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The Whole and the Parts—A New Perspective on Production Diseases and Economic Sustainability in Dairy Farming

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Abstract: The levels of production diseases (PD) and the cow replacement rate are high in dairy farming. They indicate excessive production demands on the cow and a poor state of animal welfare. This is the subject of increasing public debate. The purpose of this study was to assess the effect of production diseases on the economic sustainability of dairy farms. The contributions of individual culled cows to the farm's economic performance were calculated, based on milk recording and accounting data from 32 farms in Germany. Cows were identified as 'profit cows' when they reached their individual 'break-even point'. Data from milk recordings (yield and indicators for PD) were used to cluster farms by means of a principal component and a cluster analysis. The analysis revealed five clusters of farms. The average proportion of profit cows was 57.5%, 55.6%, 44.1%, 29.4% and 19.5%. Clusters characterized by a high proportion of cows with metabolic problems and high culling and mortality rates had lower proportions of profit cows, somewhat irrespective of the average milk-yield per cow. Changing the perception of PD from considering it as collateral damage to a threat to the farms' economic viability might foster change processes to reduce production diseases.

Keywords: profit cows; economic sustainability; knowledge transfer; production disease; production disease economics

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1. Introduction

1.1. Production Diseases Affect Animal Welfare and Economic Viability

Animal health and welfare is the subject of increasing importance in social discourse in western European societies and an important feature in the consideration of the external social sustainability of dairy farming [1–3]. It is closely linked to the concept of "one-health" and ultimately to the question of acceptance of intensive livestock production by citizens and consumers [4,5]. The short lifespan of dairy cows and the level of production diseases are a starting point for consumers' and scientists' criticism of modern dairy systems [6–8].

Production diseases reflect production induced stressors and indicate an overstressing of the ability of animals to adapt and cope with suboptimal living conditions. They cause pain, suffering and injury and indicate poor animal welfare [9,10]. Lameness, metabolic disorders, or mammary and uterine infection are not related to a single cause but are affected by multiple factors. In this context, farm management plays a pivotal role in guarding against production diseases [11,12]. At the same time, production diseases have a substantial impact on the economic performance of the farm due to a reduced milk yield and an increase in involuntary culling [2,13,14]. Additionally, antimicrobials and other pharmaceutical substances are used to mitigate economic losses reinforcing concerns about antimicrobial resistance and residues [15]. An important and often underestimated cost due to diseases is the cost of culling. The term culling is used in different ways in the literature [16]. Referring to the definition used in Germany, the term culling here includes on-farm death of cows and all sales for slaughter. Sales for breeding purposes are excluded. Voluntary and involuntary culling needs to be regarded as distinctively different. Voluntary culling occurs when the farmer decides to replace a cow for reasons other than disease or injury. This may be economically desirable when a cow has exceeded the peak of her milk production which is usually after her fifth parity [17]. However, few cows reach this age. According to Hare et al. [18], the average number of completed lactations for cows leaving the herd in the USA is three with a trend towards a shorter productive life. Vries and Marcondes [17] refer to an average productive life of 2.5 to 4 years in developed countries and of less than 3 years in the USA. Dairy cows have an average productive life of 3 lactations and are on average 5.4 years old when culled in Germany [19]. About 35% of the dairy herd is replaced each year in Germany [20]. Overton and Dhuyvetter [21] reported an average herd turnover due to mortality and culling for 50 US dairy herds of 39%, ranging from 25 to 51%. If 50% of calves are female, even raising every single female calf as a replacement heifer for a culled cow would not be enough to keep the herd size stable where the replacement rate exceeds one third [21]. Only the use of sex-sorted semen resulting in more female calves or purchasing heifers can close the gap. Raising heifers requires substantial resources in feed, labor, and housing. Increased culling rates require substantially greater numbers of heifers to be raised and in consequence a higher consumption of resources in order to provide enough replacements [22,23].

1.2. Insufficient Knowledge Transfer Regarding Animal Health

From the perspective of animal science, huge efforts have been made in order to gain knowledge on factors affecting the health of dairy cows. Several research projects investigated production diseases from different perspectives such as animal nutrition and metabolism [9,24,25], economics [15,26], veterinary science [27–29] and breeding and genetics [30–32] in addition to fundamental approaches [33]. Further research in the field of social science [34–36], veterinary advice [37–39] and agricultural extension and knowledge exchange [40–42] focused on barriers to the implementation of new knowledge aiming to reduce the prevalence of production diseases and discussed ethical perspectives [7,43,44]. Some studies explicitly addressed the systemic nature of animal health in the farming context [45] and followed a transdisciplinary and participatory research design involving expertise from different disciplines as well as stakeholders' knowledge [46,47].

Despite the vast amount of knowledge on hygiene, nutrition, milking technology etc. that is accessible in the literature and has been disseminated [33], the levels of (subclinical) production diseases remain high in modern dairy farms [48–51]. The cause(s) for the perceived "know-do" gap, i.e., the gap between what is known and what is done [52] are numerous. The linear model of knowledge transfer is often criticised for not being able to adequately deal with complex real-world situations [53–55]. A lack of success in transferring knowledge was disclosed in other domains where the impact of new knowledge was intended to have an effect in practice [56,57]. The complexity of the interactions between biological (animal) and social systems (farm) hampers the implementation of knowledge to reduce the level of production diseases in livestock farming [47,58]. In agriculture the complex nature of animal health, the significance of the (farm) context and the socio-economic environment is seldom accounted for [59].

1.3. Complexity in Dairy Farming

Although the concept of different systemic levels in dairy farming such as biological (cows) and socio-economic (farm) systems is commonly accepted (Figure 1), it is rarely accounted for in research and extension, where increases in performance are preferred to improvements in sustainability [59].

