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Review: Linking animal health measures in dairy cows to farm-level economic outcomes: a systematic literature mapping

A. af Sandeberg [a,*], R. Båge [b], A.-K. Nyman [b,c], S. Agenäs [d], H. Hansson [a]

[a] Department of Economics, Swedish University of Agricultural Sciences, P.O. Box 7013, SE-75007 Uppsala, Sweden
[b] Department of Clinical Sciences, Swedish University of Agricultural Sciences, SE-75007 Uppsala, Sweden
[c] Växa, SE-10425 Stockholm, Sweden
[d] Department of Animal Nutrition and Management, Swedish University of Agricultural Sciences, SE-75007 Uppsala, Sweden

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ABSTRACT

Farm animal health is an area of increasing interest to both the public and industry stakeholders. There is an ongoing debate on whether improving animal health, and thereby increasing welfare, is profitable or not. Improving animal health often requires investments in the farm or increases labour costs. As a result, the impact of animal health on farm economy is particularly interesting. This study systematically maps and assesses the available evidence in the published scientific literature regarding the link between farms' economic outcomes on dairy cow health, with the aim of identifying knowledge gaps in this field of research. In total, 59 peer-reviewed articles were included using a broad range of animal health variables and economic outcomes. We found a heterogeneous body of evidence in terms of both methods, animal health measures (**AHM**s) and economic outcome measures used. None of the included studies makes explicit causal claims between AHMs and economic outcomes. The results suggest that common production diseases such as clinical mastitis and lameness, which are painful and affect cow health and welfare, are costly for farmers. We found a knowledge gap and lack of evidence on the impact of animal health interventions on farms' economic outcomes, as well as the long-term effects of such interventions. Future research should aim to investigate the causal links between animal health and economic outcomes.

Implications

Good animal health combined with viable farms businesses is of interest for farmers and society. A review of the scientific literature on animal health and farm economic outcomes shows that there has been a wide variety of ways to explore this issue. The general result from the current body of research is difficult to assess. Thus, it is questionable if the evidence can be generalised to other settings and thus be externally valid. With our sample of the literature, we did not identify quantitative estimates of causal effects of animal health interventions on the economic outcome of dairy farms.

Introduction

Farm animal welfare is of increasing interest and concern to farmer organisations, policymakers, and consumers in Europe (European Commission, 2016) and other parts of the Western world (Clark et al., 2016). The European Union (**EU**) has recently raised several animal welfare issues: a call for shorter travel times for farm animals (European Parliament, 2019) and new EU legislation that prohibits all forms of routine antibiotic use in farming (Council of European Union, 2019a; Council of European Union, 2019b). Farm animal welfare issues have also received attention in North America. According to Wolf and Tonsor (2017), the U.S. public has a positive willingness-to-pay for a change in on-farm production practices related to dairy cattle welfare (e.g., maintained hoof health and treatment of sick cows). In parallel, stakeholders have voiced concern about the impact of stricter animal welfare legislation on the competitiveness of the dairy sector. For instance, a report from the EconWelfare project, commissioned by the European Commission, highlighted stricter animal welfare legislation as possibly hampering the competitiveness of the sector (Spoolder et al., 2011). A competitive dairy sector requires farm business and husbandry models that are both economically viable and comply with the animal welfare standards requested by society and consumers.

* Corresponding author.
E-mail address: agnes.af.sandeberg@slu.se (A. af Sandeberg).

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Animal health is an important aspect of animal welfare. Many farmers even consider this to be the most important animal welfare aspect (Spoolder et al., 2011) and animal health measures (**AHM**s) can be used to identify the overall welfare status of a herd (Nyman et al., 2011). Only a few review studies (Tremetsberger and Winckler, 2015; Alvergnas et al., 2019; Sadiq et al., 2019; Halasa et al., 2007; Hogeveen et al., 2011) have investigated the evidence on the links between animal health and economic outcomes in dairy farms; importantly, none of them has used a systematic mapping approach to synthesise the current evidence. Thus, there is no common overview of the state of the art, although this would be informative for efficient private and public policy formulation. In particular, we lack the understanding of how herd health affects farm business' economic outcomes. This creates uncertainty for farmers and other stakeholders about the economic value of increased efforts to improve herd health and how these investments align or conflict with the farm's economic goals and when public policy might be needed to support further investments. This uncertainty may further compromise farmers' acceptance of and willingness to comply with strict animal welfare standards. Accordingly, the aim of this paper was to describe the scientific knowledge related to herd health and farm business' economic outcomes. We did this using the systematic mapping approach (James et al., 2016; Peterson et al., 2017). In comparison with the narrower systematic review method, systematic mapping aims at investigating a broad research topic by collecting, analysing, and cataloguing multiple research studies in a replicable way. Our specific research questions were (1) What economic measures have been used in the literature on economic effects of animal health? (2) What animal health measures have been connected to dairy farm economic outcomes? (3) What data and methods have been used in this literature and are there causal claims? and (4) What factors facilitate or hinder dairy farms from simultaneously achieving good animal health and business viability? Moreover, we critically discussed the state of the art regarding methods and data and suggested avenues for future research.

Material and methods

We conducted the systematic literature mapping in accordance with the Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols (PRISMA), as proposed by Page et al. (2021) and Moher et al. (2009). The PRISMA design ensures transparency and allows for comparability with future systematic literature maps in the same field of research. The PRISMA design lists a minimum set of items, consisting of a 27-item checklist and a flowchart, for reporting in systematic reviews. We did not publish a review protocol in advance (as is customary for systematic reviews and meta-analyses that summarise aggregated data from studies and evaluate the effects of interventions). Nevertheless, before the search process started, we developed an explicit set of questions that we followed throughout the review process, with reference to participants, interventions, comparisons, outcomes, and study design. This predetermined procedure delimited the sample, helped outline means of interventions, and highlighted the diversity of measures of economic outcomes for specific AHMs.

Inclusion and exclusion criteria

The inclusion and exclusion criteria for the systematic literature mapping were determined *a priori*. Studies of commercial dairy farms using data from Europe, North America, Australia, and New Zealand were included, since these are all high-income areas with comparable approaches to dairy farm business management. We excluded studies from other parts of the world, as well as non-English, non-peer-reviewed studies, and review articles. Review articles were excluded mainly due to their lack of new additions of experimental or observational data. However, we used review articles' reference lists as a robustness check to find all relevant articles. Two articles were eligible according to our inclusion criteria but were ultimately excluded from the sample since some of the practices explored in these articles are nowadays prohibited in the EU. Table 1 summarises the inclusion and exclusion criteria.

Search strategy

We developed a search string aiming to find all published articles that studied a relationship between animal health and farm economic outcomes in commercial dairy production. We selected economic outcome measures in order to cover all studies looking at costs as well as profitability at the farm level. Animal health measures were selected to represent solid and measurable direct or indirect determinants of health and welfare (Nyman et al., 2011). We based the selection on existing knowledge on how a primary deficit in barn design, management, feeding, hygiene, etc. will give rise to a chain of welfare-threatening events that ultimately will be manifested as disturbed physiology (e.g., immunity or fertility), clinical disease registrations (e.g., mastitis or lameness) or culling (Hultgren, 2017). Common production diseases and culling reasons were selected (Table 2). Notably, we used outcome-based measures rather than resource-based measures.

