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Dairy cow welfare measures: Can production economic data help?

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ABSTRACT

Using a dataset from dairy farms in Germany that combines two types of welfare measures, namely welfare quality protocol (WQP) measures and production economic and herd-management data, this study aims to validate the use of production economic and herd-management data to proxy dairy cow welfare measures. The paper implements two multivariate estimation approaches of Seemingly Unrelated Estimation and Canonical Correlation Analysis. Data from on-farm animal welfare assessments based on WQP require time intensive collection and are typically unavailable for research based on large-scale panel datasets. On the other hand, survey data on production economic and herd management are available for such analysis, especially in European countries, but their informational value regarding animal welfare is debated. In this paper, we were able to establish relationships between the four WQP principles (feed, health, housing, behaviour) and variables from production economics and herd-management data. We find that concentrated feed, building costs, cell counts, milk fat content, calving intervals, and age at calving have strong links to the different principles of the WQP measures. In conclusion, our findings support the use of already existing and routinely collected production economic and herd-management data from dairy cows to enable an analysis of farm animal welfare on a larger scale using panel data.

1. Introduction

Growing public concern about the welfare of farm animals has been emphasised by several studies (McCarthy et al., 2004; Ingenbleek and Immink, 2011; Thorslund et al., 2017). Farm animal welfare (FAW) is often perceived as poor by consumers, reinforcing concerns with and rejections of modern production systems (Clark et al., 2016). Moreover, FAW denotes one key aspect of the overall sustainability of animal production and has links to environmental, economic, and social dimensions of sustainability (Gunnarsson et al., 2020a, 2020b; Segerkvist et al., 2020). At the same time, creating value from sustainable dairy cow husbandry requires both monitoring and communicating animal welfare within the value chain and taking a holistic view on sustainable dairy cow husbandry to account for production economic, animal health and welfare issues (Friedrich et al., 2020). To ensure sustainability objectives in animal production, and to maintain socially acceptable levels of farm animal welfare in Europe, EU regulations are complemented by member state laws as well as private certification schemes (see e.g., Veissier et al., 2008 for a review). Nevertheless, assessing farm animal welfare consistently and on a large scale constitutes a core challenge. On-farm animal welfare assessment methods offer a clear picture of the true constitution of the animal and are therefore perceived as reliable (Krueger et al., 2020). Among others, the European Welfare Quality Protocol (WQP) denotes a commonly used on-farm assessment method based on the notion of *the five freedoms* of farm animals (Botreau et al., 2007; Veissier et al., 2008; Farm Animal Welfare Council, 2009) and a standard protocol designed by the European Welfare Quality®(WQ) project (Welfare Quality, 2009; Franchi et al., 2014; Molina et al., 2019). However, generating such welfare measures comes at the cost of high labour and time-investments and are hence expensive, hindering large scale implementation (de Vries et al., 2014; Krug et al., 2015). Precision livestock farming (PLF) technologies with sensor-based measures may offer improvements in this regard (Maroto-Molina et al., 2020). Adoption rates, however, are still low (Vaintrub et al., 2021). Even they were widely adopted, data security restricts the usage of (sensor-based) animal or farm-specific WQP-based assessments for policy impact evaluation, e.g., by adding them to large-scale observational farm data sources like the EU's Farm Accountancy Data Network (FADN). Thus on-farm assessments of FAW are impractical for large-scale analysis (Knierim and Winckler, 2009; Otten et al., 2019).

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As a solution, this paper proposes identifying and validating already available production economic and herd management variables that could be used as alternative FAW indicators from large-scale national databases. Databases providing detailed herd management data on farms and cow levels already exist. In such databases, variables such as milk yield, veterinary expenses, building costs, culling patterns, pasture access, somatic cell counts and fertility are routinely collected and have previously been used as indicators of animal welfare in Swedish (Sandgren et al., 2009; Nyman et al., 2011; Adamie and Hansson, 2021) and Dutch data (de Vries et al., 2014). If such routinely collected variables could be linked to one or more FAW measures, it would benefit studies on policy impact and farm production economic analysis, both of which require large-scale panel data, especially in their quality regarding results on farm performance. Nevertheless, using such potential measures based on production economic and herd-management data to proxy FAW requires validating them; to our knowledge, no systematic validation study of dairy production exists.

Therefore, this paper aims to close this gap by examining the link between selected variables from dairy sector production economic and herd-management information, and on-farm animal welfare measures based on the four principles of WQP: feed, health, housing, and behaviour. Based on the established links, we aim to validate variables from production economics and herd-management that could be used as FAW indicators. Our data set combines on-farm WQP assessment data with dairy branch herd-management data for a western German sample of dairy farms, creating a unique dataset and opportunity to validate the informational value of dairy branch data regarding FAW. This means that our dataset contains variables that would be possibly derived from a merger between the national farm economic data of the FADN-type and data from a dairy cow recording schemes. We hypothesise that existing production economic and herd-management datasets offer suitable sources to identify farm animal welfare indicators or proxies by validating them against more reliable on-farm FAW measures based on WQP principles. Establishing the link between these data and validating FAW indicators presents more efficient and inexpensive alternative FAW indicators, which can be used not only for policy impact evaluation but also monitoring purposes at the population level. Given the complexity of dairy cow welfare and its challenges of measurement as discussed by many authors (Calamari and Bertoni, 2009; Heath et al., 2014; Thomsen and Houe, 2018), we extend previous studies on this topic that relied on regular regression analyses (e.g., de Vries et al., 2014) by implementing canonical correlation analysis. This also supports the idea of taking a holistic view of sustainable dairy cow husbandry by taking production economic and animal-related issues, including health and welfare, into account (Friedrich et al., 2020). This method is commonly applied in the psychological literature to identify relationships between constructs, and seems especially suitable for our application (Li, 2020). In our analysis, we link the four principles of the WQP measure with several available production economic and herd-management data variables from a dairy cow recording scheme, which clearly requires dimensionality reduction and going beyond linear additive relationships.

The paper is organised as follows: Section 2 introduces the data used in the paper and methods applied; Section 3 presents the results; Section 4 discusses our findings and their policy implications; and Section 5 concludes the paper.

2. Data and methods

2.1. Data

Our dataset comprises farm-level data from three sources: a) production economic data containing monetary output and used inputs based on dairy branch-specific cost accounting (economic performance); b) herd-management data of milk constituents and lactation information at the average herd level (biological performance) from regular standardised milk recording schemes (German: *Milchleistungsprüfung*); and c) farm-specific outcome-based animal welfare assessments based on the WQP index, that is, the protocol of the European Welfare Quality®(WQ) project for cattle (Keeling, 2009; Welfare Quality, 2009).