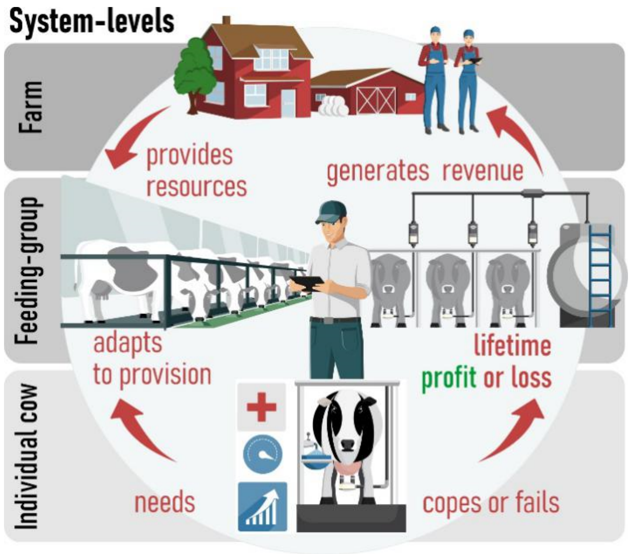

Figure 1. Concept of system levels in a farm relevant for biological and economic sustainability.

Accounting for the systemic nature of dairy farming is at the core of this study. At the level of the farm as well as at the level of the individual animal, the aim is self-preservation [9,60]. At the same time, the sub- and superordinate levels are mutually supporting and dependent. The enterprise revenue from marketable products depends largely on the amount of milk produced as the aggregated output of the individual cows. Each cow represents a single biological system with several functional regulatory circuits (e.g., metabolism and behaviour) that aim to sustain the system [61–63], thereby relying on sub-systems such as organs or the immune system and at the same time on superordinate levels of the group and the farm (social system, resources). Lactating cows are challenged by an increasing energy demand due to the onset of milk production. Cows adjust to this demand through massive changes in their metabolism, prioritising energy (glucose) flow to the udder and mobilizing body reserves from fat and tissue [64,65]. Consequently, many cows suffer from production diseases such as ketosis, uterine and udder infections in early lactation [64,66,67]. However, cows vary considerably in their metabolism and related factors such as milk yield, feed intake and loss of body weight [68,69]. For practical reasons cows are treated as a group of animals when it comes to housing and feeding [70]. Consequently, feeding strategies are generally targeted to the average energy need of cows in a group or herd, rather than the specific needs of single individuals which vary from the groups average [71].

The detection of production diseases depends on signals given by the biological systems of the cows and on a receiver that is sensitive to these signals and able to decide and act on these information (which depends on subjective personal knowledge, attitudes and the availability of resources) [72,73]. Some signals can be found in the milk which is tested regularly for specific constituents. Data on yield and content of fat, protein and from somatic cell counts amongst others provides information on the cows' health [74,75].

Consideration of the dairy herd usually relates to all the dairy cows currently living in the herd (e.g., for calculating energy requirements to adjust feed). However, the reduced lifespan of dairy cows with about 35% of a dairy herd replaced each year in Germany [20] means that information on productivity for a specific time frame (e.g., a year) includes a significant proportion of data from cows that have died. These cows form the "dead herd" of a farm. From an animal welfare perspective these mainly involuntarily culled cows failed to cope with their environmental conditions [10]. From an economic perspective, the "dead herd" must be paid for by rearing heifers. Although genetic opportunity costs must be considered, the costs associated with high rates of herd turnover are a major barrier to economic success [23].

The farm is an important unit and level when it comes to changing environmental conditions for the dairy herd to allow more animals to sustain. At the same time, efforts related to such changes have to be justified in terms of the farms' economic sustainability. Financial analysis for taxation is based on the farm level, whereas the efficiency of each enterprise within a farm may be calculated for management and controlling reasons by allocating the financial surplus and costs to each enterprise. At the individual enterprise level, the accounting of costs and revenues is based on accumulated and averaged figures such as the total milk yield in a year and the average milk produced per cow and year. The regulatory environment and the market for products are shaped by society and politics and affected by social perceptions on the sociocultural sustainability of dairy farming [76].

1.4. Challenges in Evaluating the Contribution of Individual Cows to the Economic Sustainability of a Farm

Management efforts quite often focus on ways to improve or ensure a high milk average yield per cow per lactation or year. It is often used as an indicator or even an objective in farm management, extension and for ranking/comparing farms. However, the costs and revenues of a dairy enterprise on a farm with other enterprises cannot easily be allocated to individual animals by simple division. Subject to individual factors such as the age at first calving, milk yield, days in the herd, and diseases, the contribution of an individual cow to the dairy enterprise's total result show substantial variation. The costs of diseases include the expenditures for diagnosis and treatment which show up in the financial data at herd level. In addition, production diseases are associated with reduced milk yield (e.g., due to changes in the milk glandular tissue subsequent to a mastitis), milk discarded several days after treatments to avoid drug residues and reduced life expectancy of cows due to on-farm mortality and involuntary culling and the subsequent greater need for replacement heifers. These costs are summarized in the term 'failure costs' [15,77]. These costs vary between the cows.

From the economic point of view, individual cows can only contribute positively to the financial performance of the farm system when they are able to reach beyond their individual "break-even point". That is, when the revenues for milk and slaughter value exceed the costs for raising the heifer, the full costs for feed and keep and the proportional share of the fix costs of the farm. Those cows are referred to as "profit cows" from here on in this article. A recent study developed approaches the farm level and the individual cow simultaneously by addressing the need to sustain performance at both levels. The core of the concept is the assignment of revenues and costs to the individual animal [78,79].

A survey of 32 milk producing farms in Germany revealed that a considerable share (about 60%) of culled dairy cows had not reached their break-even point [78]. The proportion of profit cows in the herd (i.e., culled cows which generated more revenue than costs during lifetime) varied between farms (0–74.1%).

Taking the proportion of profit cows as an indicator for economic sustainability, the following assessment examined the effects of production diseases on the farms' economic sustainability. Aiming to account for varying contextual conditions in different farm situations, we aimed to develop a typology of farms, which would generate roughly homogenous groups of farms regarding patterns of milk production and production diseases based on information from milk recording data. This would group farms according to their emerging output regarding yield and production diseases rather than certain input factors such as farm size, production- or milking system. Furthermore, the typology raises the question if the proportion of profit cows was different between groups and which consequences could be drawn for the farm management.