Systematic searches were conducted in four databases: Web of Science Core Collection, Scopus, CABI, and EconLit. We selected the first three based on their broad range, which enabled a broad search across disparate resources. EconLit was selected based on its niche in the economics literature, which might not be sufficiently covered in the first three databases. We considered the Google Scholar search engine and decided not to use it for two major reasons: First, Google Scholar provides different search results to different users depending on a secret algorithm. This implies a compromise with replicability. Second, Google scholar lacks a search function that permits the search string to be identical to the search string used for the other databases. The final search was made on January 10, 2022. Table 2 shows the search string used for the search in Web of Science Core Collection. The same search string was subsequently adapted for each of the other databases (see table note).

The search procedure

The search procedure (summarised in Fig. 1) was conducted in three main steps: First, we performed a main database search to generate an unfiltered list of articles. We used the search string specified in Table 2 and subsequently refined it according to the restrictions on each database's search page. The refinement procedure ensured the inclusion of peer-reviewed articles only, written in English and published between 1995 and 2022. We imported the unfiltered list of articles into the reference management software EndNote X9 (The EndNote Team, 2013) and the systematic review web app Rayyan QCRI (Ouzzani et al., 2016) to remove duplicates. Second, the main author screened the remaining articles by title according to the inclusion and exclusion criteria (Table 1), and then by abstract. Articles that the main author coded as "included" or "maybe" in Rayyan QCRI were re-screened by two co-authors using the blind screening option. Each author could only see her own decision to reduce the risk of biased decisions. Articles coded as "included" by all three screening authors were used in the final analysis. The main author full-text screened the remaining articles where co-authors were not unanimous, using the same search criteria as before (Table 1). Third, we used reference lists in review articles to find eligible articles that fell outside

Table 1
Inclusion and exclusion criteria used in the screening process of articles investigating dairy cow health and farm economic outcome.

Inclusion criteria
1. The paper explicitly discusses both an animal health measure and an economic measure.
2. The paper contributes with empirical data and/or a model to estimate the effect(s).
3. Study data are from Europe, North America, Australia and/or New Zealand.
4. The paper is published between 1995 and 2022.
5. The study investigates the effects of animal health on commercial dairy farms.
6. The language is English.
7. The paper is peer-reviewed.

Exclusion criteria
1. The paper is a review paper.
2. The paper is not published in a scientific journal (e.g., it is a book chapter, report, grey literature).
3. The study concerns a low-income country setting.
4. The paper concerns the effects of specific medication.
5. The paper explores practices that are prohibited in the European Union.
6. The paper is a duplicate.
7. The paper restricts their sample to calves and/or heifers and does not study any dairy cows.

our original search net (as suggested by Chandler et al., 2013). We searched for review articles in two ways. First by using the same search string, databases (except CABI, which did not support the search refinement to include review articles only) and inclusion criteria as in step two (Table 2). After removing duplicates, the main author screened the articles by title and then by abstract. Second, we found several review articles in our original hit list due to weaknesses of the refinement filter at each database search tool. We screened all articles in our hit list matching the keyword "review" to screen the full set of review articles. Finally, we checked the references in selected reviews to identify any additional articles. We matched the referenced sources in these reviews against the articles previously identified in our systematic mapping review to remove duplicates. The remaining records were then full-text screened.

Comparison of references

We used a narrative synthesis (Ryan, 2013) for the final analysis. Articles were compared based on region, country (origin of the data), AHMs, economic outcome measure(s) (e.g., efficiency, profitability, or monetary outcome), publication year, research method (including causal claims), and estimated effect of the AHM. We categorised articles according to AHM and choice of method to enable comparisons among the choices of economic outcome measures and AHMs. We systematically sorted and compared the findings across studies, countries, and AHMs.

Results

Search results

Fig. 1 presents the results for the different steps of the search procedure. We identified a total of 7 299 unique publications after removing duplicates. After applying our inclusion and exclusion criteria, 204 papers remained. This large number of excluded articles was mainly due to the wide scope of the original search. Many of the articles used data from low-income countries such as India, Brazil, and Ethiopia and therefore fell outside the scope of this literature mapping. Furthermore, the excluded studies were often of the wrong type (not peer-reviewed, or review articles) or had a too narrow scope; covering microbiological or veterinary medicine aspects but disregarded economic outcomes. We selected 174 articles for blind screening, of which 43 were unanimously included and 27 were unanimously excluded. The main author resolved the articles in conflict.

A lack of discussion or statement about the relation between AHMs and economic outcome measures was the main reason for article exclusion in the full-text review. Using this search procedure, we identified 49 articles eligible for use in the final analysis.

Additional records

Our review article search resulted in an unfiltered list of 429 reviews, after removing duplicates. Finally, after title and abstract screening, we found seven eligible reviews, which we used to search for additional articles missed in the database search. We added three reviews to this step of the literature search after performing an additional review search using the initial main article hit list. We screened the 609 references cited in these 10 reviews and uncovered 10 additional research articles for inclusion in the final analysis.

Methodological approaches and settings

The final sample included 59 articles (Supplementary Table S1) using data from 18 countries (for details on data origin and journals, please see the Supplementary Material S1). We categorised articles into two groups: using a simulation method or not (Table S1). Simulations were used by 28 articles and non-simulations by 32. The study by Pérez-Báez et al. (2021) used both methods and was therefore counted into both categories. In the 32 articles not using simulations, the number of farms used for the

Table 2
Search string used for the systematic search regarding the link between farms' economic outcomes on dairy cow health on Web of Science Core Collection.

Category	Section searched in	Keywords
Economic outcome measures	Topic	competitive* OR finan* OR "risk management" OR viability OR profit* OR econom* OR cost OR "technical effici*" OR "contribution margin" OR return
Animal health measures	Topic	health OR welfare OR well-being OR immunity OR regeneration OR reproduction OR (*fertility NEAR/10 dairy) OR mortality OR injuries OR mastitis OR lame* OR "pregnancy rate" OR *metritis OR "somatic cell count*" OR "somatic cell score*" OR SCC OR claws OR ketosis OR breed OR culling
Type of animals	Topic	cow OR cows OR "dairy cattle"
Sector	Topic	farm*

Note: The table presents the search string used in Web of Science Core Collection. "Topic" indicates that the search within each record is made in the fields for Title, Abstract, Author, Keywords and KeyWords Plus®. KeyWords Plus® are words and phrases harvested from the titles of the cited articles. For the search in CABI, "descriptions" was used instead of "Topic" for the "Sector" category. In EconLit, the "Anywhere except the full text" (**NOFT**) option was used. When using NOFT we got a search anywhere except in the full text. Since truncation's (*) does not work ahead of search words "(infertility NEAR/10 dairy)" and "endometritis" were added to the category "Animal health measures". The authors can, upon request, supply interested readers each of with the exact search strings for the databases.