In sum, 50 dairy farms were sampled between 2014 and 2015 in the target region of the Federal State of Lower Saxony, located in the northwest of Germany (see Schulte et al., 2018 for further details). The sampling of farms aimed to represent different milk production systems with regard to regional pasture-use levels. Sampled farms use pasture for more than 10 h (24%), 6 to 10 h (23%), and up to 6 h (24%), as well as year-round confinement systems (28%). Farm-specific selection criteria included herd size, but selection was limited by farmers' willingness to collaborate. The geographical study region represents the largest milk-producing area in Germany.

The farm characteristics, using two-year averages, are summarised in Table 1 (please see Table A1 for descriptive information by year, which we present for brevity in the Appendix). Average energy corrected (ECM) milk yield amounts to 9399 kg per cow and year, normalised to 305 lactation days. Our data set comprises dairy branch-specific cost accounting for the economic years 2013/14 and 2014/15 following the Germany-wide applied standards by the German Agricultural Society (*Deutsche Landwirtschaftsgesellschaft*). This standardised cost accounting allows for detailing milk production specific costs, and thus branch-specific net revenues.[1]

From the branch-specific cost accounting, we use variables that could proxy for animal welfare and include cost components and herd level biological variables. The cost variables include expenses for veterinary services, insemination, concentrate, and total building (see Table 1). Veterinary expenses include treatments for mastitis, injury rates, lameness, and metabolic disorders and comprise the main source of health-related costs. Thus, veterinary costs should be lower for herds with healthier animals. When fighting disease, cows' fertility can also be negatively affected, in turn causing additional (veterinary) costs through hormone treatments and insemination frequency (de Vries, 2006; Drews et al., 2018). We note that not all farms use insemination. Sampled farms' veterinary costs ranged from 0.5 (Q10) to 1.3 (Q90) Eurocents per kg ECM, indicating considerable variation, but the sample mean of 0.9 Eurocents per kg ECM is below the reported mean for Lower Saxony by about 1.26 Eurocents per kg ECM in the year 2016/17, the closest available year to our sample (LaWiKa NI, 2017). High costs for concentrates may indicate high use, potentially aimed to compensate for low energy roughage, and may negatively relate to metabolic stability and the rumen health of the cows (e.g., Humer et al., 2018).

We further argue that housing, as reflected by total dairy branch-specific building costs, concerns dairy cow welfare as it directly relates to lameness prevalence (e.g., Vanegas et al., 2006), hock lesions, and other leg injuries (e.g., Whay et al., 2003). Housing costs include depreciation but also maintenance costs. High depreciation could indicate recent larger investments and increases the likelihood of modern housing according to welfare increasing standards. Higher maintenance costs may indicate interventions to improve claw health and reduce lameness, such as improvements in the surface and flooring where the cows lie down (e.g., Bruijnis et al., 2013). Mean housing costs reported for the sample (1.6 Eurocents per kg ECM) are below the officially reported mean for Lower Saxony of about 2.37 Eurocents per kg ECM in the year 2016/17 (LaWiKa NI, 2017). This could be explained by the

[1] The goal of establishing standardised branch-specific cost accounting for agricultural businesses was to ensure comparability of economic performance between farms as a basis for assessing improvement potentials. Costs are grouped according to a Germany-wide scheme and are available for common production branches such as milk or pork production. The cost categories are as follows: direct costs, labour, land, buildings, and other costs. The direct costs for the dairy branch include sales, purchases and other outflow of livestock, roughage and concentrate feed costs, costs for insemination, veterinary and medication costs, electricity, heating, milk recording, advisory, livestock insurance and a residual category for other direct costs (DLG, 2011).

Table 1
Descriptive statistics (two-year average of economic years 2013/14–2014/15).

Variables	Unit	Mean	Std. dev.	Q10	Q90
Production economic and herd-management variables					
Number of cows	Animal stock/year	127.9	53.7	73.0	221.0
Milk yield per cow	kgECM	8867.5	1019.1	7449.0	10,098.0
Cost of concentrated feed	Eurocents/kgECM	8.6	1.7	6.6	11.2
Veterinary cost	Eurocents/kgECM	0.9	0.4	0.5	1.3
Insemination cost	Eurocents/kgECM	0.5	0.2	0.1	0.7
Total building cost	Eurocents/kgECM	1.6	0.7	0.8	2.6
Cell count (in thousands)	Cells/mm	216.5	75.3	135.0	306.0
Milk fat content	Fat (%)	4.1	0.2	3.9	4.3
Milk protein content	Protein (%)	3.4	0.1	3.3	3.5
Calving interval	Days between calving	403.2	22.4	378.0	436.0
Age at calving	Months	27.3	1.8	24.9	29.5
Health-related culling rate	Share of health-related outflow[a]	71.4	23.9	30.0	98.0
Pasture access (categorical variable)	1 (>10 h)	>10 h (24%)		1	4
	2 (6–10 h)	6–10 h (23%)			
	3 (<6 h)	<6 h (24%)			
	4 (no pasture)	No pasture (28%)			
Welfare Quality Protocol (WQP) measures					
WQP feed score index		48.0	19.6	9.4	69.1
WQP housing score index		59.6	8.9	46.9	70.3
WQP health score index		44.3	8.2	32.8	54.8
WQP behaviour score index		36.4	4.3	30.1	42.0
No. of observations		95			

Note: 50 farms were sampled; for 5 farms, we only have data for 1 year resulting in 95 observations. For reasons of data privacy protection, the minima and maxima cannot be reported.
[a] Health-related culling rate summarises the outflow reasons of fertility, milk yield, mastitis, claw lesions, metabolism and other disorders.

higher share of farms with pasture access in our sample, and farms may have fewer incentives to invest in modern housing due to space limitations compared to farms without pasture access. Some farms considered offering cows pasture access to compensate the shortcomings in terms of space per animal in older buildings (see Schulte et al., 2018).

