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A review of European models to assess the sustainability performance of livestock production systems

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ABSTRACT

A large variety of models has been developed to explore the multidimensional, and sometimes conflicting, sustainability consequences of innovations and policies for European livestock farms. Implementation of innovations and policies generally results in both synergies and trade-offs between the environmental, economic, and social dimension of sustainability, and among sustainability themes within these dimensions. An overview of the specific sustainability themes addressed by livestock models is lacking, which hinders the further development of models to evaluate a wide array of sustainability dimensions and themes. The aim of this review, therefore, is to provide an overview of European livestock models that can be used to explore synergies and trade-offs among sustainability themes. This systematic literature review yielded 215 European livestock models at the animal level, herd or flock level and farm level. Models were mainly developed in Western Europe, and may have, therefore, a reduced accuracy when applied to other regions than Western Europe. Most models cannot assess a wide array of synergies and trade-offs among sustainability dimensions and themes, as only 33% covered all three sustainability dimensions. Models addressed four sustainability themes on average. Social themes are often lacking in models and additional efforts are needed to develop more integrative models by adapting and extending existing models, especially for monogastric animals. Adaptation and extension of existing models is facilitated by improving the availability of livestock models, increasing the percentage of livestock models published open source, collaborating on the development of joint and generic models and by improving descriptions of the programming languages and programs used and the stakeholders involved. This model review can be used to identify which models or combinations of models are best suited to explore the sustainability consequences of innovations and policies for livestock farms in Europe.

1. Introduction

The livestock sector in Europe provides employment, generates income and contributes to food security. European livestock products represent 44% of Europe's total value of agricultural production (FAOSTAT, 2018). Besides food security and employment, the European livestock sector also provides ecosystem services, such as climate regulation, flood and fire prevention, and recreation (Marsoner et al., 2018; Rodriguez-Ortega et al., 2014; Ryschawy et al., 2017). Despite these benefits, the sector has a significant impact on the environment, for example via emissions of greenhouse gases and ammonia (Gerber et al., 2013; Steinfeld et al., 2006). Livestock farming, furthermore, is being questioned, discussed and criticized. Concerns arise about, for example, welfare of livestock, farm size, public health impact and economic viability of farms (Boogaard et al., 2011; Busch et al., 2018; Giannakis and Bruggeman, 2015; Robbins et al., 2016).

Decision-making on sustainable livestock farming requires consideration of the three sustainability dimensions to develop innovations and to design policies that are environmentally sound, economically viable, and acceptable from a social perspective (van Ittersum et al., 2008). For each sustainability dimension, more specific sustainability themes can be defined. For instance, greenhouse gas (GHG) emissions and land use are themes in the environmental dimension, and animal health and welfare is a theme in the social dimension. Ideally, sustainability assessments need to address a range of sustainability themes covering all three sustainability dimensions. An innovation or policy that focuses on improving one or a few sustainability themes could have adverse and unexpected consequences for other sustainability themes,

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and may decrease the sustainability performance of a system as a whole.

The sustainability performance of systems can be explored using retrospective (*ex-post*) assessments and prospective (*ex-ante*) assessments. *Ex-post* assessments evaluate the sustainability performance by calculating scores for sustainability indicators and themes from empirical data that describe systems in their current or past state (de Olde et al., 2016). The empirical data that describe the state of a system are the effect of multiple causes, but *ex-post* assessments generally do not account for mechanistic processes that link causes and effects. Causal relations between sustainability indicators and themes, therefore, can hardly be elucidated when empirical data are used. As a result, *ex-post* assessments often lack attention to causal relations, and consequently to synergies and trade-offs among sustainability themes (Binder et al., 2010; Ness et al., 2007). Hence, these assessments are generally not suited to analyse synergies and trade-offs among sustainability themes that may emerge upon the implementation of innovations and future policies.