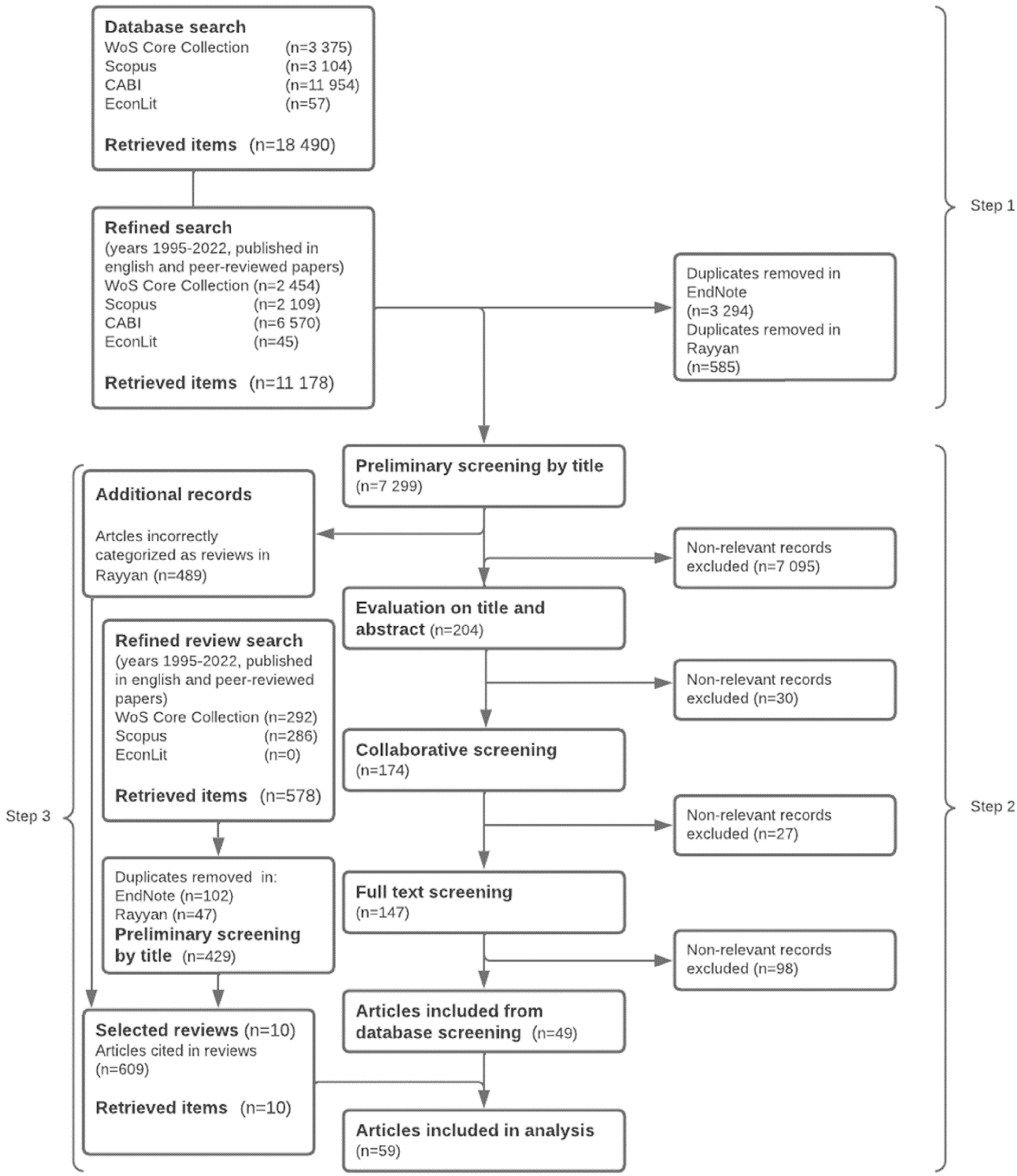

Fig. 1. Flowchart depicting the search strategy outcome at each step in the search process with articles combining animal health measures for dairy cows with economic outcome measures at farms.

analysis ranged between 1 and 2 187, and the number of cows studied ranged between 281 and 328 628. (In this section, herds and farms were seen as interchangeable and were referred to as farms. Each farm is assumed to accommodate one herd.) All articles reported the number of farms they used for their analysis; however, in 14 of the 32 observational studies, the number of cows in their data was missing. Yalcin (2000) reported the largest number of both farms and cows, in contrast to Dahl et al. (2018) who collected data from one farm (687 cows) and Maxwell et al. (2015), who had the lowest number of cows (281 from eight farms) in their analysis. Among the 28 articles using a simulation method, eight reported the number of farms (ranging between 5 and

36 804) and six studies reported the number of cows (ranging between 600 and 510 880).

Longitudinal data and causality

To investigate whether articles included explicitly or implicitly made causal claims, we turned to the non-simulation studies. Experimental design is the gold standard when investigating causal relationships. One mapped study (Maxwell et al., 2015) conducted a randomised negative controlled trial. They assessed the association between an early lactation claw trim on primiparous dairy cows and production outcomes on eight farms in the UK. Treatment was randomised at the (primiparous) cow level, but they did not have access to data on farm-level economic outcomes, which is generally the level of interest for the farmer. Thus, the effect was measured as the differences in milk yield between treated and untreated cows, but the study did not consider all associated costs and revenues that can affect farm profitability. They did not argue for any causal effects due to the level of randomisation.

Further, it is possible to claim for causal interpretations in a non-experimental setting (no randomised treatment) by using longitudinal data and methods dealing with endogeneity. Nine articles had access to longitudinal data on AHMs (Table S1). Five studies reported a monetary outcome; Delgado et al. (2018) analysed lifetime records for 13 668 cows from 113 farms over a 10-year period and estimated the cumulative lifetime profit. The cost of health traits included did not necessarily correspond to the actual cost related to each cow. Thus, profits at the farm level had to be calculated using various sources of unmatched data and estimates from previous findings in the literature. This impaired a causal interpretation of the estimates. Dillon et al. (2015) used a fixed-effects approach based on an unbalanced panel dataset with a representative sample of 1 286 Irish farms to estimate the effect of somatic cell count (**SCC**) on the gross margin per cow. They did not further assess under what assumptions their estimates could have a causal interpretation. Hultgren and Svensson (2009) followed 2 126 Swedish cows over a 4-year period. They used the estimated cost of veterinary-reported clinical mastitis as the economic outcome measure and not the actual observed cost at each case. This prevented a causal interpretation of the effect of veterinary-reported clinical mastitis prevalence on the farms' economic outcomes. Pérez-Báez et al. (2021) and Puerto et al. (2021) used mixed-effect models to analyse their data. Pérez-Báez et al. (2021) collected weekly data from 16 different U.S. farms for up to 305 days in milk. Cows diagnosed with metritis were assumed to be treated, but neither the diagnosis nor the treatment were confirmed by farm personnel. The cost of metritis treatment was estimated to be the average cost of four different treatment scenarios and not the actual treatment cost related to each specific cow. Puerto et al. (2021) used data from 15 159 first-lactation cows in 120 farms. To calculate profit, some of the costs involved in the different formulae were estimated using appropriate costs for the province; only milk value and feed cost data were included in the provided datasets. None of the mixed-effect model studies argues for a causal interpretation of their results. In total, one (Dillon et al., 2015) out of five articles reporting a monetary outcome had access to longitudinal data on both AHMs and economic outcome measures.