2. Materials and Methods

2.1. Farms and Animals

Milk recording and economic data were collected over the whole financial year from each of 32 dairy farms in Germany between May 2017 and July 2018. Farms were selected as a convenience sample to cover different farm structures and sizes (Table 1).

Table 1. Structure of farms included in the study (n = 32).

Class		Farm Size [a]		Herd Size [b]		Milk Yield [c]		Organic Farms [d]
	n	mean	min–max	mean	min–max	mean	min–max	number
<195 cows	11	138	60–290	138	95–183	8030	5557–10,647	4
195–800 cows	10	1103	130–2346	453	239–792	9428	7581–12,739	1
>800 cows	11	2225	750–5000	1327	862–2198	8551	7171–10,793	0

[a] arable land (ha). [b] number of cows after first calving (lactating and dry). [c] kg/305 days in milk. [d] Council Regulation (EC) No 834/2007 [80].

Included were five organic dairy farms. All farms used the herd management program HERDE® (dsp agrosoft, Ketzin, Germany) and were located in different regions in Germany. Holstein Friesian cows were the predominant breed (28 farms). Simmental and Brown Swiss were also kept (2 farms each). All farms kept their cows in loose pens, nine farms offered grazing for lactating cows. Total mixed rations were used in 21 farms and 11 farms followed other feeding regimes such as feeding additional concentrate. Automated milking systems were used in four farms (two farms < 195 cows, two farms 195–800 cows).

2.2. Database and Calculation of Cow Data

Information at the cow level was documented in the herd management software and included: (1) lifecycle data of each cow, including birth date, first calving, age at first calving, last calving, culling date and reasons, lactation number (Lact) and days in milk (DIM). For cows culled during the observation period, DIM_{LL} refers to the day of death in their last lactation. (2) milk yield records of the observation period as well as yield data from previous lactations. Milk recording data from monthly or bimonthly milking records of the period monitored (31 and 1 farm/s respectively) included information on somatic cell count (SCC), fat and protein for each test day. Based on these data, common indices were calculated for each cow: total and daily milk yield during lifetime (MY_L kg resp. kg/day), total and daily milk yield in productive live (MY_{PL} kg resp. kg/day), 305-d milk yield; and average daily milk yield during last/culling lactation (MY_{LL}; kg/day). Milk yield was calculated using the test-day-records based on the German ADR system according to the "Test Interval method" described in the ICAR Guidelines [81]. Overall, data on 20,644 cows were available. Of these 4962 (24%) were cows culled during the observation periods.

Information from cow individual milk recording data were aggregated at farm level to categorise individual cows in relation to certain thresholds reached at least once in one lactation that ended or began in the year of observation. These thresholds related to milk fat and protein (fat > 5%, protein < 3%, fat-protein ratio (FPR) > 1.5, fat-protein ratio at the first test day after calving (FPR_1) >1.5) and SCC (>100,000 cells/mL, three consecutive test days >700,000 cells/mL). The cure rate was calculated from cows with a SCC of more than 100,000 cells/mL) before drying off and less than 100,000 cells/mL at the first test day after calving. Variables were calculated separately for culled and retained cows; the latter were those cows that were living in the herd by the end of the observation period.

2.3. Calculation of Costs

Data at the farm level included information on the herd size. Based on the sum of the days individual cows were present in the herd during the observation period, cow-years were calculated by dividing the total sum from all cows by 365 days (observation period). Days present was based on test-day milk record information and calving dates.

Data relevant to farm economic performance were collected from financial accounting data. Farm-specific enterprise accounts were developed, following a widely used farm business budget approach of enterprises [82] that summarizes revenues from milk and slaughter as well as feed and other production costs. Factor costs for labour and capital were included. Full costs and revenues of the observation period were used to calculate the average farm-specific milk price (cent/kg), farm-specific slaughter value (EUR per cow), farm-specific average rearing costs (EUR per heifer), average farm-specific production costs without costs of rearing dairy heifers (EUR per day). Production costs were divided into feed costs (EUR per day) and other farm-specific production costs to calculate cow individual production costs, accounting for varying feed costs according to differences in milk yield. Individual cow profit (EUR) was calculated as the difference between individual revenues (from milk and slaughter) and individual costs (rearing costs and production costs per day). For more details see Habel et al. [78].

2.4. Typification of Farming Systems

Farms were selected to cover a variety of farming systems in Germany. The farm level is relevant for providing the specific conditions under which cows show certain indicators of production diseases. To establish a typology of farms we applied a factor and cluster analysis following the procedure of six stages described by Köbrich et al. [83]: (1) determination of the specific theoretical framework for typification, (2) selection of variables, (3) collection of data, (4) factor analysis, (5) cluster analyses and (6) validation.

(1) In the first step we decided to use information from milk recording data on yield and specific constituents, since these data are not subjectively biased and are available for individual cows. (2) Daily milk yield during lifetime (MY_L), daily milk yield in productive live (MY_{PL}) and the average daily milk yield during last lactation (MY_{LL}) were selected to cover aspects of yield and include effects from age of first calving and differences in the lengths of dry periods. Variables with information on a fat to protein ratio of more than 1.5 in the first test day after calving and in the first 100 days of lactation (FPR_1 > 1.5%; FPR > 1.5%) and a fat content of more than 5% in the first 100 days of lactation were selected to represent indications of metabolic problems [84,85]. Data from test days with a somatic cell count exceeding 100,000 cells/mL milk (SCC > 100,000), on SCC exceeding 700,000 cells/mL on more than three test days (SCC 3 x > 700,000), and information on the cure rate were selected to represent information on udder ill-health [20,86]. With the exception of cure rate, variables included in the analysis referred to the culled cows. Cure rate refers to all cows in the herd. This was due to the small number of cows in some farms which prevented the calculation of cure rate for the culled cows separately. (3) data were collected as described in Section 2.2. (4) We applied a principal component analysis (PCA) with varimax rotation to extract the most important independent factors from test-day milk records. Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity were used to assess the suitability of data. Only factors with eigenvalues $\geq$1 were considered [87–89]. Since the sample size of 32 farms was small, the communalities of variables, the number of factors, and the simplicity of the structure were taken into account to justify the application of multivariate statistics [90]. (5) Factors were used in a hierarchical cluster analysis using Ward's method [91] aiming for groups of farms with high internal homogeneity and maximum heterogeneity between groups [83]. Starting from individual cases with this method in each step those clusters are merged, which result in the smallest increase of total variance in the new cluster. The method aims to reduce the loss of homogeneity when combining clusters and leads in consequence to homogenous groups. (6) A comparison of means with ANOVA was used to further examine the identified clusters and their interrelation with the proportion of profit cows and other characteristics of the whole herd (culled and living). p-values below 0.05 were set as an indication of statistical significance. Statistical calculations were performed using IBM® SPSS® Statistics.

