and distribution of inflammation, and response to treatment all influence productivity losses, disease probability and severity, mortality, and culling risk (Petrovski et al., 2006; Koeck et al., 2014; Rilanto et al., 2020; Sadiq et al., 2021; Bari et al., 2022; Browne et al., 2022; Bellato et al., 2023).

Factors relating to farmers and management practices are also essential in explaining differences in health problems between farms (Nyman et al., 2007). Farmers usually implement measures to control and prevent diseases in their cattle. The interdependence between farmers' decision-making processes and the disease dynamics of their farms - that is, the heterogeneity of their characteristics and actions - can result in variations in disease prevalence and severity on their farms. Numerous studies in the literature have examined farmers' behaviours towards diseases and treatments (Espetvedt et al., 2013; Jones et al., 2015; Kayitsinga et al., 2017; Vilar et al., 2018; Suit-B et al., 2020; Relic et al., 2021). Moreover, a diverse range of studies have analysed the relationship between various farm characteristics and animal diseases (Raboisson et al., 2011; Seppä-Lassila et al., 2016; Deng et al., 2019; Rilanto et al., 2020; Zanon et al., 2021). Some of the studies have focused on claw or hoof health, lesions, or lameness, and their determinants such as in Canada (Solano et al., 2016), Spain (Charfeddine and Pérez-Cabal, 2017), Ireland (Browne et al., 2022), Denmark (Thomsen et al., 2019), Mexico (Mellado et al., 2018) and Malaysia (Sadiq et al., 2021).

On the other hand, extensive research has been carried out to calculate the costs of different diseases in dairy herds. For hoof disorders, Cha et al. (2010) calculated (using dynamic programming) that the average cost per case was $216 for sole ulcers, $133 for digital dermatitis and $121 for foot rot. In addition, they calculated that the overall cost per case for sole ulcers consisted of milk loss (38 %), treatment costs for digital dermatitis (42 %) and the effect of reduced fertility for foot rot (50 %). Another dynamic programming approach by Kaniyamattam et al. (2020) calculated an average cost of $186–219 per lameness case. An empirical study conducted for Spanish Holstein cows reported that sole ulcer and white line disease can cause 1.5–2.7 kg/day loss of energy-corrected milk (Charfeddine and Pérez-Cabal, 2017). They calculated that the cost of a mild lesion is $53–$232 per affected cow and year, and it could be increased to $402–$622 for severe lesions. The study also highlighted that while severe cases have a lower incidence (10 %), their contribution to economic loss was higher (30 %) (Charfeddine and Pérez-Cabal, 2017).

In Finland, where the dairy farming is one of the most important agricultural sectors, there have been many studies on animal health problems and various factors affecting them, especially on claw health or lameness has been studied extensively (Kujala et al., 2009; Häggman et al., 2013; Sarjokari et al., 2013; Häggman and Juga, 2015; Kontturi et al., 2019; Pirkkalainen et al., 2021). Kujala et al. (2009, 2010) analysed prevalence and risk factors for hoof disorders such as sole ulcer, white line disease and haemorrhages by using the Finnish Healthy Hooves project records. Sarjokari et al. (2013) studied lameness in free stall barns, and Häggman and Juga (2015) addressed a wide range of factors that affects claw health. Frondelius et al. (2020) investigated the relationship between animal welfare indicators (including hoof health) and productivity. While a considerable body of literature address the effect of preventive measures on hoof health in different countries (Smith et al., 2007; Groenevelt et al., 2014; Van Hertem et al., 2014; Thomsen et al., 2019), no studies have been made in Finland that investigate the effects of preventive treatment practices on hoof health. Moreover, no studies have been found that analyse the impact of hoof trimming on farm economics, particularly farm profitability.

Farmers are concerned with maintaining the profitability, health, and welfare of their animals, as well as securing their farms' long-term viability (Rushton and Bruce, 2017). Reduced incidences of hoof disorders are vital to improve farm profitability, it is therefore important to consider their impact on hoof health and make any necessary improvements to management (Alvergnas et al., 2019). Nevertheless, convincing farmers to invest in animal welfare improvements can be challenging, especially when the financial benefits are uncertain (Villettaz Robichaud et al., 2019). In this context, preventative hoof care raises numerous questions regarding its implementation: when and how should it be done, who should carry it out, what frequency is optimal, which equipment should be used, and what are the economic realities and outcomes of the whole process (Pedersen et al., 2022). To address farmers' questions and ensure the sustainability and profitability of farms, it is vital to explain the economic links to animal diseases, evaluate the preventive treatments, and illustrate areas of potential improvement for farmers. Within this framework, this research aimed to achieve three main objectives; 1) to present the hoof health status of dairy cows and herds in Finland, 2) to examine the factors that affect the frequency of hoof trimming, and 3) to evaluate the effect of hoof trimming on farm profitability.