Four of the articles using longitudinal data estimated farms' technical efficiency, a measurement of how successful the farm business was in transforming its production factors to production outputs, considering simultaneously all production factors and outputs (Farrell, 1957; Coelli et al., 2005). The technical efficiency measure assesses whether the farms in a sample operated at, or below the production frontier and how far away from the production frontier the inefficient farms are situated. Allendorf and Wettemann (2015), Pérez-Méndez et al. (2020), Skevas and Cabrera (2020) and van der Voort et al. (2014) all had access to longitudinal data on both AHMs and economic outcome measures. However, a technical efficiency approach does not per se permit causal interpretations of the associations found and the included studies did not extend to consider causality. In this review, no articles claimed to identify a causal relationship between animal health and farm economic outcomes.

Synthesising the results

The 59 articles that were kept for our main analysis used 11 different AHMs (Table 3). One of the measures is coded as "multiple health measures," a category used when an article looked at several different AHMs to investigate their effects on economic outcomes. The most explored AHM was clinical or subclinical mastitis. This was used as the only AHM in 24 articles and was included in seven out of 11 articles looking at multiple AHMs. The second-most-explored AHM was lameness, used in 12 articles (and nine multiple-AHM articles). Table 3 lists the eight economic outcome measures used in the literature. They were divided into two overall categories: monetary outcomes and efficiency outcomes. Seven measures were categorised as monetary outcomes and one as an efficiency outcome. The most frequently used monetary outcome was a direct cost calculation of either a combination or a single measure of total, direct, net, or indirect cost measures (n = 30). This measure aimed to capture the cost at the cow level, in contrast to the second-most-common monetary outcome (impact on profit), which tried to capture the economic effects at the farm level. All articles in the efficiency outcome category reported technical efficiency (n = 10). Those articles focused on AHMs' effect on maximum output (given current levels of production factors)

Table 3
Summary of mapped articles comparing animal health measures for dairy cows, and economic outcome measures at farms.

Animal health measures	No. of articles (multiple measures)	Economic outcome measures[1]	No. of articles
Mastitis[2]	24 (7)	Monetary outcomes	
Lameness[3]	12 (9)	Cost[4]	30
Multiple animal health measures	11 (-)	Impact on profit	9
Ketosis	3 (3)	Gross margins[5]	3
Fertility[6]	2 (4)	Economic value	2
Welfare quality protocol	2 (0)	Financial impact	2
Bovine leucosis	1 (0)	Net revenue	2
Bovine viral diarrhoea	1 (0)	Profitability index	1
Johne's disease	1 (0)	Efficiency outcomes	
Metritis	1 (1)	Technical efficiency	10
Parasites	1 (0)		

[1] These were based on self-reported economic measures, which were defined by the authors themselves.
[2] Clinical and/or subclinical mastitis, measured as udder health management, veterinary treatments/self-reported treatments and/or (self-reported) somatic cell count.
[3] Including one or more types of foot and claw diseases such as: Interdigital dermatitis, Heel horn erosion, Digital dermatitis, Sole haemorrhage, White line disease, Sole ulcer, Interdigital hyperplasia, and Foot rot (Interdigital phlegmon).
[4] Includes studies looking at one or a combination of the following: direct cost, indirect cost, total cost, net cost, treatment cost.
[5] On herd or cow level.
[6] Treatments for oestrus-not-observed, time to calving, number of inseminations, calving interval.

rather than costs. In the following synthesis, we discuss articles reporting monetary and efficiency outcomes separately.

Association between mastitis and monetary outcomes

Mastitis was discussed as a single AHM in 24 articles. Four of them discussed the effect of mastitis (in one case in the form of udder health management) on efficiency outcomes. The remaining 20 articles all reported mastitis incidence in terms of monetary outcomes. For example, Stankov (2020) estimated that the profit derived from healthy cows was between 8.4 and 21.2% higher than that from affected cows. Clinical mastitis not only reduced cows' profitability but also reduced their productive longevity and total lifespan at the time of culling. Survival is an important component of profitability. Among the 31 articles that used mastitis as an AHM, 14 estimated the average cost of a clinical mastitis case (listed in Table 4). Seven articles used data from North America (Bar et al., 2008; Cha et al., 2011; Rollin et al., 2015; Liang et al., 2017; Aghamohammadi et al., 2018; Dahl et al., 2018; Delgado et al., 2018) and seven used data from Europe (Yalcin, 2000; Wolfová et al., 2006; Pérez-Cabal et al., 2008; Hagnestam-Nielsen and Østergaard, 2009; Hultgren and Svensson, 2009; Heikkilä et al., 2012; Doehring and Sundrum, 2019). The estimated cost per case of clinical mastitis varied widely, as did the input parameters chosen to estimate the cost (Table 4). All articles used different sets of input factors to calculate the cost per case. The highest and lowest estimates for each currency were Can$311–662, US $95–444 and €62.6–485, respectively. (Table 4; not adjusted for inflation).

Huijps et al. (2008) and Pfützner and Ózsvári, (2017) both estimated the economic effect of subclinical mastitis and concluded that subclinical mastitis has negative effects on farms' economic outcomes. Huijps et al. (2008) estimated the total economic losses from mastitis (subclinical and clinical) to vary between €65 and €182 per cow per year. This is at the lower end of estimates among the articles that limit their attention to clinical mastitis. Pfützner and Ózsvári (2017) found that reducing subclinical mastitis generates considerable financial returns for the farmer, even for cows with SCC levels between 50 000 cells/mL and 100 000 cells/mL. Five studies, four from Europe: (Rougoor et al., 1999; Yalcin et al., 1999; Geary et al., 2012; Dillon et al., 2015) and one from North America: (Dekkers et al., 1996) looked at the economic effects of different thresholds of SCC or bulk tank somatic cell count (BTSCC). Awareness of BTSCC was found to be positively related to milk production. Dekkers et al. (1996) and Rougoor et al. (1999) both found that efforts to reduce BTSCC resulted in substantial extra milk revenues. Two of the articles (Yalcin et al., 1999; Geary et al., 2012) mainly focused on the cost of herds that were close to the upper limit of BTSCC (>400 000 cells/mL) and found that those BTSCC levels were associated with considerable losses of profits. Finally, Dillon et al. (2015) investigated the effect of increased SCC levels on gross margins and found that a 100 000 cells/mL increase in SCC was associated with a reduction in gross margin of €19/cow, or about 2%, everything else being equal.

Table 4
Estimated costs and loss of profit from clinical mastitis incidence in dairy cows and the input parameters included in the calculations (sorted by frequency). Simulated results indicate whether the results were estimated using a simulation model.