3. Results

The Kaiser–Meyer–Olkin measure of sampling adequacy was 0.616, representing a medium sampling adequacy, and Bartlett's test of Sphericity was significant ($p < 0.001$), indicating that correlations between variables were sufficiently large for performing a PCA [87,88]. The principal component analysis yielded three factors with eigenvalues, exceeding 1 which accounted for 78.4% of the total variance. (Table 2).

Table 2. Communalities and Factor loadings, resulting from a principal component analysis on milk recording variables, KMO = 0.616.

	Communalities (Extraction)	Rotated Component Matrix		
		Component		
		"Milk Yield"	"Metabolism"	"Udder Ill-Health"
MY_{PL} ^{CC} (kg/day)	0.880	**0.936**	−0.049	0.029
MY_{L} ^{CC} (kg/day)	0.879	**0.920**	0.006	0.183
MY_{LL} ^{CC} (kg/day)	0.835	**0.902**	−0.003	−0.144
FPR > 1.5% ^{CC} (%) [1]	0.906	0.003	**0.952**	0.032
FPR_1 > 1.5% ^{CC} (%) [1]	0.884	0.069	**0.933**	0.092
Fat > 5% ^{CC} (%) [1]	0.733	−0.120	**0.846**	−0.045
SCC > 100,000 ^{CC} (%) [1]	0.680	0.079	−0.151	**0.807**
SCC 3 x > 700,000 ^{CC} (%) [1]	0.682	0.187	0.102	**0.798**
Cure rate ^{AC} (%) [2]	0.579	0.330	−0.150	**−0.669**
% of the total variance explained		30.8	28.0	19.6

Extraction method: Principal component analysis. Rotation method: Varimax with Kaiser Normalization. Rotation converged in 4 iterations. ^{CC} = culled cows; ^{AC} = all cows, culled and persistent; MY_L = daily milk yield during lifetime; MY_{PL} = daily milk yield in productive live; MY_{LL} = average daily milk yield during last lactation; FPR = fat to protein ratio in the first 100 days of lactation; FPR_1 = fat to protein ratio in the first test day after calving; SCC = somatic cell count. [1] Proportion of cows that exceeded the threshold in the first 100 days of the lactation on at least one test day. [2] Proportion of cows with SCC < 100,000 cells/mL at the first test day from cows with SCC > 100,000 cells/mL at the last test day before dry-off. Highest loadings for each variable are in bold.

The first component of aggregated variables describing the average daily performance level based on (1) the milk yield per day of living (MY_L), (2) the milk yield per day of milking (MY_{PL}) and (3) their average daily milk yield during last/culling lactation (MY_{LL}), calculated as the milk yield in their last lactation (kg). The second component covered aspects of metabolism, combining information on the percentage of cows showing (1) a FPR above the threshold of 1.5 during the monitoring period (FPR) and (2) in the first test day after calving (FPR_1)) and (3) milk fat above 5% (Fat > 5%). The third component aggregated information on udder ill-health, represented by variables on (1) SCC > 700,000/mL milk in three consecutive test days, (2) the cure rate and (3) the percentage of cows with a SCC above 100,000 at one test day in their last lactation.

Based on the three components, the hierarchical cluster analysis identified five clusters represented in the dendrogram in Figure 2.

Table 3 shows the final cluster centres representing the average value of components in each cluster, based on variable values estimated in the PCA for each case (farm). The factor milk-yield was dominant in defining Cluster 3 (highest absolute value within the cluster); the factor metabolism had a major influence on defining Cluster 1, and Cluster 5, while the factor udder ill-health was most important to define Cluster 2 and Cluster 4.