1.1. Hypotheses

The study has three hypotheses:

H_1 = The amount of labour and capital invested per cow positively and significantly affect the frequency of hoof trimming.

H_2 = Preventive hoof trimming significantly reduces the occurrence of hoof disorders.

H_3 = The frequency of hoof trimming has an impact on the profitability ratio of the farm.

2. Methodology

2.1. Data management

The study's quantitative data was sourced from various databases, including milk yield records and economic information from the database of the Finnish Rural Advisory Services (ProAgria, Vantaa, Finland) as well as hoof health and treatment data maintained by the Finnish Animal Breeding Association (Faba, Vantaa, Finland).

The dataset initially comprised a three-year panel from 2016 to 2018, consisting of 207 farms (621 herd-year datasets in total). To align with the study's objective, 71 conventional dairy farms with valid data on preventive hoof care for each year were included (213 herd-year datasets in total). The sample farms were distributed across Finland, with 39.4 % located in Central Ostrobothnia, 28.2 % in Eastern Finland, 22.5 % in Southern Finland, 5.6 % in Oulu region, and 4.2 % in South Savo region.

In this study, hoof disorders were divided into infectious and non-infectious ones. The non-infectious category included seventeen different hoof disorders: sole haemorrhage, chronic laminitis, white line fissure, sole ulcer, corkscrew claw, other hoof diseases, toe ulcer, double sole, white line ulcer, asymmetric claws, overgrown claws, scissor claws, lameness, thin sole, axial fissure, vertical horn fissure, and trauma. The infectious category included mild dermatitis, heel horn erosion, digital dermatitis, interdigital phlegmon, interdigital hyperplasia and chronic dermatitis.

In Finland, hooves are usually trimmed and treated by professional hoof trimmers. In some cases, farmers perform the hoof trimming, and usually in very severe cases, or epidemic eruptions of infectious disorders, veterinarians' services are used. The data in this study included records only from trimmings and treatments made by hoof trimmers. Each time the hooves were trimmed, the trimmer recorded a treatment code for preventive hoof trimming (822). If, in addition, one or several hoof disorders were found during the trimming, the trimmer also recorded a health code for the diseases. In case no disorders were found, the cow was considered healthy, and we categorised the trimming occasion as "pure" preventive hoof trimming.

The dependent variables used in the statistical inference comprised of pure preventive hoof trimming and the profitability ratio. The profitability ratio accounts for the cost of capital and the income requirement of the entrepreneur as well as the farm family income. The pure preventive hoof trimming represented the ratio of total number of trimmings to the number of dairy cows in the herd, thereby indicating a percentage. Henceforth, this variable is denoted as "treatment". The control variables included measures on productivity, labour input, capital, treatment frequency of infectious and non-infectious hoof disorders, and NTM (A total merit index to measure the genetic level of dairy cattle. It includes all economically important traits for the Nordic Red (including Ayrshire), Holstein and Jersey breeds in Denmark, Finland, and Sweden.) Some variables checking for the environmental effects were captured by the type of housing and feeding type. The descriptive statistics of the selected variables that were used in the analyses (for 213 farms, for the years 2016 to 2018) are presented in Table 1.

2.2. Statistical analysis

Causality, the connection between cause and effect, is a subject of great concern in the fields of economics and animal sciences. The aim of this study was to identify the causal effect of preventive treatment, specifically pure preventive hoof trimming, on dairy cows using observational data, acknowledging the presence of confounding factors. The confounder effect presented a significant challenge to accurately inferring causal relationships between treatment and outcome in observational studies, as shown in Fig. 1.

A confounder is an extraneous variable that is associated with both the treatment and the outcome, thereby introducing bias into the estimated treatment effect. This can lead to incorrect conclusions about the true causal impact of the treatment on the outcome. The presence of an uncontrolled confounder can disrupt the causal pathway between the treatment and outcome, resulting in spurious associations and potentially misleading conclusions. Therefore, it is essential to carefully consider and adjust for confounders, particularly in observational studies. It is necessary to validate the ignorability assumption, ensuring that the treatment assignment is unconfounded based on the conditional independence of treatment and potential outcomes. This enhances the validity of causal inferences.

To mitigate the confounding effect, this study employed the inverse propensity score weighting (IPW) to control for potential confounding effects. Thus, minimizing the impact of the imminent selection bias as suggested by both Hirano and Imbens (2004) and Robins et al. (2000).

Table 1
Descriptive statistics.