Study	Estimated cost per case	Input parameters	Simulated result
Aghamohammadi et al. (2018)	Can$662	Discarded milk, culling and mortality, drugs, labour, veterinary services, diagnostics, material and labour for implementing preventive measures, milk yield reduction, product quality.	No
Delgado et al. (2018)	Can$311[1]	Feed cost, calves value, milk revenue, disease cost, heifer cost, quota interest, salvage value, service cost.	No
Bar et al. (2008)	US$179	Milk price, feed costs, culling, milk loss, beef price, fixed costs, probability of pregnancy, variable costs.	Yes
Cha et al. (2011)	US$95–US $211[2]	Milk price, discarded milk, feed cost, culling, drugs, labour, calves value, calving interval, antibiotics cost, cow maintenance, culturing, insemination cost.	Yes
Dahl et al. (2018)	US$149[3]	Milk price, milk loss, costs of treatment, pregnancy loss attributable to exposure to clinical mastitis between d 1 and 75 of gestation.	No
Hultgren and Svensson (2009)	US$95	Milk price, discarded milk, extra labour, veterinary services, increased culling and replacement rearing, production loss/305-d lactation.[4]	No
Liang et al. (2017)	US$326,[5] US$427[6]	Discarded milk, culling, labour, death, decreased milk production, extended days open, veterinary and treatment.	Yes
Rollin et al. (2015)	US$444	Milk price, feed costs, culling, death, diagnostics, milk production loss, non-saleable milk, treatment labour.	Yes
Doehring and Sundrum (2019)	€158–483	Discarded milk, culling/deaths, drugs, extra labour for the farmer, veterinary service, replacement costs, laboratory costs, milk yield, preventive costs.	No
Hagnestam-Nielsen and Østergaard (2009)	€97	Milk price, extra labour cost, antibiotics, feed intake, livestock prices, milk withdrawal, other costs, veterinary costs, yield loss.[7]	Yes
Heikkilä et al. (2012)	€485	Discarded milk, feed cost, milk revenue, replacement cost, beef revenue, cost of excess labour required by clinical mastitis, replacement decision, value of genetic progression, value of production loss, veterinary treatment cost.	Yes
Pérez-Cabal et al. (2008)	€117	Milk price, discarded milk, treatment administration.[8]	No
Wolfová et al. (2006)	€63	Milk price, drug cost, charge for veterinary service, calving interval,[9] charge for herdsman's time, depreciation cost for extra milking machine, price of antibiotics for drying cows, proportion of cows dried with antibiotics per calving interval proportion of cows on lactation,[10] veterinarian time per clinical mastitis case.	No
Yalcin (2000)	£140	Milk price, milk discarded or downgraded, premature culling, labour costs, death, feed saved per 1L milk reduction, milk yield depression, treatment and veterinary expenses.[11]	No

[1] For every case of clinical mastitis, the cumulative lifetime profit result is expected to decrease by Can$311 ± 16.
[2] The average costs per case of gram-positive and other clinical mastitis, respectively. The cost for gram-negative clinical mastitis was found to be in between. The average costs per case of gram-positive and other clinical mastitis, respectively. The cost for gram-negative clinical mastitis was found to be in between.
[3] When it occurs in the first 75 days of gestation.
[4] Depending on parity and lactation stage when veterinary reported clinical mastitis was reported.
[5] The cost per case of primiparous cows.
[6] The cost per case of multiparous cows.
[7] Approximations made by authors.
[8] Veterinary honoraries and production loss were not included because of incomplete information in data.
[9] Calving interval for lactations 1, 2 and $\geq$3.
[10] On lactations 1, 2 and $\geq$3.
[11] Except antibiotic residue.

Association between lameness and monetary outcomes

Lameness was discussed as a single AHM in 12 included articles: nine using data from Europe (Enting et al., 1997; Ettema and Østergaard, 2006; Bruijnis et al., 2010; Barnes et al., 2011; Bruijnis et al., 2012; Bruijnis et al., 2013; Maxwell et al., 2015; Charfeddine and Pérez-Cabal, 2017; Ibishi et al., 2021) and three using data from North America (Cha et al., 2010; Dolecheck et al., 2019; Puerto et al., 2021). Barnes et al. (2011) used a technical efficiency approach presented in the efficiency outcomes section. All other articles used a monetary outcome measure to estimate the effect of lameness. All found that lameness prevalence was associated with costs for the farmers, and Charfeddine and Pérez-Cabal (2017) and Puerto et al. (2021) found negative effects of lameness on milk production, longevity and cumulative milk yield, respectively. The costs of different claw disorders varied greatly and were highest for sole ulcer, followed by white line disease and interdigital and digital dermatitis (Cha et al., 2010; Charfeddine and Pérez-Cabal, 2017; Dolecheck et al., 2019). The estimated total cost per disorder case varied between studies. The estimate by Dolecheck et al. (2019) was about three times higher than the estimate of Charfeddine and Pérez-Cabal (2017). Although claw disorders were found to be costly to farmers, not all interventions were found to be cost-effective. Based on their simulation model, Cha et al. (2010) recommended that 97.3% of all foot rot (interdigital phlegmon) cases, 95.5% of digital dermatitis cases and 92.3% of sole ulcer cases should be treated, and the remaining affected cows should be culled immediately. Bruijnis et al. (2013) found that improved lying surfaces, reduced stocking density and additional claw trimming were cost-effective ways to reduce claw disorders. Maxwell et al.'s (2015) study does not fully support this conclusion, finding that based on milk production alone, it would not have been cost-beneficial to claw trim all heifers in their randomised controlled trial. However, they note that a targeted intervention aimed at lame animals would have delivered a substantial return on investment.

Association between ketosis, fertility problems, metritis, bovine leucosis, bovine viral diarrhoea, Johne's disease and monetary outcomes

Steeneveld et al. (2020) estimated the overall costs of treating all subclinical and 10% of the clinical ketosis cases at be €3 613 per year and farm. Raboisson et al. (2015) and Mostert et al. (2018) estimated the total average costs of subclinical ketosis to vary between €130 and €257 per case per year. Fertility problems expressed as a negative change in 6-week calving rate, suboptimal estrus detection, and increased age at first calving were all associated with increased cost for farmers (Stott et al., 1999; Shalloo et al., 2014; Delgado et al., 2018). Pérez-Báez et al. (2021) found that metritis caused large economic losses to dairy herds by decreasing milk production, reproduction, and survival in the herd. They estimated the decrease in profit per case of metritis to be approximately US$512. According to the model developed by Kuczewski et al. (2019), economic losses due to bovine leucosis were found to be considerable and the authors recommended the implementation of bovine leucosis control programmes for economic reasons. Han et al. (2020) used a model and estimated the direct losses of a bovine viral diarrhoea outbreak at NZ$22.22 per mixed-age cow per year. Rasmussen et al. (2021) estimated that 1% of gross milk revenue—equivalent to US$33 per cow—is lost annually in herds with Johne's disease (paratuberculosis). In their study, the United States was estimated to have the highest total annual losses due to Johne's disease of all major dairy-producing regions in the world.