Our dataset enhances the production economic data with information about biological performance based on regular milk recording schemes over the same period (economic years 2013/14 and 2014/15). These include milk content (fat, protein, somatic cell count) and cow specific information (age at first calving, last calving interval, and reason for outflow). The sampled farms' fat and protein content seems to fall within a satisfying range with means of 4.1% fat and 3.4% protein, comparable to the results by Hoedemaker et al. (2020, Table 35), who report 4.1% fat and protein content of about 3.4% for their sample in northern Germany. Somatic cell count seems at first glance also to lie within a satisfying range regarding the mean of 216.5 thousand cells per ml of milk; Hoedemaker et al. (2020) report for a subsample a mean of about 205 thousand.

A mean calving interval of 403 days seems to be positioned at the upper range of recommendations to prevent economic losses (e.g., Esslemont et al., 2001); whereas a recent study points to higher reproductive performance with greater persistence for longer calving intervals without significant reductions in milk yield (Niozas et al., 2019a; Niozas et al., 2019b). However, a longer interval could also be the result of fertility mismanagement, where stress and feed mismanagement could lead to insufficient heat indication. Hoedemaker et al. (2020) report 410 days for their sample at the mean and 392 at the median. An age at first calving of 27 months is at the upper range of the age recommended; for economic reasons, between 24 and 26 months is preferred.

We rely on herd averages and note the share of specific reasons related to culling rates, including insufficient milk yield, fertility and health reasons, such as claw lesions, metabolism, mastitis and other sickness (see Table A2 in the Appendix). Compared to Hoedemaker et al. (2020), the share of animal outflow is larger in our sample (24.9% vs. 16.6%) with smaller shares of outflow due to sales for breeding (8.2% vs. 18.1%) and larger shares of health-related reasons for outflow (71.4% vs. 43.0%).

Last, we have the unique opportunity to additionally rely on WQP indicators for housing, feeding, behaviour, and health ranging from 0 to 100, with the overall assessment taking the unweighted mean of these four indicators. According to the welfare quality protocol, pasture access enters the measure of housing via the dimension of *movement*. That is, availability of pasture access increases the housing score compared to confinement systems, even if all remaining measures are identical. To ensure comparability of welfare without potential biases, scoring by pasture access in the WQP was therefore excluded from the WQP-score calculation. The respective schematic assessment according to the WQP was carried out by a trained expert twice (July–October 2014; January–April 2015). All assessments were carried out by the same person, in close collaboration with researchers from the field of animal science and the Chamber of Agriculture. We rely on the values of both visits, where we relate assessments in 2014 to the economic year 2013/14, and those of 2015 to 2014/15, respectively. While the housing index seems rather high with a mean above 50, other WQP indicator values reveal considerable improvement potential in the respective dimension of the animal welfare of the sampled farms.

To summarise, the sample characteristics are within the ranges found by other studies. Furthermore, the sample appears heterogeneous across the dimensions of farm animal welfare, in the branch-specific accounting and cow-specific milk recording scheme data. Therefore, even though small, the suitability for further analysis and reliability of results seem given.

2.2. Methods

To validate the use of production economic and herd-management variables for farm animal welfare assessment purposes, we examine the relation of these variables to the on-farm WQP index variables. To examine the relationships between WQP principles and the production economic and herd-management variables, we propose two approaches: Seemingly Unrelated Regression (SUR) (Zellner, 1962; Wooldridge, 2010) and Canonical Correlation Analysis (CCA) (Hotelling, 1935; Härdle and Simar, 2015).

The SUR model performs a joint estimation for principles of WQP variables $Y_{i,\ wqp}$ as functions of the production economic and herd-management variables and allows the error terms of the respective equations to correlate. The SUR model is given by:

$$Y_{i,wqp} = \alpha + \beta X_i + \varepsilon_i \tag{1}$$

where Y_i denotes the vector of the WQP principles (WQP-feed, WQP-health, WQP-housing and WQP-behaviour). X_i denotes the vector comprising the production economic and herd-management variables that may proxy animal welfare as listed in Table 1: milk yield, cost of concentrated feed, veterinary cost, insemination cost, building cost, cell count, milk fat content, milk protein content, calving interval, age at calving, and culling due to health and pasture. This setup will provide evidence of how related the WQP principles are to the production economic and herd-management variables, where ε_i is the random disturbance term.

The model provided in Eq. (1) imposes a linear relationship between the individual on-farm WQP principles and the production economic and herd-management variables. The SUR implements the regression of 4 WQP principles on 12 production economic and herd-management variables. However, it is highly likely that the two sides of the regression have a considerable level of interdependence within the sides. To account for possible interdependence between variables within WQP principles on one hand and the production economic and herd-management variables on the other, we implement a CCA approach, which enables us to reduce the dimensionality from both sides. This approach endogenously suggests the number of dimensions sufficient to capture WQP principles as well as the production economic and herd-management variables. Therefore, CCA offers dimensionality reduction on both sides endogenously. Based on dimensions' loadings, the approach seeks to identify the appropriate number of dimensions of FAW measures that maximise the correlation between the constructs of the WQP principles and those of the production economic and herd-management variables. The CCA approach examines the linear link between and within the on-farm WQP constructs and the constructs of the production economic and herd-management variables.

To set up the CCA model, Y represents the set of 4-dimensional on-farm WQP measures, and X represents the set of production economic and herd-management variables. The canonical correlation analysis establishes a set of linear combinations or canonical variates of Y variables and X variables that maximise the correlation between them. The canonical variates or constructs are given by:

$$f_i(Y) = \gamma_{ij} Y' \text{ and } g_i(X) = \beta_{ik} X' \tag{2}$$

where f_i represents the i^{th} canonical variate/latent of the on-farm WQP measures, and g_i denotes the i^{th} variate of the production economic and herd-management variables that we use to explain farm animal welfare. Symbol γ_i denotes the vector of coefficients of the i^{th} canonical variate based on the WQP variables, while β_i denotes the vector of coefficients of the i^{th} canonical variate from the production economic and herd-management variables. The coefficients (γ_i,β_i) are chosen to maximise the correlation between the first canonical variates, and successive variates are extracted from the residual variance of the preceding variate and formalised as:

$$(\gamma_i^*, \beta_i^*) = argmax\ corr(\gamma_i Y', \beta_i X'), \tag{3}$$

where, γ_i and β_i have the same interpretation as regression coefficients given that the canonical variates or constructs (not original variables) are the dependent variables. The CCA is restricted to establish four dimensions or canonical functions given the number of Y variables, which have the smallest set of variables. However, the number of statistically significant canonical correlations determines the final dimensions needed for the analysis. Canonical correlations are Pearson correlation coefficients between pairs of variates, and these reflect the strength of their relationship.