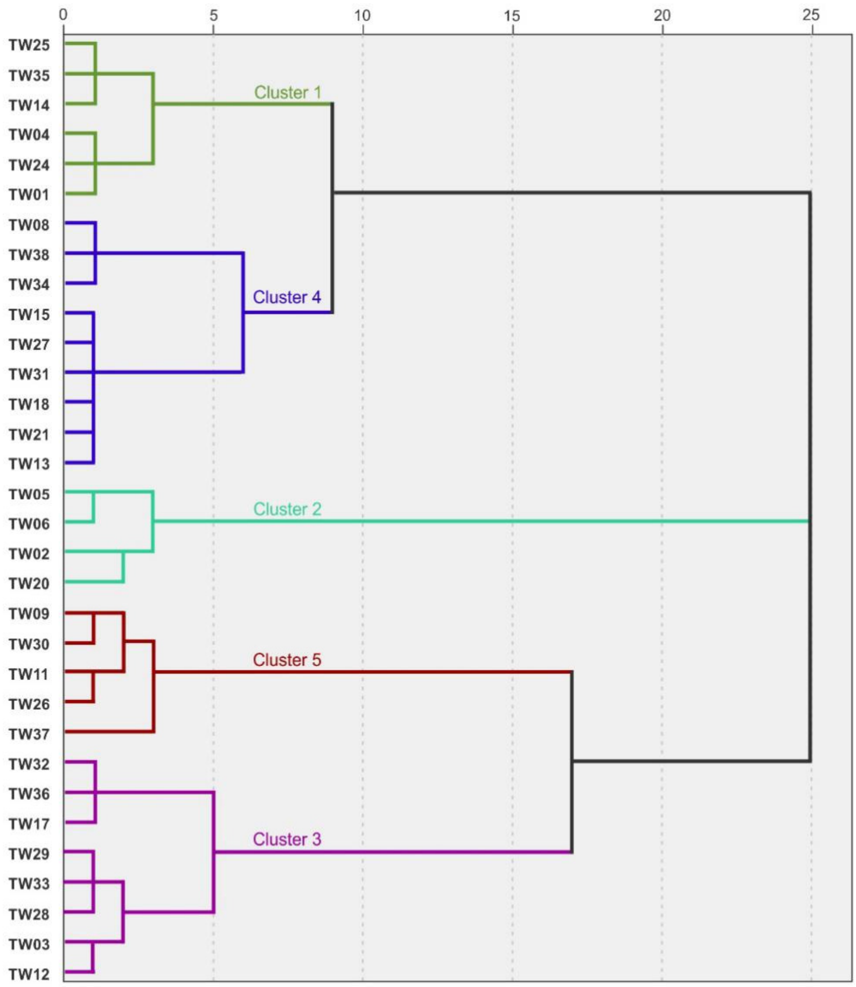

Figure 2. Dendrogram (using Ward linkage) for 32 dairy farms (named TW01–TW38; 6 farms missing) with five clusters.

Table 3. The contribution of the three classification factors to the five cluster centres.

	Cluster				
	1	**2**	**3**	**4**	**5**
Number of farms	6	4	8	9	5
Milk-yield	0.444	−0.951	1.206	−0.513	−0.777
Metabolism	−0.973	−1.140	0.412	0.043	1.343
Udder ill-health	−0.622	1.632	0.541	−0.919	0.230

Clusters were compared with respect to the proportion of profit cows and other attributes (Table 4). Profit cows accounted for 57.5% of culled cows on six farms in Cluster 1. These farms were characterized by the second-highest value for the factors milk yield and metabolism (referring to a small proportion of cows with an indication of metabolic diseases in their test-day results) and the second lowest values for the factor udder ill-health (i.e., high cure rates and few cows with high cell counts) compared to the other clusters (Table 3). Accordingly, the cluster can be described as *high performer with good health status*. The six farms in this cluster realized high 305-day milk yield in the whole herd (culled and living, 9248 kg) and had a low percentage of cows with an FEQ higher than 1.5 in the first test day in a lactation or test day results showing a fat content > 5%, indicating few cows with metabolic problems. Furthermore, the cure rate in this cluster was the highest

(68.7%). Farms in this cluster had the second highest production costs per day (EUR 9.23) but on average realized a quite high milk price compared to the other clusters (n.s.) and the highest slaughter value (n.s.). One farm in this cluster was an organic farm with a higher milk price than non-organic farms. In this cluster the average culling rate was 29% in this cluster which was slightly lower than the average culling rate of all farms (29.5%).

The second highest proportion of profit cows (55.6%) was detected in farms of Cluster 2. The four farms of Cluster 2 were characterized by the lowest values for the factors milk yield and metabolism and the highest value for the factor udder ill-health (Table 3). The cluster can be described as *low performer with impaired udder health*. This low performing cluster had the largest proportion of cows with increased SCC and the lowest cure rate. On average these farms had the highest average cow age of all clusters (n.s.). The age at first calving (28.5 month) and the last calving interval (426 days) was highest in this cluster. The highest milk price of all clusters (45 c/kg) and combined with the lowest production costs per day (EUR 8.00) contributed to a positive effect on the economic performance. Two farms in this cluster were organic farms with a higher milk price, but also both non-organic farms realized relatively high milk prices (39.2c, 42.0c) above the average milk price for non-organic milk (36.9c). This cluster had the lowest culling rate (27.2%). The cows left the herd later in lactation (DIM_{LL} 258) than in other clusters. Farms in this cluster tended to be smaller.

Cluster 3 ranked at the third position with 44% of profit cows on average, however showing a quite large variation. Cluster 4 aggregated eight farms with the highest value for milk yield and at the same time the second highest values for the factors of udder ill-health and metabolism, indicating higher proportions of cows with impaired udder health and metabolism (Table 3). Accordingly, the cluster is described as *high performer with impaired health status*. This cluster includes the highest performing farms (average 305-d milk yield 10,138 kg/cow/year) and with the lowest age at first calving (25.7 month). The highest production costs per day per cow (EUR 10.20) and the lowest milk price (no organic farm in this cluster) were unfavourable conditions regarding the economic success as well as the effect of the second highest on-farm mortality (6.3%, n.s.). Farms in this cluster managed a low rate of culling of primiparous cows (4.4%).

In the biggest cluster (Cluster 4) with nine farms, less than a third of all culled cows were profit cows (29.4%). This cluster was characterized by the lowest values for the factor udder ill-health (indicating few cows with an indication of impaired udder health in their test-day results) in all clusters. The value for the factor milk yield was below average, while the factor metabolism was at a medium level compared to the other clusters. This cluster is described as *average performer with good udder health*. At a medium level of milking performance these farms showed the best results on SCC indicators, and the second highest cure rate (62.3%). With 3.05 lactations culled cows were the youngest in all clusters (n.s.) and they left the herd early in the lactation (DIM_{LL} 178). This corresponded with the highest culling rate (32%, n.s.), especially for primiparous cows (8.4%). In this cluster, the milk price was at the lowest level for the eight non-organic farms (36.1c). In addition, this group realized the lowest slaughter value (n.s.). With quite some variation, the biggest farms were in this cluster.

In the five farms of Cluster 5 only 19.5% of culled cows were profit cows. The farms were characterized by the highest values for the factor metabolism and second lowest values for milk yield (Table 3). This cluster is described as *poor performer with metabolic problems*. At a low performance level farms in this cluster had the highest proportion (35.4%) of cows showing a fat content of more than 5% in at least one test day result. At the same time, the calving interval (414 days) was above average (404 days) and the second highest in the five clusters. Farms in this cluster had the second highest culling rate (30.9%) and the highest on farm mortality (7.3%), and a high rate of culling of primiparous cows (7.5%).