Association between multiple animal health measures and monetary outcomes

Eight of the included articles (three from Europe, four from North America, and one using data from both; Table S1) investigated farm economic outcomes using multiple AHMs. It was found that different health problems were associated with different costs to farmers. Liang et al. (2017) found that left-displaced abomasum had the greatest estimated total costs in all parities; however, this is not a prevalent disease in dairy cattle. Instead, the most common diseases—mastitis and lameness—were regularly found to be the main causes of production losses (Kossaibati and Esslemont, 1997; Stott et al., 2005). Results from the papers by Villettaz Robichaud et al. (2019a and 2019b) suggested that improved cow comfort and welfare are positively correlated with increased herd productivity and profitability in both freestall and tiestall farms. However, they could not determine whether confounding factors other than cow comfort and welfare were driving the results. Moreover, using a decision support model, Gröhn et al. (2003) found that disease outbreaks left less room for voluntary culling and decreased net revenues. They suggest that farmers cannot compensate for the negative consequences of diseases by increased culling and achieve the same profitability. This was consistent with the findings of Bell and Wilson (2018), who suggested that improved health and fertility of cows lead to increased overall survival, which they found to have a positive impact on profitability. The tipping point where animal health interventions go from profitable to unprofitable (in strict economic terms) is not well investigated in the articles included. Villettaz Robichaud et al. (2018) investigated the effect of meeting the proAction Animal Care criteria (DFC-PLC, 2015; Table S1) on economic outcomes. They found that these criteria did not impose any economic burden on the Canadian dairy industry as a whole and could potentially benefit individual farms financially, but that further research was needed to verify the thresholds at which the positive economic effects of cow health are maximised.

Association between animal health measures and efficiency outcomes

Ten articles reported their results in terms of efficiency. All were non-simulation articles studying the impact of AHMs on the farm technical efficiency. Six articles addressed a single AHM (Barnes et al., 2011; Hansson et al., 2011; Luik-Lindsaar et al., 2019; Pérez-Méndez et al., 2020; Skevas and Cabrera, 2020; van der Voort et al., 2014). One article addressed lameness, three mastitis, one udder health management, and one the impact of parasites (the gastrointestinal nematode *Ostertagia ostertagi*; Table S1). All six articles reported a positive relationship between technical efficiency and good animal health or low disease incidence (the AHMs used were share of lame cows, mastitis incidence, udder health management skills, and exposure to gastrointestinal nematodes). Two of the studies, both analysing the effect of SCC on economic outcomes, reported the estimated economic effect of increased technical efficiency. The results by Hansson et al. (2011) indicated that costs would decrease, on average, by almost 30% if best-practice farming were applied at all farms. Results by Pérez-Méndez et al. (2020) suggested that decreasing SCC from its third quantile value to its first quantile value would increase profits by almost 6%.

Four articles on technical efficiency used broader definitions of animal health, by either using an Animal Welfare Protocol approach (Welfare Quality Network, 2009; used in Schulte et al., 2018; Tremetsberger et al., 2019) or simply investigating multiple AHMs as in Allendorf and Wettemann (2015) and Lawson et al. (2004). They all found ambiguous relationships among recommended levels of animal health and welfare criteria and technical efficiency. Schulte et al. (2018) found that farm animal welfare (measured using the Welfare Quality® Assessment Protocol (Welfare Quality Network, 2009)) and technical efficiency were positively correlated, and that pasture access may help (but does not guarantee) higher levels of animal health and welfare. Tremetsberger et al. (2019) found indications that farms with a higher health status achieved higher technical efficiencies. However, they could not show that changes in welfare status over a 1-year period affected technical efficiency. Allendorf and Wettemann (2015) found that the investigated animal health indicators (e.g., stillbirth rate, cow losses and SCC; Table S1) mattered for farm efficiency, but that maximum efficiency did not always correspond with the across-the-board recommendations for animal health and welfare. The results of a Danish study reported by Lawson et al. (2004) indicated that farms with lower technical efficiency reported more cases of milk fever and longer calving intervals. However, milk producers reporting more treatments of lameness, ketosis, and digestive disorders were found to be the most technically efficient. Reporting more subtle cases might be an indicator of better management. Thus, current knowledge suggests that the high prevalence of a single disease such as lameness or mastitis can have a negative effect on technical efficiency but that the direction and size of an effect have been difficult to disentangle when looking at multiple AHMs at the farm level.

Discussion

The aim of this systematic map was to synthesise the current evidence in the published scientific literature related to the impact of animal health on farm economic outcomes. In the mapped literature, we found economic outcome measures to be expressed in two major ways: either in terms of monetary outcomes or in terms of efficiency outcomes (which considers farms' ability to transform production factors into outputs) associated with AHM(s). The AHMs connected to farm economic outcomes were primarily represented by the most common production diseases such as mastitis and lameness. Considering the data and methods used, we found a wide variety of approaches, methods and data sources. Notably, only a few studies collected economic and biological data from the same unit of analysis. The wide use of different economic outcome measures, AHMs and methods makes comparisons of studies difficult as well as drawing general conclusions of what animal health factors hinder or facilitate viable farm businesses. However, the results mapped in this review support the idea that common production diseases such as mastitis and lameness reduce milk production and increase costs for farmers. The literature also points to a negative association between these diseases and technical efficiency. However, studies that focus on multiple AHMs or that look at animal health and welfare beyond production diseases such as mastitis and lameness find less support for a uniform direction of effect between good animal health and technical efficiency. To our knowledge, this is the first systematic literature map of the current scientific knowledge about the effect of animal health on farm economic outcomes in the dairy sector. We intended to include as many definitions of economic outcome measures and AHMs as possible. This enabled us to identify knowledge gaps in the current evidence and identify strengths and weaknesses in the research field.

Potential biases in the mapping process

We acknowledge the risk of potential bias in the systematic mapping process. First, studies were not captured in our search if they did not match all four search terms categories (Table 2). This implies that studies not mentioning any of the health measures covered in the search terms would not show up in our original search list. Among studies not explicitly mentioning health, welfare or well-being (in either title, keywords or abstract), only the studies mentioning the production diseases listed in our search string would appear but not studies covering other diseases. This could possibly skew the result towards diseases included in the search string. Four studies did not enter the hit list but were added after the review reference screening. All of them lacked the word 'farm*' in either title, keywords or abstract. We argue that the farm level is of great importance for the economic evaluation of farm business performance and a legitimate search constraint. It is however possible that some studies that did not enter the hit list due to their lack of 'farm*' could be eligible for this systematic map. Second, the screening process was not fully blinded: only the main author conducted the first screening of titles and abstracts. We took several actions to minimise this bias. All articles that the main author classified as "maybe" or "included" were re-screened blindly by the co-authors. In addition, reference lists from review articles were tracked back to find additional articles eligible for the current systematic map. Third, our search strategy may have had limitations: the backtracking of review reference lists was performed to both validate our screening process and identify articles that had mistakenly been rejected in the main screening (n = 6). When we found additional articles, we went back to our original hit list to examine if and why they were excluded. Five articles with the same prerequisites (e.g., the same model) were added to the review after reclassification. Fourth, the language restriction excluded 1 191 studies from the initial search (many of which, however, did not fulfil all inclusion criteria). We included only published literature in this systematic literature map. The exclusion of grey literature may have led to publication bias in the final analysis. We may also have missed some relevant results. On the other hand, the peer-review process sets a baseline for quality that reduces the risk of bias. Furthermore, we are specifically interested in peer-reviewed research, which is the basis for policy decisions, and we believe that this limitation is appropriate in order to fulfil our objective. Fifth, we excluded studies published before 1995, which biased our results towards newer studies. However, we argue that production and economic conditions have changed substantially which motivates a cut-off in time of publication. Lastly, we excluded studies limiting their analysis to calf and heifer rearing. We are interested in the farm economic outcome, which can arguably be difficult to estimate without the use of dairy cow data.