3. Results

This section displays the estimation results of the models presented in the section above. Table 2 presents the SUR estimations of the model given in Eq. (1). The findings show that production economic and herd-management variables seem to relate differently, in terms of magnitude and sign of effect, to the different principles of WQP.

As shown in Table 2, the *feed* principles of the WQP are negatively related to cell count and age at calving, while positively related to the milk fat content and calving interval production economic and herd-management variables. The *housing* principle is positively related to veterinary cost and building cost, while the *health* principle of WQP is positively related to age at calving and negatively related to cell count and calving interval. Finally, the *behaviour* principle is negatively related to cost of concentrated feed, building cost, milk fat content and calving interval.

These results show that some variables show varying degrees of statistical significance and/or effect signs on different principles of WQP. For instance, the milk fat content variable is positively related to the feed principle of the WQP (coef = 21.492) and negatively related to the behaviour principle (coef = −8.115). Based on the SUR model, the relationships between the milk fat content and the WQP principles are not consistent. Such an inconsistency of effects also holds for other production economic and herd-management variables such as building

Table 2
Seemingly unrelated estimation results of different principles of the WQP concerning production economic indicators.

Variables	WQP feed		WQP housing		WQP health		WQP behaviour	
Milk yield	−8.975	(7.487)	3.594	(3.314)	1.843	(3.059)	−1.937	(1.221)
Cost of concentrated feed	−0.490	(1.546)	−0.418	(0.653)	−0.567	(0.572)	−0.651***	(0.235)
Veterinary cost	−9.998	(7.512)	7.487**	(3.539)	0.835	(2.926)	1.093	(1.729)
Insemination cost	12.619	(9.383)	−6.646	(6.396)	−4.455	(2.931)	−1.180	(2.158)
Building cost	5.997	(3.842)	3.066**	(1.523)	−1.544	(1.220)	−2.181***	(0.646)
Cell count	−0.047*	(0.024)	−0.013	(0.016)	−0.026*	(0.014)	0.015**	(0.006)
Milk fat content	21.492*	(12.394)	−1.621	(7.351)	2.753	(6.637)	−8.115**	(3.515)
Milk protein content	66.285	(40.970)	4.616	(19.288)	12.283	(14.371)	5.558	(6.376)
Calving interval	0.215**	(0.109)	−0.073	(0.049)	−0.139***	(0.033)	−0.047**	(0.023)
Age at calving	−2.428*	(1.426)	1.157	(0.736)	1.245**	(0.618)	−0.435	(0.280)
Culling due to health	−0.038	(0.091)	−0.005	(0.039)	−0.046	(0.032)	0.012	(0.020)
Pasture (>10 h)	−1.815	(6.908)	−2.720	(3.294)	−2.447	(2.942)	−1.566	(1.400)
Pasture (6–10 h)	5.388	(7.216)	0.033	(4.053)	−3.102	(2.751)	−0.414	(1.558)
Pasture (<6 h)	−0.152	(8.563)	3.758	(3.355)	−2.898	(2.909)	0.077	(1.329)
Constants	−186.570	(138.090)	14.167	(76.794)	16.349	(60.674)	104.457***	(31.222)
N	95		95		95		95	
R^2	0.305		0.188		0.317		0.305	

Note: Year-fixed effects are included in all of the estimations. Cluster standard errors in parentheses *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$. Confinement or no pasture is the reference group for the pasture categorical variable.

cost, cell count, calving interval, and age at calving. Building costs are statistically significant and positively related to the WQP housing principle (coef = 3.066), but negatively related to behaviour (coef = −2.181). Cell count is negatively related to the feed (coef = −0.047) and health principle (coef = −0.026) and positively related to the behaviour principle (coef = 0.015) of the WQP. Calving interval relates positively to the feed principle of the WQP, and negatively to health and behaviour principles. In addition, age at calving relates positively to the health principle of WQP, and negatively to the feed and behaviour principles. Lastly, the cost of concentrated feed has a significant relationship with the behaviour principle of WQP (coef = −0.651) but not with other principles.

The results from the SUR estimation in Table 2 present a challenge to the use of production economic variables as direct indicators or proxies of animal welfare as measured by on-farm WQP principles, particularly because of differences in the effect signs and levels of significance of a given production economic and herd-management variable on different principles of WQPs.

To examine the dimensionality and relation between the resulting constructs, we apply the CCA approach. Table 3 shows the results of several multivariate tests to determine the optimal number of constructs suggested by the model. The upper chamber shows the results of the F-test for the statistical significance of the overall model for the null hypothesis that the canonical correlation coefficients of all functions are zero, which is rejected at common levels. All types of these F-tests as presented in Table 3 reveal consistent results, and all lead to rejecting the null hypothesis of zero canonical correlations. This suggests that the model has at least one statistically significant canonical function. A simple correlation analysis of the variables used in the analysis is given in Table A3 in the Appendix.

The lower chamber of Table 3 reports results for the statistical test for the null hypothesis that the canonical correlation coefficients of each pair of functions are zero. Following the test results, the first two functions reveal correlations different from zero at common significance levels. This implies that the first two canonical functions have a canonical correlation that is statistically and significantly different from zero and two functions, as represented by the variates, that can model farm animal welfare given the data set. These two statistically significant functions determine the number of variates for the subsequent investigation of the link between variates from the WQP variables, and the production economic and herd-management variables.

The values of canonical correlations for the first and second canonical functions, as given in the lower chamber of Table 3, are 0.652 and 0.514 respectively, and indicate the magnitude of correlation between the pair of canonical variates from the two variable sets (WQP, and production economic and herd-management variables) in each of the functions. For example, the value 0.652 is the correlation between canonical variate 1 of the WQP, and variate 1 of the production economic and herd-management variables. The values reflect the percentage of variance in the respective WQP principle-based canonical variate (dependent) explained by the production economic and herd-managerial canonical variate (explanatory). Therefore, the first function is derived to maximise the correlation between its variates and thus show the highest correlation coefficient. Successive functions show gradually declining canonical correlations.

In order to see which variable contributes to the respective variates, we rely on the standardised coefficients of the linear combinations of canonical variates, their rotations and significance levels (see Tables 4A and 4B). Given the difference in the standard deviation of the variables in our sample, the standardisation facilitates the comparison of the weights or canonical coefficients, while rotation provides a clearer picture of the factors that show a higher importance in magnitude. Given the statistical significance of the variables, the larger the standardised canonical coefficient is, the more it contributes to explaining the variate. The signs of the standardised canonical coefficients denote the direction of the variables' loading to their respective canonical variate.