In summary, farms with a high proportion of profit cows were found in Cluster 1 and Cluster 2 with either high (Cluster 1) or low (Cluster 2) performance levels. The above average milk price plays an important role for farms to realize a larger proportion of profit cows, especially at a low performance level. This differentiated Cluster 2 from Cluster 5. Metabolic problems were low in Cluster 1 and Cluster 2 in contrast to 4 and 5 which were at a high- and low performance level, respectively.

Smaller proportions of profit cows were found in the clusters with the highest culling rate (Cluster 4 and Cluster 5) and high rates of on-farm mortality (Cluster 3 and Cluster 5). Very high milk performance levels were not associated with the highest proportions of profit cows where production costs were high and the milk price low (Cluster 3). Furthermore, death or culling early in the lactation and culling of quite young cows countered higher proportions of profit cows, even with lower production costs (Cluster 4). A very low share of profit cows was associated with high proportions of cows with metabolic disorders as observed from in test day milk results, especially when this was accompanied by a low performance level, even with production costs at a medium level (Cluster 5).

A large share of profit cows was incompatible with high incidences of metabolic problems, a low milk price and/or high culling and mortality rates.

Table 4. The number of farms and the averages ± standards deviation of a range of characteristics of dairy farming systems identified by cluster analysis.

			Cluster											
	Eta^2	***p***	**1**		**2**		**3**		**4**		**5**		**Total**	
Number of farms			6		4		8		9		5		32	
Profit cows ^{CC} (%)	0.442	0.003	57.5	±11.9	55.6	±10.6	44.1	±20.9	29.4	±17.5	19.5	±16.7	40.1	±21.0
Cow years ^{AC}	0.193	0.198	434	±394	111	±55	486	±276	745	±658	398	±275	488	±451
305-d milk yield ^{AC} (kg)	0.435	0.003	9248	±1128	7580	±786	10,138	±1696	7822	±1126	7876	±1130	8646	±1578
Milk price (ct)	0.243	0.099	0.40 [1]	±0.07	0.45 [2]	±0.05	0.37	±0.02	0.37 [3]	±0.04	0.39 [4]	±0.06	0.39	±0.05
slaughter value (€)	0.123	0.452	732	±121	766	±107	680	±166	636	±129	703	±34	692	±127
production costs/day €	0.367	0.012	9.23	±0.83	8.00	±1.22	10.20	±1.37	8.74	±0.76	9.06	±0.57	9.15	±1.17
FPR > 1.5, 1st test day ^{AC} (%)	0.400	0.007	9.8	±3.0	8.5	±3.4	17.6	±5.8	15.4	±4.8	16.5	±4.5	14.2	±5.6
FPR > 1.5 ^{AC} (%)	0.236	0.110	15.8	±6.0	22.7	±12.9	29.1	±11.9	27.1	±7.5	29.8	±11.6	25.4	±10.6
Fat > 5% ^{AC} (%)	0.429	0.003	18.4	±6.8	24.4	±4.3	30.9	±9.9	32.3	±4.1	35.4	±9.2	28.8	±9.0
SCC > 100,000 ^{AC} (%)	0.538	0.000	61.1	±8.2	80.1	±3.4	69.2	±8.5	58.2	±5.3	67.2	±7.8	65.6	±9.7
SCC 3 x > 700,000 ^{AC} (%)	0.553	0.000	3.7	±1.6	9.4	±4.0	6.7	±1.9	3.1	±1.8	5.8	±1.0	5.3	±2.9
Cure rate ^{AC} (%)	0.462	0.002	68.7	±4.6	46.7	±10.4	58.8	±9.8	62.3	±4.6	57.5	±6.8	59.9	±9.3
Age at first calving ^{AC}	0.369	0.012	26.2	±1.2	28.5	±1.8	25.7	±0.7	26.0	±1.6	27.0	±1.0	26.4	±1.5
Calving interval ^{AC}	0.423	0.004	397	±8	426	±23	399	±10	396	±14	414	±11	404	±16
Culling rate (%)	0.076	0.697	29.0	±6.6	27.2	±4.3	27.8	±6.6	31.8	±7.3	30.9	±7.7	29.5	±6.6
Culling rate primiparous (%)	0.366	0.013	7.7	±3.2	4.1	±1.0	4.4	±2.1	8.4	±2.8	7.8	±3.1	6.7	±3.1
On farm mortality	0.099	0.573	5.1	±2.6	5.2	±3.6	6.3	±3.5	4.8	±2.9	7.3	±1.4	5.7	±2.9
Lact ^{CC}	0.200	0.181	3.3	±0.5	3.9	±0.6	3.4	±0.3	3.1	±0.5	3.5	±0.9	3.4	±0.6
DIM_{LL} ^{CC}	0.309	0.035	196	±35	258	±54	213	±38	178	±37	204	±38	204	±44

^{CC} = culled cows; ^{AC} = all cows, culled and persistent; FPR = fat to protein ratio; SCC = somatic cell count; Lact = lactation number; DIM_{LL} = days in milk in the last/culling lactation [1] one organic farm (53.4c,), five non-organic farms (Ø37.7c). [2] two organic farms (Ø48.8c), two non-organic farms (Ø40.6c). [3] one organic farm (48.5c), eight non-organic farms (Ø36.1c). [4] one organic farm (48.5c), four non-organic farms (Ø36.1c).

4. Discussion

4.1. Test Day Results as Systemic Farm Output

Farms included in this study covered a wide range of farm types for example regarding their herd size, structure of the farm business (family farm/farm cooperative) and production systems (conventional/organic). They provided their dairy cows with conditions resulting in five different patterns of milk yield and proportions of cows showing an indication on metabolic diseases and impaired udder health evident from milk recording data.

The advantage of using milk records lies in the fact that they are recorded routinely monthly for many dairy farms. They provide information on health traits [74,84,92] while not being affected by subjective judgements as is the case for the documentation of diagnoses and treatments. Test-day milk somatic cell count (SCC) is an established indicator for udder infections [93–95]. Various thresholds to classify a cow with udder infection are used worldwide. However, at a level of more than 100,000 cells/mL (SCC100) an inflammation is the likely cause [96] and this level is established to distinguish cows with healthy udder in Germany [20,86]. Even though more accurate blood tests are required for diagnosis when assessing the metabolic health status of an individual cow, high milk fat and low milk protein percent as well as a fat-to-protein ratio above 1.5 are associated with increasing risks of subclinical ketosis [84,85,97] and provide an information on the metabolic status of the herd.