Dependent variables	Min.	Max.	Mean	Std. Dev.
Pure preventive hoof trimming (%)	1.6	228.7	92.8	51.2
Profitability ratio	-2.12	2.26	0.61	0.57
Independent variables	**Min.**	**Max.**	**Mean**	**Std. Dev.**
Milk yield (ECM kg/year)	7825	12,414	10,462	965
Family labour (per cow)	14.0	208.6	78.5	36.7
Hired labour (per cow)	0.00	89.7	13.4	13.7
Capital (per cow)	-1054	23,798	9862	4041
Non-infectious hoof disorders (%)	0.00	526.7	138.7	100.9
Infectious hoof disorders (%)	0.00	227.1	28.4	48.8
Nordic Total Merit (NTM)	-13.3	11.7	3.4	3.9
	Type of variable	**Description**	**Frequency**	**%**
Conventional barn	Dichotomous	0: No	67	31.5
		1: Yes	146	68.5
Separate feeding	Dichotomous	0: No	98	46.0
		1: Yes	115	54.0

This study adopted the binary treatment assignment framework proposed by Rosenbaum and Rubin (1983). The expected outcome was denoted as:

$$e(x) \equiv \Pr(Z = 1 | X = x) \quad (1)$$

where the notation represented the conditional probability of being assigned a specific treatment based on a vector of observables.

Logistic regression is typically used to estimate the propensity score of being exposed to the intervention for each individual following the approach outlined by Austin (2011). To ensure a robust propensity score model, all baseline covariates potentially influencing the relationship between the treatment and outcome need to be included (Jager et al., 2008).

Expanding on the basic binary model/analysis (untreated-treated or $e(x) = r(1, x)$), which has been widely used to estimate average treatment effects (ATT) related to cow health (Verschave et al., 2014; Odermatt et al., 2019; van Aken et al., 2022) this study endeavoured to determine the average treatment effect for the annual number of exclusively preventive hoof trimming occasions, where the treatment was defined as a treatment percentage on farm level.

In the continuous treatment framework, the first step for estimating the probability weights involved defining the confounding covariates and estimating the formula for the generalized propensity scores (GPS) as suggested by Hirano and Imbens (2004). Where $r(z, x) = f_{Z|X}(z|x)$ is the conditional density function of the treatment conditional on the observed covariates. The GPS estimation was then expressed as $R = r(Z, X) \equiv \Pr(Z = z | X = x) = E[D(z)|X = x]$ (Hirano and Imbens, 2004). Where the expression $E[D(z)|X = x]$ determines the evaluation of the dose response at each level of treatment. The GPS for each subject was calculated using their specific treatment (Z) and covariate values (X), as described in the GPS development framework above.

To estimate the conditional density of the treatment variable given a set of observed covariates, a propensity function was constructed using an ordinary least squares (OLS) regression. The coefficients and estimated residual variances were then used for estimating the conditional distribution. The GPS was then evaluated according to the balancing requirement of $D(z) \perp X | r(z, X)$, *for all* $z \in Z$, which gave us an unconfounded treatment assignment for each level of treatment. The unconfoundedness balancing requirement, or balancing property is similar to the balancing property seen in traditional analysis with binary treatments. Where the treated and control subjects having the same propensity score value have the same distribution of observed covariates (Rosenbaum and Rubin, 1983). The theoretical framework, assuming weak unconfoundedness was consolidated and was assumed to be sufficient for the purpose of this study. For more detailed definition of the independency of treatment assignment see Hirano and Imbens (2004).

After obtaining the GPS, the weights were defined as $\frac{W(Z_i)}{GPS}$, where the numerator represents the marginal density of the treatment and is suggested to be estimated in a similar way as the GPS, while excluding the covariates (Robins et al., 2000). To clarify the linkage between the theoretical framework and the estimated weights, the denominator of weight represents the value of the treatment density function at each treatment level, where the treatment is conditionally normally distributed. Essentially, farms with values closer to the conditional mean have higher density function values, leading to lower weights assigned to them.

After estimating the GPS and further the weights for each individual, both Hirano and Imbens (2004) and Robins et al. (2000) propose the use of IPW to account for and remove the occurring selection bias. The IPWs were then used in the regression model using the svyglm function of the survey R package, which is specifically designed to fit a linear model to data from a complex survey design with inverse probability weighting (Lumley, 2023).

The dose-response function of interest which was defined as $E[Y_i(z)] = \mu(z)$ was then estimated for each treatment level, which in

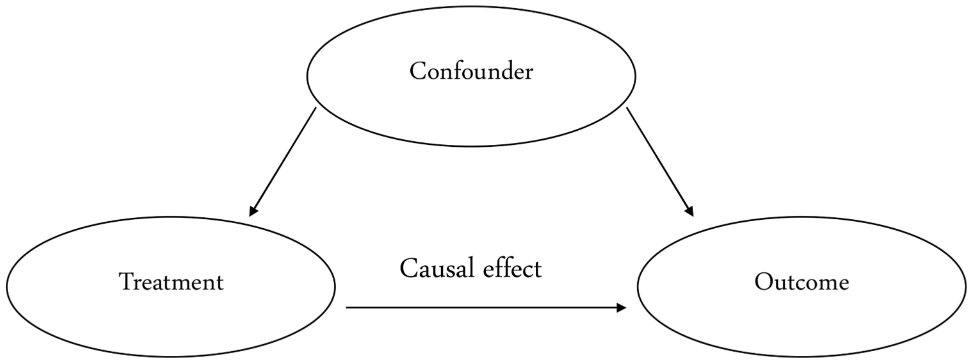

Fig. 1. Causal effect, adapted from Jager et al. (2008).