Farm experiments and farm models can assess synergies and trade-offs among sustainability dimensions *ex-ante*. Farm experiments have been conducted in several European countries to assess the sustainability consequences of innovations and future policies (Flessa et al., 2002; Langeveld et al., 2005; Morel et al., 2016). Such experiments, however, are costly and time-consuming, and their results have generally limited scope for extrapolation to different farms types, different management strategies, and other regions within Europe. Farm models allow to conduct relatively rapid and cost-effective sustainability assessments once operational, although their development is often laborious and costly. These models have been widely used to assess effects of innovations and policies in Europe (Acs et al., 2010; Cortignani and Dono, 2015; Veysset et al., 2005). Various reviews of existing models at the farm level, herd or flock level and animal level have been conducted (Bryant and Snow, 2008; Gouttenoire et al., 2011; Janssen and van Ittersum, 2007; Reidsma et al., 2018; Tedeschi et al., 2014).

To assess potential synergies and trade-offs of innovations and policies, farm models are needed that can account for a wide array of sustainability dimensions and themes. Using a model that integrates fewer dimensions and themes involves the risk of overlooking important synergies and trade-offs, which may result in poor recommendations. For that reason, integrative models are needed that address a wide array of sustainability themes and account for more interactions between sustainability indicators, which increases model complexity. The need for more integrative and complex models requires insight in the characteristics of existing models to allow further development.

Given the large amount of existing models, there is a need to identify which models integrate environmental, economic and social dimensions and themes to adequately assess the sustainability performance of livestock production systems. So far, no reviews have been conducted that specify the sustainability themes addressed by models. Due to lack of this overview, similar livestock models may be developed independently by different research institutes, adding to a continuous proliferation of models. Consequently, modellers risk reinventing the wheel and limiting the complexity and integrative approach in model development. Instead, more progress could be made if research institutes work more on joint models that are easily and freely accessible (i.e. open source). Such overview can also help to identify which livestock sectors and regions are not or hardly covered by the existing models, which can direct further research and model development.

The objective of this review, therefore, is to provide an overview of models useful to assess the sustainability performance of livestock farms in Europe by describing the sustainability themes addressed, whether the model software or source code is available online and whether it is published open source. This study focuses on models developed in Europe, because of similarities in farming systems and legislation. Eventually, the overview of models can be used as a basis to determine which models may be best suited for simulating the effects of particular innovations and policies on the multi-dimensional sustainability performance of livestock production systems.

2. Materials and methods

2.1. Criteria for model selection

A literature review was conducted to create a list of models that simulate farms with livestock in Europe. Five criteria for model selection were defined. First, models must include at least one specific livestock species, which excluded models simulating crop production only and models with a generic description of livestock. Second, the model had to be focused on the farm level, the herd or flock level, or the animal level. Models at the farm level were selected because the farm is the main management unit of an agricultural system (Payraudeau and van der Werf, 2005). Models at the animal and herd or flock level were selected because these models generally can simulate effects of technological innovations and management strategies on livestock in more detail than farm models. Outputs of models at the animal and herd or flock level can be used as input for farm models to assess consequences of innovations and policies. Models simulating livestock production below the animal level were excluded. These models, for instance, simulate processes at the organ level (e.g. the rumen). Models that primarily focussed on other issues than livestock itself, such as stables, feed formulation and evaluation, electricity use, grasslands, product quality, or transmission of pathogens, were not included either. Models simulating livestock production beyond the farm level were excluded too, such as models simulating interactions among farms in a region or in a catchment area of a river. Models focussing on complete production chains, up to distribution, retail, and consumption, were excluded also.

Third, only quantitative models that describe interactions among components within the boundary of a system were included in the list of models. Qualitative models and conceptual frameworks were excluded, as well as mere statistical models (e.g. regression analysis) and growth curves. Fourth, given the large number of models that has been developed, this study focuses on models applicable in countries that are geographically situated in Europe. Europe was selected also because of similarities in farming systems, agricultural legislation and trade legislation, especially in member states of the European Union. To ensure the applicability under European conditions, only models that were developed in countries that are geographically situated in Europe (fully and partly) were selected. Many livestock models from other continents, however, might be applicable under European conditions as well. This holds in particular for livestock kept indoors, where the ambient environment of the animals, feed quality, and feed availability can be controlled to a large extent. The country a model was developed in was chosen over the application domain of the model to determine applicability in Europe, because the application domains of models are often not described in publications, or only at a superficial level. The affiliation of the first author on the first publication describing the model was used as a criterion to decide in which European country a model was developed. A considerable percentage of the livestock models was developed by international teams. Hence, one should not put too much emphasis on the absolute number of models developed in a particular country. This review did not include models developed by European researchers that were applied outside Europe only. Fifth, we selected documents describing an original model, a new combination of existing models, or a major extension of an existing model.