The proportion of cows showing at least one test day with an SCC100 in this investigation was 65.6% and 25.4% of the cows had a fat-to-protein ratio above 1.5 in the early lactation (first 100 days) (Table 4). According to the assessment scheme applied, a cow was counted as a cow with SCC100 if at least one test-day result per lactation reached this threshold. This cow and lactation-based assessment was chosen to capture long time effects of cured inflammations e.g., on reduced milk yield in the ongoing lactation. However, common assessments of udder health indicators focus on the cross-sectional analysis of the herd or cow individual samples at one test day [20,96]. On a test day base, the proportion of milk samples with an increased SCC100 in this study was 36.4% (result not shown). In other studies from Germany, including samples from 2000 to 2008 the proportion was 38% [96] with regional variation between 39.5 and 42.8% in a recent study involving 723 farms. The proportion of cows with a fat-to-protein ratio above 1.5 in early lactation in the same study ranged from 25.0 to 29.7% [20]. On a test day base rather than per cow per lactation the proportion in our data was 23.6% (result not shown). The slightly better results in our data might be affected by the selection of farms, which as a prerequisite had to use the herd management software 'HERDE' by dsp-agrosoft to participate in the study. This could be related to a higher management standard.

While milk recording data can only provide information on some disease complexes and miss others such as lameness, they provide valuable information because they represent an objective measurement of output variables measured on single cows in a herd.

Beside the factor milk yield, the PCA distinguished between factors representing metabolic problems and udder health, which are however related to different management areas at the farm level. Metabolic problems are strongly related to the adequate supply of energy and feeding resources in relation to the milk yield at the cow level [24]. Somatic cell counts (SCC) as a proxy for mastitis are related to various management practices, mostly about milking hygiene, hygienic conditions in the housing, protecting the teats and udder from adverse effects of the milking system and applying control measures as well as effective treatments [75]. However, the effect of various measures was not consistent in different studies, while herd managers attitude on SCC was detected as a meta-factor with an effect on SCC [73,75]. This emphasizes the effect of farm specific conditions and the role of the farmer, steering the system. The proportion of profit cows can function as a starting point for a weak point analysis and the identification of effective measures to improve the situation. It would provide orientation for setting strategic goals in the farm management which serves economic and sociocultural sustainability of dairy farming [76].

4.2. Factor and Cluster Analysis for Farm Typology

A typology of farms aims at homogenous groups of farms out of a diverse range of variables. Multivariate statistics can be used to build a typology of farms [83,98]. The number of farms involved in this study is quite low for the application of multivariate statistics. A sample size of at least 50 cases and/or a specific number of cases per variable is usually recommended [89]. However, according to several authors those propositions were inconsistent and such recommendations on absolute values have gradually been abandoned as misconceived [90,99,100]. Winter et al. [90] revealed that even small sample sizes well below 50 could yield reliable solutions with exploratory factor analysis. For situations with high communalities, few factors, a simple structure, and large number of variables even sample sizes smaller than 10 were sufficient. Small sample sizes should not ban the application of such analysis, since it might reveal valuable latent patterns [90]. In our analysis, the revealed three factors were well defined, with only weak interfactor correlations well below 0.2 for all variables except for the correlation of cure rate with the still low correlation of 0.3. Furthermore, the communality for all variables was above 0.5 with one variable above 0.9, four variables above 0.8 (Table 3). Furthermore, comparing the resulting farm typologies offers explanatory classifications regarding the varying proportion of profit cows for which they were intended. According to Köbrich et al. [83] this confirms the conceptual validity of the farm typology.

Farms in this study were selected to reflect the diversity of dairy farms in Germany, thereby providing the variation needed for segmentation. Furthermore, the data involved were objectively measured. Using these data to create homogenous groups does not alter the information at the farm level. However, the typology classification should not be used to predict results e.g., the proportion of profit cows for individual farms. It shows that for farms of different type (regarding yield and production diseases) different management goals should be implemented to align management strategies to increase or ensure a sufficient proportion of profit cows.

4.3. Profitability at the Cow Level Linked to Production Diseases

As a parameter, the proportion of profit cows brings together economic and welfare criteria at the farm level [79]. Whether a dairy cow reaches her break-even point is affected by cow related factors of production (milk yield) and farm-level economic factors such as the milk price and the farm specific costs for keeping dairy cows [78]. The role of diseases is indirect since diseases affect milk yield, culling decisions, and production costs. At the level of the individual animal, milk yield and early death (lower lactation number and fewer days in milk) determine the economic result of the individual cow [78]. However, from a management perspective the lactation number and especially early culling in the lactation are often the consequence of health problems which are related to metabolic problems, rooted in a negative energy balance in early lactation [24,101]. The results of the cluster analysis indicate that a lower share of cows with indicated metabolic problems in test day results is associated with the bigger share of profit cows in Clusters 1 and Cluster 2. Although milk price was quite high in these clusters (for both conventional and organic production, the low rates of (involuntary) culling and the highest average day of lactation at culling (DIM_{LL}) might explain the higher share of profit cows in those clusters. The smaller proportion of profit cows in Clusters 4 and Cluster 5 seemed to be related to medium milk yield in combination with lower milk prices and an earlier average day of culling (DIM_{LL}). The latter had a significant effect on individual cow profit in some farms [78]. These clusters showed the highest culling rates, especially for primiparous cows. Farms in Cluster 5 also had the highest on-farm mortality of cows. Accordingly, a high proportion of profit cows cannot be achieved with a high rate of culling that reflects the number of cows that ultimately fail to cope within the farming system [79,102]. In the systemic view of dairy farming, the coherence between indicators of metabolic diseases and a lower share of profit cows underlines the nested and interdependent system levels. The lack of energy in early lactation is a major cause for several disease complexes linked to culling decisions. Beside direct consequences of a negative energy balance on metabolic problems, it impacts on reproductive performance and lameness [101,103]. Metabolic problems are a major cause for culling decisions in early lactation [104,105], whereas failure to reproduce and lameness are important culling reasons later in the lactation [106].