this study implied preventive treatment percentage. The computed outcome represented the average treatment effect across all exposure levels. Survey (Lumley, 2023), cobalt (Greifer, 2024a) and WeightIt (Greifer, 2024b) R packages were used for analysis. In the analyses, a p-value of less than 0.05 was interpreted as statistically significant.

Covariate balance for selected variables are presented in Fig. 2, illustrating improved balance between groups after applying the propensity-score weighting. The use of propensity score weighting reduced the confounding effect and improved the reliability of the results.

To sum up, unlike animal science studies that focus on the effects of treatment on cow health and behaviour, or social science studies that focus on specific effects of investments, participation, adaptations, etc. (Hadrich and Johnson, 2015; Carillo and Abeni, 2020; Maina et al., 2020; Faisal et al., 2021; Sánchez-Castro et al., 2023), this study integrated the effects of preventive treatment (hoof trimming) on the economic performance (profitability) of the farm. In this context, this study was one of the first to use continuous treatment effects to integrate animal health and farm performance.

3. Results and discussions

3.1. General characteristics

Over the three-year study period, the number of dairy cows per farm varied from a minimum of 16.5 to a maximum of 233.3, with an average of 74.2 ± 49.3. There were also 42.8 ± 32.7 heifers on the farms. The average annual milk yield was 10,462 ± 966 kg energy-corrected milk (ECM kg/y) or 9148 ± 867 litres per cow.

The profitability ratio of the farms was 0.61 ± 0.57 on average over three years. In terms of annual results, it was 0.62 in 2016, 0.67 in 2017 and 0.52 in 2018. The correlation coefficient between milk yield and profitability ratio was 0.32, indicating a positive but weak relationship. It was inevitable that there was a relationship between dairy cow productivity and farm profitability (Bhuyan and Postel, 2009; Krpalkova et al., 2016; Zakova Kroupova, 2016; Chetroiu et al., 2022), but productivity alone does not explain the changes in the profitability ratio.

The share of Holstein (48 %) and Ayrshire (51 %) on the farms was almost equal. A higher share of Holstein breed in the farm correlated positively with milk yield (0.30) and profitability (0.05). The average of the NTM in a herd was 3.4 ± 3.9, and the average estimated breeding values for fertility, udder health and claw health were 100.7, 101.6 and 100.9 respectively. The higher NTM, i.e. higher genetic potential of cows, was positively correlated with both productivity (0.30) and profitability ratio (0.24).

Almost half of the farms (46 %) had an automatic milking system (AMS), and one in three (30 %) had a traditional pipeline milking system. The most common barn types were the warm free-stall (37 %) and the conventional tie-stall (32 %), followed by the cold free-stall (20 %). Farms with cold free stalls were typically larger in scale, with an average of 118 cows, and had the highest milk yield (10,996 ECM kg/y) and profitability ratio (0.79). Farms with warm free-stall and conventional

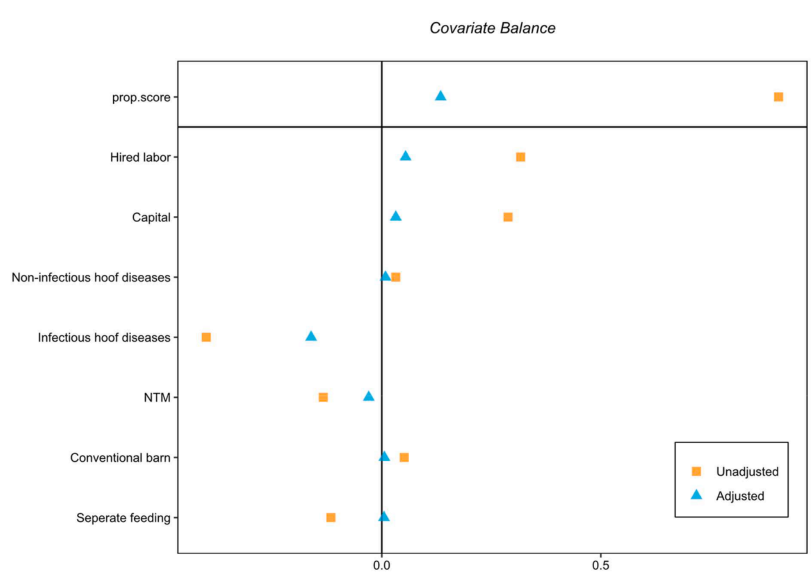

Fig. 2. Covariate balance.

tie-stall had lower profitability ratios; 0.53 and 0.53, respectively.