Quality assessment and external validity

The compiled results for associations between animal health and economic outcomes are difficult to assess and generalise to other settings, which poses a threat to the external validity of the evidence. Our systematic literature map identified articles from a total of 18 different countries, all of which have different animal health and welfare and farm business legislation. Two studies (Gröhn et al., 2003; Raboisson et al., 2015) even combined data from several countries, which complicated the interpretation of the results since the economic setting is disconnected from the animal health of the investigated dairy cows. There are also differences across studies in both the type of farming (conventional versus organic) and in typical farm facilities such as housing, flooring, herd size, breeds, parities, farm management styles (e.g., grazing), and local climate (which can differ substantially even within countries). However, many articles did not acknowledge the setting and its potential impact on their results in any way. We also found that methods for calculating costs and profits varied substantially between studies. These circumstances made it difficult to compare the outcomes in the mapped articles, since it is possible that different AHMs affect economic outcomes differently depending on the underlying characteristics of the farm, the livestock, and management methods. It is also possible that these underlying characteristics in and of themselves drive the economic results rather than the animal health interventions. This can make comparisons of farms in different settings misleading. This also highlights the need to use clear definitions of costs and profit, which would simplify comparisons of future research.

Quality of the evidence

Our systematic map reveals that research about animal health impacts on economic outcomes has not been able to strengthen assumptions by arguing for causal associations rather than correlations. It is interesting to note that none of the mapped articles explicitly claimed to identify a causal relationship. For example, Barnes et al. (2011) found that farms with a low rate of lameness performed much better than other farms, e.g., by being more resource-use efficient. Nevertheless, there might be other significant differences between the farms apart from cows' lameness incidence driving the result. This implies that less efficient farms may not necessarily succeed in increasing their technical efficiency even if they succeed in reducing their lameness incidence. This lack of knowledge about the causal relationship also creates uncertainty about the external validity of the results. One underlying reason for the lack of causal interpretations, aside from the diversity of input parameters in cost calculations, is the apparent lack of data. This also has had consequences for the type of questions that have been asked so far in the research area. Only a few articles covered by this systematic map have access to data on several AHMs combined with farm accountancy data. This has led to many imputed values in the calculations of farm economic outcomes, which increases the uncertainty about the real effect. Furthermore, we note that all data used in mapped articles cover only the dairy enterprise of the farm business, thus neglecting possible economic interconnections within the whole farm (e.g., the possibility of decreased costs when diversifying the products and services offered). In addition, only a few of the included articles could follow the farm accounting records over time and most were therefore not able to investigate threshold effects of different AHMs on the farm economic outcomes over time. This prevents us from drawing wider conclusions about the long-term economic effects at the investigated farms.

Our findings are in line with the findings reported in Tremetsberger and Winckler's review (2015). They highlighted the lack of research on health and welfare aspects that goes beyond the most important production diseases and linking those to the economic and non-monetary benefits of improving health and welfare in dairy cattle. Most of the articles included in our systematic map exclusively investigated health measures. Only two of the included papers tried to capture a broader notion of cow health by using the Welfare Quality® Assessment Protocol (Welfare Quality Network, 2009). A reason behind this may be the practical difficulty of gathering objective welfare data. Clinical health issues can be regarded as manifestations of welfare-related deficiencies in herd management. The cumulative, negative effects of suboptimal management weaken the animal's immune defence and resilience against infections and production diseases. Reproduction is a particularly sensitive body function, and it has been shown that key performance indicators for fertility and udder health are the best indicators also for animal welfare on herd level (Nyman et al., 2011). As indicated by the authors, prerecorded register data can be useful for the evaluation of animal welfare in a herd (for an elaboration of this conclusion, please see the Supplementary Material S2). Our results are also in line with Sadiq et al. (2019), who reviewed economic observations relating to lameness (treatment, treatment and detection) and found that both the animal welfare and the economic implications of lameness are aspects that require more evaluation. We found that this conclusion holds even in our setting and for AHMs other than lameness. However, only a minority of the articles included in our systematic map go beyond mastitis and lameness, and we did not find any literature reporting the effects of positive welfare indicators on farm economy, which would be needed to evaluate the role of animal welfare, for instance across the five domains (Mellor and Beausoleil, 2015) on farm economic outcomes. This highlights a knowledge gap regarding how welfare aspects beyond direct health measures affect the farm economic outcomes and the current lack of decision-making guidance for policymakers and producers.

Among mapped articles, nine had access to longitudinal data and of these, only five had access to longitudinal data on both AHMs and economic outcome measures. Several mapped studies used self-reported data and clinical data where data quality was difficult to assess for the reader. Few authors using locomotion scores, body condition scores and self-reported medical treatment recognised problems with validity and precision of the scores. This could cause misleading or biased results in terms of both health impact and the effect on economic outcomes. Further, several health measures can be difficult to interpret. For instance, a high culling rate could both indicate unhealthy cows or on the contrary a high level of healthy cows and calves, which may increase the number of recruitment heifers and force the farmer to cull healthy cows (Owusu-Sekyere et al., 2023). Several articles used a simulation model with the intention of developing a hands-on tool for farmers and advisors working directly in the field (Gröhn et al., 2003; Raboisson et al., 2015; Rollin et al., 2015). Simulations are useful for creating scenarios matching circumstances at a specific farm. However, all these tools rested on assumptions and estimations previously found in observational studies. This implies that the models' findings were shaped by assumptions and research design used in the underlying observational or randomised controlled trials.

Furthermore, we conclude that only one of the included articles used data from Oceania (aside from the article by Rasmussen et al. (2021) covering all dairy regions concerned in this review). In New Zealand, most cows are kept in a grazing system year-round, which could underlie a less intensive animal health and welfare debate due to the closeness of the husbandry model to the animals' natural behaviour. It is, however, similar to Irish practices, which were studied in three articles. This leaves us with little knowledge about external validity when extrapolating results from dairy cows in indoor housing systems to full-time pastured systems and vice versa. It also highlights the importance of the context of the research, since both animal health and welfare issues and farm economic outcome are expected to vary depending on the setting.

Overall, the synthesised evidence we collected gives us an overview of the AHMs, economic outcome measures, and methods that are used in current scientific literature. However, we found few answers to our question of what factors facilitate or hinder dairy farms from simultaneously achieving good animal health and business viability.