While metabolic diseases seemed to have an effect on the proportion of profit cows which could be explained through the effect on early culling in the lactation, an impaired udder health (Cluster 2 and Cluster 4) was not associated with a lower-than-average proportion of profit cows. However, this might be affected by calculating the individual cow profit from the total amount of milk produced (MY_L) rather than the milk sold. Information on discarded milk due to medical treatments (e.g., of udder infections) were not regularly recorded for individual animals and therefore not available for this analysis. At the farm level, however, about 6.4% (0.9–17.0%) of the milk recorded was not sold (data not shown). More data on the discarding of milk from single animals might provide more insight on possible effects of impaired udder health on the proportion of profit cows. The very best results for indicators for udder health were found in Cluster 3 with a low average of 32% of profit cows. It remains an open question whether the lowest proportion of cows with chronical udder diseases (SCC 3 x > 700,000 cells/mL) was a consequence of high culling rates. However, with the 305-day milk yield below average, possible advantages from good udder health were countered by negative effects from the earliest day of culling and the high culling rate.

The cow level is the level where disease parameters are manifested and where action plans must start. Increasing efficiency of dairy farms by intensification was (and still is) a main driver in dairy system policies [107]. Production diseases seem to be regarded as collateral damage: an externality like environmental effects of intensive cropping systems [108]. Negative effects from production diseases on the whole farm system are obscured by aggregated data on costs at the farm level and the lack of information on the costs of invisible failures. Furthermore, the effect of an inefficient dairy enterprise on the whole farm is blurred by EU agricultural payments, which are usually accounted for at the farm level (not the level of the dairy enterprise). Zhu et al. [109] found that a higher degree of public payments in the total farm income reduced the motivation of farmers to improve efficiency. This study points to an approach that production disease are not externalities but should be integrated as an emergent intrinsic factor of production processes and management decisions. The approach provides an option on how to deal with culling and production diseases as an essential intrinsic factor of a farm system, which needs to be addressed appropriately to support self-maintenance of dairy cows and dairy farms.

5. Conclusions

Some realignment is required to overcome the negative side effects established by the productivist approach to dairy farming [108], which culminates (beside the considerable environmental externalities) in a loss of dairy cows. This is due to both the overstressing of the cow's ability to sustain as well as the poor economic results of dairy farms, which is the opposite of sustainability. In the thirty-year period from 1983 to 2013, 6% of the dairy farms in the older EU member states closed down each year amounting to a decline of 81% of farms with dairy cows. Farms of all types decreased by 55% [110] in this period.

Information from milk recording test-day results is a representation of the cows' ability to cope with its environment [9,62] and are in this context the result of complex system interaction. According to Wells and McLean [57] a systemic perception of change requires management that focuses on shaping the environment. From the recognition of the cows failing to cope with their environment as an indication of a lack of animal welfare follows the obligation to design an environment that is better adapted to the needs of the animals. To change the level of production diseases requires the shaping of an environment from which the desired change, a different level of production diseases, may emerge.

The current study highlights the need to shift priorities from milk outputs to a wider range of goals that better sustain the system in the longer term. This takes account of the needs at the different levels in the farming system considering the individual cow level at the same time so that the two levels sustain each other. By taking the single animal into consideration, rather than an average of the herd, the proportion of profit cows is proposed as an indicator of productivity that accounts for the complexity of the dairy farm system. The focus on the economic contribution of cows that left the farm for slaughter or died on the farm addresses the importance of production diseases (the most common reason why cows are culled) for the viability of the farm business. It is a starting point for further analysis (diagnosis) of how cows could be supported, and how the cows' environment could be improved to allow a greater proportion of animals to cope.

We argue that the proportion of profit cows serves as a more sustainable objective for the farm management than other measures of (economic) performance such as 305-day milk yield, milk price or feed costs. It brings more attention to the creation of environmental conditions for the dairy cows that are suited to reduce metabolic stress (Cluster 1 and Cluster 2 with more than 50% of profit cows) and culling (Cluster 4 and Cluster 5 with less than 30% of profit cows). The identification of farm-specific economic benefits, i.e., prevention of losses due to involuntary culling, might foster the awareness for giving attention to single animals and their demands.

The concept of knowledge transfer refers to the paradigm of rational choice, assuming that people will use the information provided (from research findings) to decide on the option with the best utility [56,111,112]. However, social science and psychology have shown that behavioural change does not solely depend on the availability of certain information. Kahneman [113] described the strength of loss aversion as a driver which might support consideration of individual cow profit and the share of profit cows an advantage in supporting changes for improved health and welfare in dairy farms.

The proportion of profit cows was identified for each of the five types of farms characterized by milk yield, an indication of metabolic problems, and impaired udder health. These farm types require different strategic approaches to protect and increase the proportion of profit cows in the herd, thus improving economic performance. Identifying the proportion of profit cows in a farm rather than focusing on average milk production traits, such as 305-day milk yield as a measure for success, uncovers synergies between health and longevity of single animals and economic performance of the farm business. It puts a focus on the context-dependence of output variables and requires and allows for various equifinal individual farm solutions. By this, it qualifies as an approach that deals with the complexity of biological and socio-economical system levels. Future research should assess differences in efficient strategies to increase the proportion of profit cows in various initial and boundary conditions, as reflected by the farm typology. Furthermore, research should improve methods to assess cow individual costs more accurately, e.g., due to discarded milk as well as methods that account for the farm-specificity of both economic and biological conditions.

Raising the proportion of profit cows is a suitable strategic goal to provide orientation for the farm management and validation for implemented measures that consider heterogeneous farming conditions. It addresses the need to shape environmental conditions for the dairy cows to allow for a desired outcome, rather than to strive for measures that generalize farm performance. Joining economic results and animal health and welfare of individual animals is a way to change the perception of production diseases from collateral damage to a cause for losses. This might foster farm individual, iterative change processes, aiming for less production diseases and for a higher farmers' income.

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