Column 1 and 2 of Table 4 (both Tables 4A and 4B) present the standardised canonical coefficients and their rotations, respectively. The size indicates the individual variables' contribution to each variate in standard deviations for one unit of standard deviation change in the construct variables. According to the standardised coefficients given in column 1 of Table 4A, the first canonical variate of the WQP variables is mainly a construct of health and behaviour, while the second variate is mainly a construct of the WQP principles of feed, housing and health. The raw (non-standardised) coefficients of the CCA results with the significance test of individual variables are given in Table A4 in the Appendix. Likewise, column 1 of Table 4B shows that the first canonical variate of the explanatory production economic and herd-management variables is mainly a construct of building cost, cost of concentrated feed, milk fat content, and calving interval, while the second variate is a construct of cell count, milk protein and fat content, and pasture as well as building cost.

The canonical loadings given in column 3 and 4 of Table 4 (both in Tables 4A and 4B) measure the linear correlation between the original variables and their corresponding canonical variates. Table 4A presents results for the WQP variables and their variates and Table 4B those for production economic and herd managerial variables and their corresponding variates. The canonical loading reflects the variance that the original variables share with their corresponding canonical variates and have the same interpretation as factor loadings in factor analysis. From column 4 of Table 4A, the estimates of the rotated canonical loadings indicate that feed and behaviour are mainly loading to the first canonical variate of the dependent variables, while health and housing variables load to the second variate. This result is consistent with the results from the rotated standardised canonical coefficients, and such similarity provides evidence of the robustness of the results in the model (Rencher, 1992). From the explanatory variables side, given in column 4 of Table 4B, building cost and milk content of fat and protein seem to load high to the first canonical variate, while calving interval, cell count, pasture and cost of concentrated feed load to the second variate. Fig. A1 in the Appendix provides graphic illustration of canonical coefficients and their loadings (given in Column 1 and 3 in both Tables 4A and 4B) and the correlation coefficient for variates in canonical function 1.

Lastly, the canonical cross-loadings from the variates of WQP and PEHM are given in Tables 5A and 5B, respectively. Cross-loadings link the original variable with the opposite canonical variates and are interpreted as measures of correlation between the original variables and their opposite variate. It measures how the original dependent variables correlate to the explanatory variate (Table 5A) or how the original explanatory variables correlate to the corresponding dependent variate (Table 5B) included in the canonical functions. These cross-loadings provide a more direct interpretation of the loading between the canonical variates of WQP measures and the individual variables from the production economic and herd-management data or vice versa.

Table 3
Canonical correlation analysis: overall model fit and test of canonical correlations.

Multivariate tests of significance of all canonical correlations

Test statistics	Statistic value	F	Prob > F
Wilks' lambda test	0.311	2.261	0.000
Pillai's trace test	0.970	2.189	0.000
Lawley-Hotelling trace test	1.437	2.320	0.000
Roy's largest root test	0.738	5.041	0.000

Test of canonical correlations: Wilks' lambda test

Canonical functions	Statistic value	F	Prob > F	Canonical correlations
1	0.311	2.261	0.000	0.652
2	0.540	1.665	0.017	0.514
3	0.734	1.351	0.155	0.450
4	0.921	0.782	0.633	0.281

Table 4A
Standardised canonical coefficients and canonical loadings of the first two canonical functions of WQP variables ($N = 95$).

Variables	Standardised canonical coefficients (1)		Standardised canonical coefficients (rotated) (2)		Canonical loadings (3)		Canonical loadings (rotated) (4)	
	Variate 1	Variate 2	Variate 1	Variate 2	Variate 1	Variate 2	Variate 1	Variate 2
WQP variables								
WQP feed	0.26	0.74	0.71	0.34	0.56	0.62	0.83	0.05
WQP housing	−0.12	0.38	0.18	0.35	−0.22	0.46	0.17	0.48
WQP health	−0.65	0.58	−0.05	0.87	−0.63	0.59	−0.04	0.86
WQP behaviour	−0.67	−0.06	−0.51	0.43	−0.63	−0.41	−0.73	0.16

4. Discussion and policy implications

This study was motivated by the need to validate the use of routinely collected production economic and herd-management data to measure FAW against on-farm measures based on WQP principles. Using the SUR model and CCA, our study finds important relations between production economic and herd-management variables and the principles of WQP-based on-farm FAW measures. This suggests that the use of production economic and herd-management variables offers a way to measure dairy cow welfare and lends support to our hypothesis.

Using the SUR approach we find that milk fat content is negatively related to the feed principle in WQP. In line with this, Hoedemaker et al. (2020) indicated that the use of high concentrate along with a lower roughage share in the feed ration can be reflected in the milk content, such as the fat-protein ratio, where fat-protein ratios lower than 1.1 were negatively associated with lameness risk for their sampled farms. We also find that the calving interval is positively related to the principles of feed, and negatively to the principles of health and behaviour. This is in line with the findings by Niozas et al. (2019a) and Niozas et al. (2019b), who found higher reproductive performance and persistence for dairy cows in a longer calving interval without significant reductions in milk yield. For milk yield and mortality rates, our results do not reveal any relation to the WQP principles, which is in contrast to the findings of de Vries et al. (2014) and Thomsen and Houe (2018).

By specifically addressing the potential relationship between FAW as assessed from production economic and herd-management indicators and FAW as assessed from on-farm WQP assessment by canonical correlation analysis, an enhanced understanding about the relationship between the two types of FAW indicators emerged. First, the dimensionality of animal welfare as measured by the WQP is reduced to two constructs: feed-health-behaviour and feed-health-housing, where a clearer structure from rotated loadings suggest feed-behaviour and health-behaviour as first and second constructs/variates from the WQP principles. Second, from the production economic and herd-management data, building cost, milk fat content and calving interval variables provide the first construct, while cost of concentrated feed, cell count, milk protein, calving interval and pasture variable make the second construct. In the first canonical function, the correlation between the first variates of WQP principles and production economic variables is the strongest in the data followed by the second variates in the second canonical function as given in Table 3. In other words, the correlation between the first variate from WQP variables and the PEHM variables is the strongest, followed by the second variates from the respective variable groups.