More than half of the farms (54 %) used separate feeding, while 29 % used mixed feeding with supplementary nutrients and 14 % used only mixed feeding. It is noteworthy that the mixed feeding strategy with supplementary nutrients had the highest milk yield (10,620 ECM kg/y), but the farms using separate feeding had the highest profitability ratio (Kruskal-Wallis test, ECM kg/y $p = 0.02$, profitability ratio $p = 0.02$).

3.2. Hoof health

Across all farms in the study, the average incidence of non-infectious hoof-disorders among dairy cows was observed to be 139 %, surpassing the annual cow population in the herd. In addition, infectious hoof disorders were detected on 67 % of the farms. Among these affected farms, the average prevalence of infectious hoof disorders accounted for 43 % of the herd size. It is important to note that a single cow may experience multiple infections within a year, thus the reported infection rate does not necessarily indicate that 43 % of the herd was infected at any given time, the same principle applies to non-infectious hoof disorders. Furthermore, the scope of this study extended beyond farms with infectious diseases, with the corresponding infection percentage across all farms standing at 28 %. These findings support the study by Häggman and Juga (2015), who found that the prevalence of non-infectious hoof disorders was often higher than that of infectious hoof disorders in Finland. Moreover, the correlation coefficient of 0.58 suggested a possible association between infectious and non-infectious hoof disorders. Farms with poor management practices, such as inadequate hygiene, nutrition, or care, may be at a higher risk of encountering animal diseases.

The number of dairy cows in the farm positively associated with both infectious (0.24) and non-infectious (0.25) hoof disorders, in line with previous study by Holzhauer et al. (2006). For dairy breeds, the share of Holstein cows on the farm was positively correlated with the percentage of treatments for both infectious (0.20) and non-infectious (0.17) hoof disorders. Previous studies support this finding that Holsteins are more likely to have hoof disorders or be lame (Kujala et al., 2009, 2010; Sarjokari et al., 2013; Bran et al., 2018). The fact that Holstein cows are usually larger and heavier than Ayrshire cows may be the cause of this, adding additional weight and pressure on the claws (Sarjokari et al., 2013). On the other hand, Häggman and Juga (2015) reported that Holstein cows had a higher risk of non-infectious and a lower risk of infectious hoof disorders compared to Ayrshire cows. Additionally, it should be noted that both infectious (-0.25) and non-infectious (-0.16) hoof disorders in herds decreased as the average breeding value for claw health increased.

Hoof disorders and lameness have been associated with a reduction in yield and quality of milk (Koeck et al., 2014; Randall et al., 2016; Charfeddine and Pérez-Cabal, 2017). Farms without infectious hoof disorders had numerically higher milk yield and profitability ratios (Mann-Whitney U, ECM kg/y and profitability ratio, with p-values of 0.53 and 0.66, respectively). Farms without infectious hoof disorders had an 86 ECM kg/y higher yield per cow, and a 0.04 higher profitability ratio.

The highest rate of treatment for infectious and non-infectious hoof disorders was in the warm free-stall barns. Prevalence of infectious and non-infectious hoof disorders were 44 % and 183 % in warm free-stalls, while it was only 9 % and 75 % in conventional tie-stall barns. Previous studies have also reported higher risk or prevalence of hoof disorders and lameness in free-stall farms (Sogstad et al., 2005; Haskell et al., 2006). The studies highlighted the importance of several factors as essential components influencing hoof disorders in housing environments (Beaver et al., 2021). In the context of a free-stall housing, the type of flooring emerges as a key factor inducing hoof disorders (Somers et al., 2003; Sogstad et al., 2005).

On average, 92.8 ± 51.2 % of cows per herd received pure preventive hoof trimming. It is also worth noting that the frequency of pure preventive treatment tended to increase from year to year, reaching 83 %, 93 % and 100 % in the years studied. Increasing pure preventive hoof trimming was associated with reduced infectious and non-infectious hoof disorders, with correlation coefficients of -0.25 and -0.09, respectively. This finding is supported by a large body of literature reporting the positive effect of hoof trimming on reducing the risk of hoof disorder (Hernandez et al., 2007; Smith et al., 2007; Thomsen et al., 2019; Sadiq et al., 2021). On the other hand, it should be noted that the effect of hoof trimming is positive or more efficient if a sufficiently frequent and correct trimming protocol is used (Manske, 2002). The detailed effect of pure preventive hoof trimming is discussed in the next section.