Directions for future research

Based on our systematic mapping review, we have several suggestions for future research. First, future research should aim to investigate the causal effect of animal health on farm economic outcomes to deliver enhanced evidence about their relationship. Causal interpretations are generally made based on experimental studies. When an experiment is not feasible (e.g., due to ethical, practical or cost reasons), access to good data sources (with longitudinal data) and a source of exogenous variation in the data is essential. Then, a quasi-experimental method could be used in order to demonstrate a causal link. This permits a non-randomised sample but requires a design testable for confounders. It should be noted that about half of the articles included used or developed a model (n = 28), which reflects the need of farmers and other professionals in the field to have access to economic tools to guide their decision-making. Simulation models are strong in investigating the systems' hierarchy where complicated relations can be specified in the model. This helps us to get a general idea of the costs and benefits of interventions to prevent diseases and address welfare issues beyond diseases. However, future research on causality would contribute to improving the input data for such modelling tools and ensuring more accurate model predictions. A better understanding of the causal effect of animal health on farm economic outcomes would also serve policy makers with better guidance in, for example, legislative processes.

Second, there is a need for more and better data on AHMs and economic outcome measures, irrespective of analytical method. We found few studies that used health measures beyond diseases, which leaves us with little knowledge of the effect of other AHMs (and ultimately other welfare measures) on farms' economic outcomes. Future research should aim to collect longitudinal data on a wider range of AHMs. Longitudinal data are important to be able to follow farms and patterns over time. Data availability may also be different in Europe compared with North America. All but one out of the 10 included articles that reported an efficiency outcome used European data. This could be due to a lack of access to longitudinal data in other parts of the world or a lack of interest in the concept of technical efficiency. That could lead to less credible research articles from North America as well as a dependence on European articles and data that might not fully explain the North American setting. Future research should aim to collect longitudinal data from outside Europe in order to assess the effect of animal health on economic outcomes in different countries and settings.

Third, future research should aim to specify the setting of research in order to identify differences in effects for different subsets of cows in a herd. It is possible that certain animal health interventions are cost-effective in certain settings (such as freestall or tiestall housing) or for a subset of cows (based on parity, high- or low-yielding cows) but that this may not hold for all settings. Many of the important production diseases, such as mastitis, are more likely to affect high-yielding cows, and the simple loss calculations that are commonly used in mapped articles might overestimate the loss from a "typical" cow (Seegers et al., 2003). In most of the papers that used a simulation model to estimate the effect of animal health on farm economic outcomes, the authors attempted to estimate an effect for the average cow on a typical farm in the country of interest. This can be very useful tools for farmers and advisors but tells us little about differences between settings if not collected in a meta-analysis.

Fourth, there is a lack of evidence on the differences between the "typical" cow and the unhealthiest cows in terms of their impact on farms' economic outcomes. Future research is necessary to determine the characteristics of the cows that are driving the results. This includes conducting research using objective measures of subclinical disease, which generally affects a larger share of cows in a herd and potentially has a larger effect on economic outcomes than a few cases of clinical disease. There is also a need to distinguish which key figures indicate good or bad underlying health, and under what conditions. Seemingly bad animal health outcomes could potentially signal more proactive management. Larger and more technically advanced farms may be more attentive to minor deviations in underlying herd health. This could affect key figures such as the number of inseminations, as well as preventive management costs. Difficulties in how to measure non-disease production disturbances that affect animal health create a research gap in identifying settings where good animal health can be combined with good economic outcomes. We recognise a need for a more sophisticated investigation of the linkage between AHMs and economic outcomes since the mere fact that a certain disease is costly is not enough information when making long-term farm management decisions. In line with Halasa et al. (2007), we find that some studies ignore important cost factors. They provide a framework, with a list of factors to include in the analysis, for future studies on the economics of mastitis and mastitis management. We argue that this is not enough in the case of AHMs, and when farm economic outcome is the point of interest, economic calculations must be more robust and based on farm accounting data to capture the full effect and to enhance the comparability of articles.

Fifth, there is a need to follow farms over time to capture the long-term effects of AHMs, investigate thresholds of when an AHM is profitable and not, and how this affects the whole production cycle. Through our systematic map, we found little evidence concerning thresholds of incidence at which the positive economic effects of cow health interventions are maximised. This leaves us without answers to questions concerning the trade-offs between animal health efforts and economic outcomes. Future research should focus on determining the mechanisms that underlie how animal health affects economic outcomes, as well as non-monetary values in the long run, to enable stakeholders to make more informed decisions.

Lastly, there is a lack of evidence that considers the time constraint farmers face when making production decisions. Future research should focus on the whole farm business to investigate what factors facilitate or hinder the simultaneous achievement of good animal health and good economic outcomes, acknowledging farmers' time constraints. An extra hour allocated to animal health and welfare interventions leaves less time for other tasks or for leisure time, which could also affect the total profit or utility of the intervention for the farmer. None of the included articles considered averse economic impacts on other parts of the farm enterprise in the dairy businesses studied. A diversified farm business encounters a time trade-off in whether to invest more time in the dairy production or other farm endeavours (e.g., growing cereals). This leaves us with little knowledge about the mechanisms and trade-offs behind welfare inputs and their relationship to output. On diversified farms, we do not know whether economically non-viable dairy businesses might be kept running thanks to other, more profitable, farm activities and vice versa.

In conclusion, we find two major ways of expressing economic outcome measures. In terms of monetary outcomes or efficiency outcomes, monetary outcomes are defined in a wide variety of ways and researchers should seek to standardise monetary outcome measures to enable comparisons of studies. We find that AHMs are commonly expressed as the large-production diseases such as mastitis and lameness. Studies measuring other health and welfare aspects were typically excluded due to not meeting the inclusion criteria for economic measurements. Mapped studies use a wide range of methodological approaches. This in combination with lack of data and use of economic data and health data not connected to the same unit of analysis makes comparisons between studies difficult. Our systematic map supports that major production diseases such as mastitis and lameness are costly for farmers. However, with our sample of the literature, we do not identify evidence on farm-level effects of animal health interventions on the total economic outcome of farms. We conclude that the relation between animal health and farm economic outcomes generally is not well investigated and that it is essential for future progress to assess this relation using biological and economic data from the same unit of analysis. Future research should aim to investigate the causal relationship between animal health and economic outcomes, using e.g., econometric methods. This would be useful to assist stakeholders in making better decisions and to improve the baseline data to power simulation models.

Supplementary material

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Ethics approval

Not applicable.

Data and model availability statement

None of the data was deposited in an official repository. The data that support the mapped findings are available via the references cited.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors did not use any artificial intelligence-assisted technologies in the writing process.

Author ORCHIDs

Agnes af Sandeberg: https://orcid.org/0000-0002-7541-3067.
Renée Båge: https://orcid.org/0000-0003-1413-6913.
Ann-Kristin Nyman: https://orcid.org/0000-0002-6643-0404.
Sigrid Agenäs: https://orcid.org/0000-0002-5118-7691.
Helena Hansson: https://orcid.org/0000-0001-9609-4387.

Author contributions

Agnes af Sandeberg: Methodology, Validation, Writing – Original Draft.
Renée Båge: Conceptualisation, Validation, Writing - Review and Editing.
Ann-Kristin Nyman: Conceptualisation, Writing - Review and Editing.
Sigrid Agenäs: Conceptualisation, Writing - Review and Editing.
Helena Hansson: Conceptualisation, Supervision, Validation, Writing - Review and Editing.

Declaration of interest

None.

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