Third, our results establish important relations between WQP principles and PEHM variables. Data from the milk recording scheme enhance insight into the animal welfare constructs based on costs: fat content and calving interval relate to the feed-behaviour construct together with the cost positions. The cost of concentrates positively relates to the feed-behaviour construct; this may point to the relation to animal welfare and a sufficient energy balance. This is in line with Drews et al. (2018) who find non-sufficient feeding harming biological performance. Milk protein and cell count relate negatively to the feed-health-housing construct, along with building cost. Protein content seems to be a plausible indicator for energy supply and successful feed management. Undersupply of energy may affect metabolism, e.g. ketosis, and lower protein and/or higher fat may be the result (see Humer et al., 2018). Somatic cell count negatively relates to the feed-health-housing construct. Somatic cell count can be a useful indicator for herd mastitis monitoring (Bradley and Green, 2005; Jadhav et al., 2018), where mastitis is still the most prevalent disease in dairy herds (Viguier et al., 2009; Hogeveen et al., 2019). Our results indicate that somatic cell count also relates to three welfare quality principles and thus seems useful. We further note the negative, but statistically non-significant coefficient for cost of concentrates: too high concentrates may concern ruminal health with metabolic disorders as a result.

Our results underline the challenge of relying on single FAW indicators despite the temptation to do so. Nevertheless, they also illustrate potential benefits of merging already existing and routinely collected data for dairy cows with production economic data of the FADN type. Such datasets are typically not merged by default. Instead, initiatives to merge such datasets are taken occasionally by individual research

Table 4B
Standardised canonical coefficients and canonical loadings of the first two canonical functions of production economic and herd-management (PEHM) variables (N = 95).

Variables	Standardised canonical coefficients (1)		Standardised canonical coefficients (rotated) (2)		Canonical loadings (3)		Canonical loadings (rotated) (4)	
	Variate 1	Variate 2	Variate 1	Variate 2	Variate 1	Variate 2	Variate 1	Variate 2
PEHM variables								
Milk yield per cow	−0.01	−0.04	−0.04	−0.02	−0.14	−0.04	−0.13	0.07
Cost of concentrated feed	0.38	−0.12	0.18	−0.36	0.38	−0.11	0.19	−0.35
Veterinary cost	−0.27	−0.09	−0.25	0.13	−0.19	−0.12	−0.22	0.05
Insemination cost	0.29	0.05	0.24	−0.17	0.21	0.11	0.23	−0.08
Building cost	0.53	0.33	0.61	−0.14	0.49	0.41	0.63	−0.06
Cell count	−0.08	−0.58	−0.47	−0.35	0.25	−0.47	−0.15	−0.50
Milk fat content	0.33	0.34	0.48	0.01	0.17	0.37	0.38	0.14
Milk protein content	−0.10	0.39	0.21	0.35	0.11	0.42	0.38	0.22
Calving interval	0.77	−0.17	0.43	−0.66	0.59	−0.28	0.22	−0.62
Age at calving	−0.23	0.19	−0.03	0.29	0.01	0.05	0.05	0.03
Culling due to health	0.04	−0.29	−0.18	−0.24	−0.01	−0.28	−0.20	−0.20
Pasture	−0.25	0.30	0.03	0.39	−0.05	0.44	0.28	0.35

Table 5A
Canonical cross-loadings between canonical variates of PEHM and individual WQP variables ($N = 95$).

Variables	Variate 1 of PEHM	Variate 2 of PEHM
WQP variables		
WQP Feed	0.36	0.32
WQP Housing	−0.14	0.24
WQP Health	−0.41	0.30
WQP Behaviour	−0.41	−0.21

projects. However, a default merge of data of the FADN type with other sources of farm and/or herd level data would facilitate a large-scale monitoring and analysis of FAW in the supply chain. Moreover, it would also facilitate creating value from sustainable dairy cow husbandry (Friedrich et al., 2020). Research has already pointed to the usefulness of expanding FADN by merging with complementary data sources to better be able to assess sustainability, but it has so far not validated this usefulness in the FAW domain of sustainability (Buckley et al., 2015; Kelly et al., 2018).

By validating production economic and herd-management data against on-farm WQP assessments of FAW, we contribute to a policy of sustainable production economics but also business management literature about how existing data can be used efficiently by merging register data with data from dairy cow recording schemes to proxy FAW. In fact, using pure accountancy data has been demonstrated for investigating trade-offs between FAW and farms' production efficiency to facilitate the development of FAW-increasing measures (Hansson et al., 2020; Adamie and Hansson, 2021).

We are first to consider production economic data along with herd-management data, e.g., milk yield, quality and mortality, and cost items to make it explicit how to proxy FAW by validating against on-farm measures of FAW based on the WQP principles. From a method perspective, we contribute by demonstrating the use of canonical correlations in this type of validation study. Data are formed into dimensions based on the underlying structure in the dataset with explicitly acknowledged relationships between dimensions. Our study used production economic and herd-management data on one hand and data based on WQP-principles on the other to create latent constructs. These FAW constructs are based on the actual correlation of the variables in the data, instead of evaluating the FAW measure in terms of a priori determined variables. By establishing a significant correlation between on-farm WQP measures, and production economic and hermanagement variables, our approach provides a basis for developing indicators from data routinely collected on a farm scale to measure dairy welfare on a larger scale.

Recent and future projected development in terms of digital data collection and resources could greatly facilitate the compilation of data on a routine basis that offer developing iceberg indicators for dairy cow welfare on a large scale. Such indicators would facilitate performance-monitoring processes on the farm and advisory levels, as well as policy evaluation towards more sustainable animal production and value creation.

Table 5B
Canonical cross-loadings between canonical variates of WQP and individual PEHM variables (N = 95).