3.3. Analysing results

Table 2 shows the results of a linear regression model estimating the treatment size. The results show the linear effect of the independent variables on pure preventive hoof trimming. Non-infectious hoof disorders in the herd had a positive effect on the employment frequency of pure preventive hoof trimming, while infectious hoof disorders reduced the application of pure preventive hoof trimming. In the event of a high incidence of infectious disorders the focal point is on treating the animal, usually by veterinarian, and other existing conditions rather than applying more preventive measures such as hoof trimming. As a result, the employment for preventive measures decreased. NTM describes the genetic potential of cows and the effect on pure preventive hoof trimming was negative. The negative relationship indicated that herds with higher genetic potential had a lower frequency of pure preventive hoof trimming application. Both the capital and labour (family and hired) per cow had an increasing effect on the treatment size. This was expected because implementing preventive measures requires more time, effort, and costs, which in turn requires additional labour and financial resources.

The GPS was estimated based on a linear model. The mean of the GPS was derived using the fitted values of the linear regression, while the standard deviation was estimated using the model residuals. The distribution of selected variables is displayed in Fig. 3. The GPS was then used as a weight when estimating the survey weighted GLM model.

Table 3 and Fig. 4 presents the results of the survey weighted GLM model, which was conducted to analyse the average treatment effect (ATE) of pure preventive hoof trimming percentage on farm profitability ratios at each treatment percentage frequency level.

The results of our study showed that preventive hoof trimming had a very small, but statistically significant impact on dairy farm profitability. Interestingly, this effect was non-linear, indicating that the impact on farm profitability varied with frequency of pure preventive hoof trimming. At a first glance, preventive hoof treatment has a negative impact on the profitability ratio, suggesting that it may be more beneficial for farmers to exclude this practice from health care measures.

Table 2
Results of a linear regression model estimating treatment size.

Dependent variable: pure preventive hoof trimming (%)	Estimate	St. Error	*t* value	*p* value
(Intercept)	56.83	12.487	4.55	< 0.001
Family labour (per cow)	0.30	0.108	2.81	0.006
Hired labour (per cow)	0.60	0.241	2.48	0.014
Capital (per cow)	0.00	0.001	3.11	0.002
Non-Infectious hoof disorders (%)	0.12	0.042	2.73	0.007
Infectious hoof disorders (%)	-0.37	0.079	-4.67	< 0.001
Conventional barn	31.15	9.154	3.40	< 0.001
Separate feeding	-36.90	7.898	-4.67	< 0.001
NTM	-2.70	0.822	-3.28	0.001

Multiple R-squared: 0.27, Adjusted R-squared: 0.24, $F(8, 204) = 9.27$, $p < 0.001$.

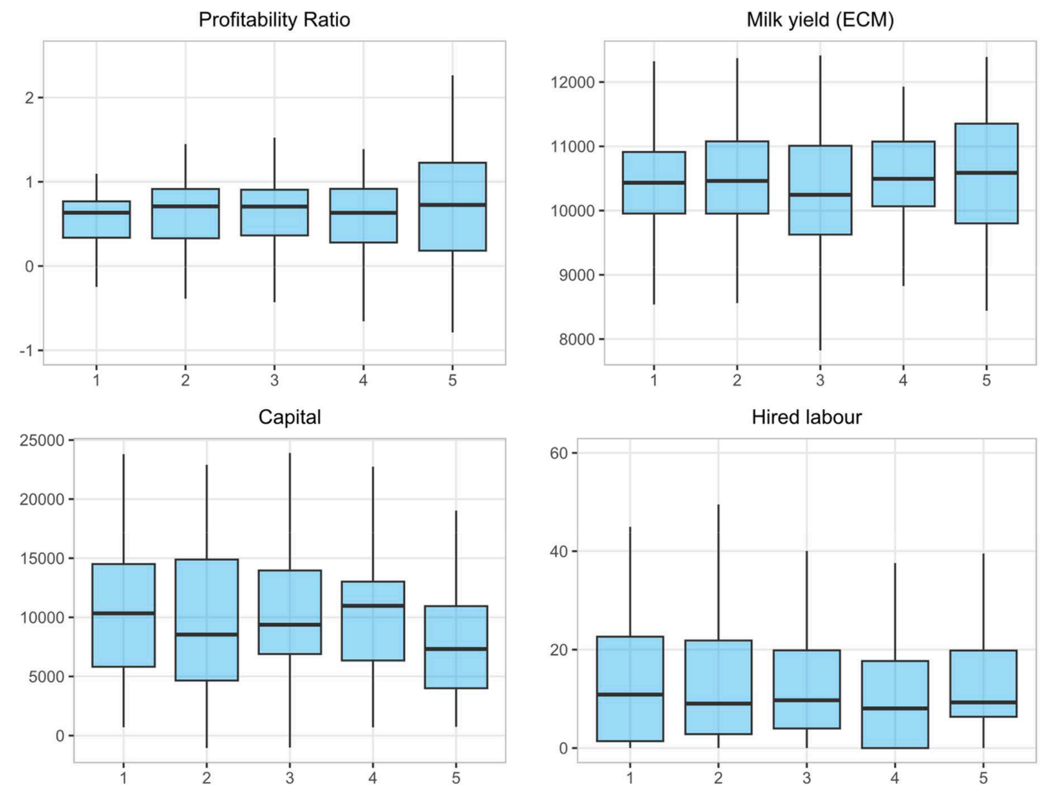

Fig. 3. Distribution of selected variables across GPS strata.

Table 3
Average treatment effect.

Dependent variable: profitability ratio	Estimate	St. Error	*t* value	*p* value
(Intercept)	-1.99063	0.607	-3.28	0.001
Pure preventive hoof trimming (%)	-0.00753	0.004	-2.15	0.033
Pure preventive hoof trimming (%) ^{2}	0.00004	0.000	2.04	0.042
Labour (per cow)	0.01045	0.005	2.27	0.024
Labour (per cow) ^{2}	-0.00003	0.000	-1.80	0.073
Conventional barn	-0.19562	0.099	-1.98	0.049
Milk yield (ECM kg/year)	0.00022	0.000	5.21	< 0.001
Capital (per cow)	0.00003	0.000	1.33	0.185
Capital (per cow)^2	-0.00000	0.000	-2.74	0.007

$F(8, 212) = 6.00$, $p < 0.001$, the degrees of freedom for the t-test is 212.

However, a comprehensive analysis must account for the indirect routes, or "backdoor paths", through which preventive hoof trimming contributes to the overall profitability of the dairy farm. The backdoor paths considered include various types of hoof-diseases. However, the estimated effect, which had a positive turning point, suggested that a direct effect of pure preventive hoof treatment frequency could be identified. The impact was not solely negative, as it incurs associated costs, but also yielded positive outcomes.

An important aspect to consider was the importance of preventive hoof trimming to avoid not only hoof-related problems but also other diseases. These preventive measures create a ripple effect and directly affect the health of the dairy herd, and subsequently the overall profitability of the farm. The initial negative effect observed in the profitability ratio may therefore be misleading if the broader health benefits are not accounted for.

Furthermore, the observed non-linear relationship has shed light on the benefits of a systematic hoof trimming approach. As the frequency of pure preventive hoof trimming increased, clear positive effects became apparent. It is obvious that a more strategic and systematic hoof treatment provides positive results for farm profitability.

The positive coefficient associated with the squared term introduced an interesting turning point in the relationship between preventive trimming and profitability. Above a certain threshold, as indicated by the squared term, the profitability ratio began to improve as the level of preventive hoof trimming increased. This turning point revealed a U-shaped relationship, indicating that there is a minimum frequency, when pure preventive hoof trimming begins to positively affect the profitability of dairy farms (Fig. 4).

Our findings identified a critical inflection point at 97.4 % hoof trimming frequency, beyond which the effect of preventive trimming underwent a positive shift (Fig. 4). At this juncture, the profitability ratio started to increase, challenged the initial impression of a purely negative impact. This highlighted the importance of reaching a certain level of pure preventive hoof trimming frequency and emphasised that insufficient preventive measures may not yield the desired economic outcomes for dairy farmers.

In conclusion, our study underlined the complexity of the relationship between preventive hoof trimming and farm profitability. While an initial negative effect was observed, a more comprehensive analysis revealed the convoluted interplay of factors, demonstrating the importance of preventive measures in maintaining overall herd health. The U-shaped relationship further highlighted the need for a nuanced and strategic approach to hoof trimming, with the turning point serving as a guide for dairy farmers looking to make informed decisions and accounting for specific actions in their health strategy.

4. Conclusions

This study was one of the first to investigate the complex determinants that influence the frequency of hoof trimming on dairy farms, accounting for management, farm and cow-related factors. It was also one of the first attempts to systematically assess the economic impact of preventive hoof trimming on farm profitability.

The results of the study indicated that both infectious and non-infectious hoof disorders are notable on dairy farms in Finland. It is

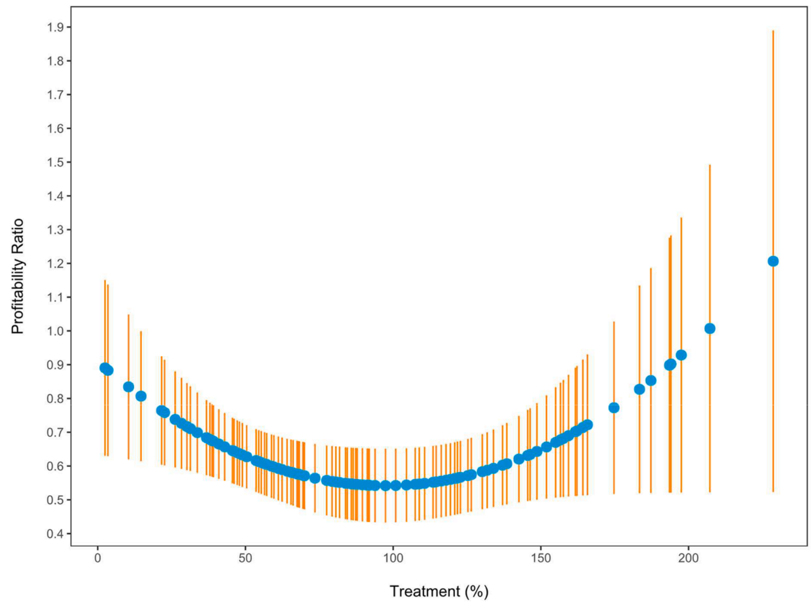

Fig. 4. Relationship between profitability ratio and the treatment percentage.