Variables	Variate 1 of WQP	Variate 2 of WQP
PEHM variables		
Milk yield per cow	−0.09	−0.02
Cost of concentrated feed	0.25	−0.06
Veterinary cost	−0.12	−0.06
Insemination cost	0.14	0.06
Building cost	0.32	0.21
Cell count	0.16	−0.24
Milk fat content	0.11	0.19
Milk protein content	0.07	0.22
Calving interval	0.38	−0.15
Age at calving	0.01	0.03
Culling due to health	0.00	−0.15
Pasture	−0.03	0.23

Limitations of our study should be acknowledged. First, our dataset must be considered small. This is a direct effect of the time-consuming WQP on-farm assessment. Compared to average herd sizes in the region (Lower Saxony) of 85.5 cows, with the German average being about 61 cows (Destatis, 2017), the sampled farms can be categorised as medium-large. Milk yields in the region of northern Germany (Hoedemaker et al., 2020) are also comparable to our sample. We argue that the sampled farms represent typical production structures for north-western German milk production. Despite the limited sample size, we could identify interesting relationships between the WQP and the production economic and herd-management data; however, with a larger dataset we could have identified more precise relationships. Second, the WQP on-farm assessments of FAW were conducted by only one person. This could have prevented subjective bias from different persons while collecting the data and forming the FAW assessments. At the same time, the data collection for the WPQ assessment remain a subjective collection by one trained person without controlling instances, such as a two-person rule, and could therefore have an effect on the results. Third, our findings are restricted to dairy production, where animals are kept in production for a rather long period. In this respect, it would also be interesting to investigate whether non-dairy production systems with shorter periods, for fattening purposes rather than reproductive systems, would lend themselves more easily to this type of validation. Time in production for individual animals could affect production features, which are manifested through cost items, such as veterinary treatments, but also building cost determining the housing environment and thus possibilities for the animals to follow natural behavioural habits. Given the usefulness of large-scale panel datasets for policy evaluation and performance monitoring, future research will have important roles in further adding to insights about how FAW can be proxied and evaluated from already existing datasets in other types of animal production and other types of case study areas.

5. Conclusions

Our study investigated the potential use of production economic and herd-management data to measures dairy cow animal welfare by validating against WQP measures, which are on-farm based welfare measures. We found a strong link between these measures, which suggests the efficient use of production economic type data to proxy dairy cow welfare measures. Looking at individual WQP principles, we found that the WQP *feed* principle is negatively related to cell count and age at calving, while positively related to milk fat content and calving interval variables of production economic and herd-management variables. The *housing* principle is positively related to veterinary cost and building cost. The *health* principle of WQP is positively related to age at calving and negatively related to cell count and calving interval, while the *behaviour* principle is negatively related to cost of concentrated feed, building cost, milk fat content and calving interval. The CCA reveals the holistic measure of dairy cow welfare by introducing dimensionality in our analysis. For example, the feed-behaviour construct relates to calving interval, building cost and milk fat content while health-behaviour construct relates to cost of concentrated feed, cell count, calving interval and pasture access.

The findings presented in this paper are useful for the development of public and private FAW policy in several respects. First, they can facilitate research on the impact of various public and private policy initiatives related to FAW. Second, they can be used to facilitate research on the relationships between FAW and other sustainability aspects of animal production. Third, they can also be applied to monitor FAW related progress on a large scale.

These areas of evidence-based policy advice could benefit from further research using historical panel data to trace major patterns of development over time. Using such data, it is typically not feasible to merge with current on-farm assessments of FAW. Instead, such research can use findings presented here to obtain insight into how indicators from production economic type data can be used to proxy animal welfare. The design of public and private policy related to FAW can then benefit from the type of long-term monitoring of FAW progress that can be enabled by a wider spread use of already existing panel datasets that cover historical data for several years.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A1
Descriptive statistics of variables in the analysis per year.

Variables	2013				2014			
	Mean	Std. dev.	Q10	Q90	Mean	Std. dev.	Q10	Q90
Production economic and herd variables								
Number of cows	124.1	51.5	71.0	227.0	131.6	56.0	75.0	221.0
Milk yield per cow	8979.1	989.7	7628.0	10,091.0	8758.3	1045.9	7365.0	10,204.0
Cost of concentrated feed	9.1	1.7	7.2	12.1	8.1	1.7	5.9	10.5
Veterinary cost	0.8	0.3	0.5	1.4	0.9	0.4	0.5	1.3
Insemination cost	0.5	0.2	0.1	0.7	0.4	0.2	0.1	0.7
Total building cost	1.4	0.6	0.6	2.3	1.8	0.7	1.0	2.6
Cell count	222.3	73.8	129.0	336.0	216.5	75.3	135.0	306.0
Milk fat content	4.1	0.1	3.9	4.2	4.1	0.2	3.9	4.3
Milk protein content	3.4	0.1	3.3	3.5	3.4	0.1	3.3	3.5
Calving interval	405.0	19.6	380.0	430.0	403.2	22.4	378.0	436.0
Age at calving	27.5	1.8	25.0	29.5	27.3	1.8	24.9	29.5
Health-related culling rate[a]	71.1	24.0	26.0	99.0	71.4	23.9	30.0	98.0
WQP measures								
WQP feed score	48.5	19.6	9.4	70.9	48.0	19.6	9.4	69.1
WQP housing score	59.7	9.0	46.9	70.3	59.6	8.9	46.9	70.3
WQP health score	44.2	8.2	32.8	54.8	44.3	8.2	32.8	54.8
WQP behaviour score	36.3	4.3	30.1	42.0	36.4	4.3	30.1	42.0
No. of observations	47				48			

[a] Health-related culling rate summarises the outflow reasons of fertility, milk yield, mastitis, claw lesions, metabolism and other health disorders. Q10 and Q90 represent the 10th and 90th percentiles of the variables.

Table A2
Descriptive statistics for outflow variables.

Variables	Mean	Std. dev.	Q10	Q90
Total outflow rate (%)	24.9	8.3	15.0	37.3
Derived reasons (%) for outflow				
Breeding	8.2	15.3	0.0	30.0
Age	2.9	5.3	0.0	10.0
Milk yield	4.8	7.1	0.0	12.0
Fertility	24.3	17.2	3.0	44.0
Other sickness	6.5	9.3	0.0	19.0
Mastitis	16.7	14.5	0.0	37.0
Claw lesions	16.0	12.1	0.0	33.0
Other reasons	14.8	20.9	0.0	35.0
Metabolism	3.3	5.0	0.0	10.0
Milkability	2.5	4.6	0.0	7.0
No. of observations	95			

Table A3
Correlation matrix of variables in the study (N = 95).

	Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	WQP feed	1.000														
2	WQP housing	−0.129	1.000													
3	WQP health	−0.155	**0.291**	1.000												
4	WQP behaviour	**−0.267**	−0.185	−0.134	1.000											
5	EC milk yield	−0.141	0.092	0.086	−0.018	1.000										
6	Cell count	−0.017	−0.142	**−0.291**	0.060	−0.047	1.000									

(continued on next page)

Table A3 (*continued*)

	Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
7	Milk fat content	0.196	0.010	0.055	−0.147	−0.147	**0.226**	1.000								
8	Milk protein content	**0.225**	0.055	0.045	−0.070	0.088	**0.221**	**0.267**	1.000							
9	Calving interval	0.151	−0.191	**−0.334**	−0.156	**−0.240**	**0.316**	−0.033	−0.046	1.000						
10	Age at calving	−0.074	0.010	0.119	−0.158	**−0.363**	0.136	0.106	0.036	**0.399**	1.000					
11	Veterinary cost	−0.105	0.109	−0.027	0.148	−0.018	−0.157	−0.044	−0.145	−0.080	**−0.303**	1.000				
12	Insemination cost	0.157	0.013	−0.118	−0.034	0.094	**−0.219**	−0.019	−0.139	0.022	**−0.257**	**0.486**	1.000			
13	Culling due to health	−0.097	−0.028	−0.100	0.069	−0.024	−0.112	−0.003	−0.053	−0.131	−0.097	0.105	0.026	1.000		
14	Pasture	0.188	0.127	0.073	0.029	−0.017	−0.182	0.101	−0.018	0.009	−0.162	0.065	0.183	−0.029	1.000	
15	Building cost	**0.274**	0.163	−0.124	**−0.278**	0.018	0.012	−0.056	0.193	−0.129	−0.182	−0.085	0.080	−0.018	0.115	1.000
16	Cost of concentrated feed	0.050	−0.075	−0.136	**−0.205**	−0.045	0.102	−0.040	**0.202**	−0.032	−0.107	−0.056	−0.107	0.108	0.041	0.110

The bold values indicate correlation coefficients greater than 0.2 in absolute terms.

Table A4
Linear combinations of the two canonical functions – row coefficients (N = 95).

Variables	Canonical function 1			Canonical function 2		
	Coef.	Std. err.	*P*-value	Coef.	Std. err.	P-value
On farm variables						
WQP feed	0.013	0.007	0.047	0.038	0.010	0.000
WQP housing	−0.013	0.015	0.364	0.042	0.021	0.048
WQP health	−0.079	0.016	0.000	0.071	0.023	0.002
WQP behaviour	−0.155	0.031	0.000	−0.014	0.044	0.752
Economic variables						
EC milk yield	−0.036	0.374	0.924	−0.101	0.535	0.850
Cost of concentrated feed	0.220	0.079	0.006	−0.071	0.113	0.530
Veterinary cost	−0.741	0.431	0.089	−0.240	0.617	0.698
Insemination cost	1.262	0.695	0.072	0.233	0.995	0.816
Building cost	0.787	0.208	0.000	0.499	0.298	0.098
Cell count	−0.001	0.002	0.582	−0.008	0.003	0.009
Milk fat content	2.105	0.925	0.025	2.200	1.325	0.100
Milk protein content	−1.494	2.214	0.501	6.011	3.171	0.061
Calving interval	0.034	0.007	0.000	−0.007	0.010	0.465
Age at calving	−0.125	0.090	0.168	0.102	0.129	0.430
Culling due to health	0.002	0.006	0.754	−0.012	0.008	0.125
Pasture	−0.221	0.120	0.070	0.259	0.172	0.136
Canonical correlation	0.652			0.514		

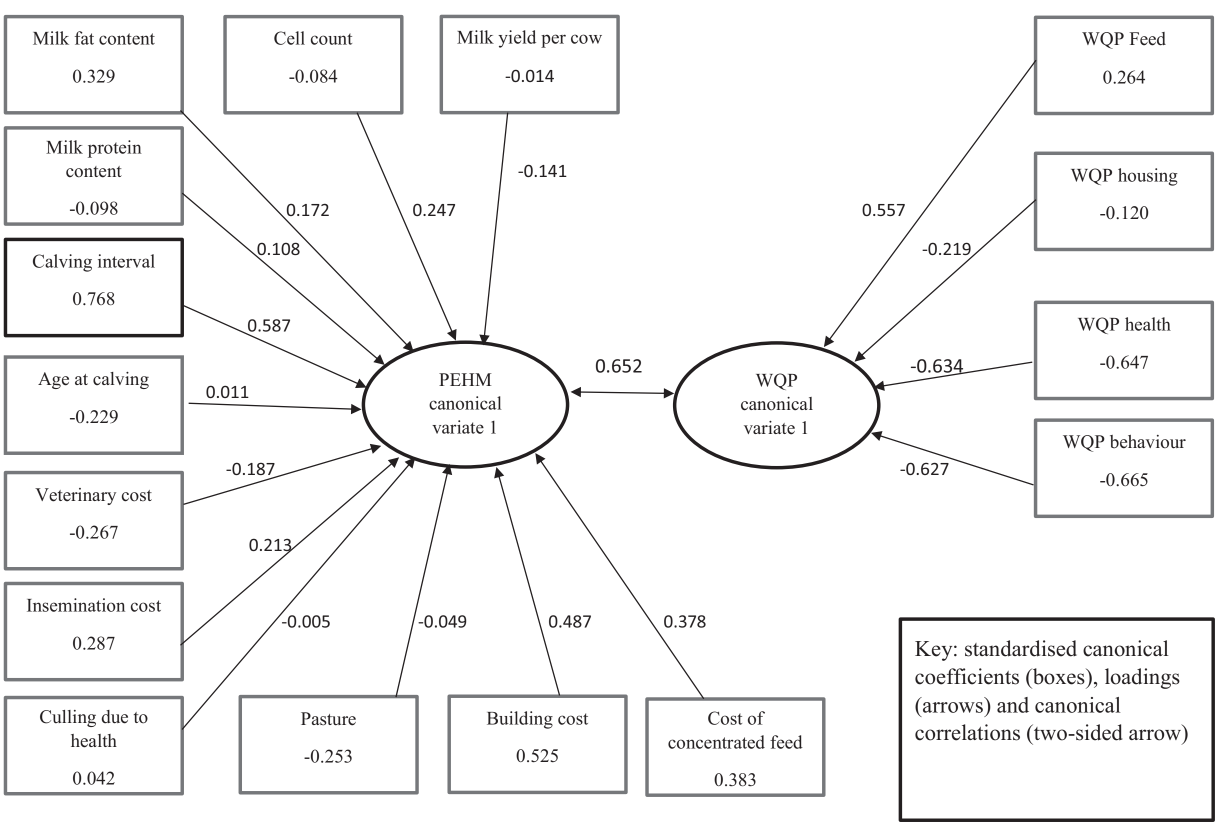

Fig. A1. Canonical function 1 (unrotated): standardised canonical coefficients, loadings and canonical correlations.

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