noteworthy that the average occurrence of infectious and non-infectious hoof disorders was 138.7 % and 42.5 % respectively. In response to the challenges posed by these common diseases, a significant proportion of the herds were using pure preventive hoof trimming (92.8 %). This practice is a proactive measure aimed at reducing the incidence of hoof disorders or mitigating the effects of avoidable diseases.

The decision-making process regarding the frequency of hoof trimming was complex and influenced by many factors. Hoof health, farm characteristics, and managerial decisions all shaped the farmer's approach to hoof care. It became evident that a nuanced understanding of these interrelated factors is crucial for developing effective strategies to promote systematic and regular hoof trimming among farmers.

Our analysis also revealed a U-shaped relationship between hoof trimming frequency and farm profitability. The initial observation was that the profitability decreased with increasing pure preventive hoof trimming, but then a turning point was observed. When the level of hoof trimming exceeded 97.4 %, the profitability ratio began to move in a positive direction, indicating an improvement in economic results. This U-shaped pattern suggested that there was a clear threshold for preventive hoof trimming, above which there was a net positive effect, although small effect, on dairy farm profitability.

It may be argued that doing nothing is more profitable than taking action. However, the estimated effect in this study focused on the direct effect of preventive hoof trimming percentage on the farm profitability. While the indirect effect of preventive treatment in improving hoof health was accounted for, where preventive hoof trimming improves the profitability through paths like decreased disease frequency, thus impacting the farm profitability indirectly. Therefore, if a farmer has chosen to do nothing, the farm has an increased risk of escalating the disease prevalence, with negative consequences for the production, including reduced profitability. The interesting part of the result was the inflection point. In other words, as the so-called backdoor paths were considered, we could assume that we had identified the direct effect of the pure preventive procedure. This means that there is a positive impact of doing preventive treatments, even though there are direct costs associated with the treatment procedure.

By highlighting the importance of systematic and regular hoof trimming in maintaining profitability, our study has provided valuable information for dairy farm management. While the initial costs associated with pure preventive hoof trimming practices may be seen as unacceptable, our findings highlighted the long-term economic benefits that exist. Farmers should be aware of the economic benefits of maintaining hoof health. Consequently, programs for the dissemination of knowledge and best practice in hoof health should be tailored to take account of the uniqueness of each farm and the diversity of factors affecting it.

The use of inverse propensity score weighting (IPW) with continuous treatments in our study has been a significant advancement in research methodology for observational studies, particularly in the fields of animal science and agricultural economics. Traditional approaches often struggle to account for the nuanced nature of treatments, especially in cases where interventions are continuous rather than binary. Our study acknowledged the dynamic nature of pure preventive hoof trimming on dairy farms and provided a more unbiased understanding of its economic effects by applying IPW to a continuous treatment context.

This enabled us to address potential biases associated with observational studies, where the occurrence of different confounding effects distorts the estimation of economic impacts. By assigning weights based on the inverse probability of treatment percentage frequency, this effectively adjusted for biases and offered a more accurate assessment of the economic benefits associated with the applied pure preventive hoof trimming. This approach enhanced the robustness of our study's findings and established a precedent for future research in the field of dairy farming economics. It encouraged a more sophisticated understanding of the economic implications of preventive measures in animal health management.

In conclusion, this study has shed light on the diverse factors influencing hoof trimming frequency on dairy farms and contributed to the understanding of the economic impacts of pure preventive hoof trimming. This study also highlighted the complexity of hoof health management and the indefinite effects of preventive hoof trimming frequency. Our research aimed to helping farmers to make more informed and profitable decisions. The estimation of this study was based on a Finnish and Nordic environment, thus future studies can be expanded to include other regions of the world. The methodological advancements and substantive results of this study will contribute significantly to the evolving knowledge of animal science, veterinary medicine and agricultural economics.

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CRediT authorship contribution statement

Mikael Dahlvik: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Visualization, Supervision, Writing – original draft, Writing – review & editing. **Gökçe Koç:** Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Elina Paakala:** Conceptualization, Data curation, Writing – review & editing.

Declaration of competing interest

The authors report that there are no competing interests to declare.

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