2.2. Model collection and literature review

This review was conducted within the ERA-NET SusAn project 'AnimalFuture', in which livestock researchers from seven European countries participated. Researchers from France, Germany, Spain, and the United Kingdom provided a first set of literature on livestock

Table 1
Search terms used in the literature review. Searches were a combination of the model type (n = 6) and the livestock species, type or product (n = 17), resulting in a total of 102 searches.

Number	Search term[a]	
	Model type[b]	Livestock species, type or product[b]
1	Farm model*	Dairy cattle
2	Livestock model*	Dairy cow*
3	Optimization model*	Beef cattle
4	Linear program*	Suckler cow*
5	Bio-economic	Sheep
6	Ecological-economic	Lamb*
7		Goat*
8		Pig
9		Chicken
10		Turkey
11		Laying hen*
12		Broiler
13		Milk
14		Beef
15		meat
16		Wool
17		Egg*

[a] All document types were included in the searches.
[b] Search engines return any word that begins with the letters in front of the asterisks.

models in August and September 2017. In addition, the existing reviews of Janssen and van Ittersum (2007) and Reidsma et al. (2018) on modelling and agricultural policies were checked for models meeting the selection criteria specified in Section 2.1. The same procedure was conducted for reviews listing farm models (Bryant and Snow, 2008) and reviews of models for particular livestock species (Crosson et al., 2011; Pla, 2007; Tedeschi et al., 2014).

Next, a systematic search was performed using the search engines Scopus and Web of Science. Keywords used in the searches were based on the first set of literature and the existing model reviews. Searches were a combination of the model type and the livestock species, type or product (Table 1). Keywords used for searches with the search engines were in English. As a result, models fully published in other languages were not listed by the search engines, which may have introduced a slight bias in the number of models developed per country. Countries of affiliation were used to narrow search results down to authors employed in countries that are fully and partly located in Europe. After merging results for all searches, duplicate papers were removed using EndNote X8.

References to relevant models were tracked in the documents that met the selection criteria, which is also referred to as the snowballing method (Wohlin, 2014). This method allowed to investigate the completeness of the list of models already found. The list of models found was presented and evaluated at a workshop of the project 'Animal-Future', and any omissions identified were added to the list of selected models. We used the snowballing method and evaluation by researchers next to the search engines, because using search engines only may result in omission of a large percentage of relevant documents on extensive topics (Greenhalgh and Peacock, 2005).

2.3. Model evaluation

Models meeting the selection criteria were evaluated to develop an overview of the livestock species and types that were simulated, the countries models were developed in, their aims, the sustainability themes addressed, and the availability of models. Livestock species and types were classified as dairy cattle, beef cattle, sheep, goats, pigs, laying hens, broilers and turkeys. Dual-purpose cattle were classified as either dairy or beef cattle, depending on the main product. Models simulating breeder hens used as parent stock for broiler production were classified as broiler models. Furthermore, livestock products were listed (milk, beef, meat, wool, eggs), as well as the country the model was developed in and the primary aim of the model described in the first publication. Eight categories of primary aims were specified: getting insight in animal physiology, optimizing herd and flock management, getting insight in crop-livestock interactions (e.g. grazing systems), assessing effects of policies, breeding, assessing environmental impacts of livestock production, optimizing farm management, and improving animal health and welfare.

A list of 19 sustainability themes that are widely used in sustainability assessments for livestock production was used to group sustainability indicators simulated by the models (De Vries and De Boer, 2010; Lebacq et al., 2013; Steinfeld et al., 2006; van Calker et al., 2008) (Table 2). A theme was considered to be addressed if an indicator included in the model input, variables, or output could be classified under one of the 19 sustainability themes. Some models were updated with additional sustainability themes after publication of the original model, and these were included as well. Models addressing multiple indicators

Table 2
Sustainability themes used to group sustainability indicators addressed by models.

Sustainability theme	Sustainability dimension	Remarks
Land use	Environmental	
Water use	Environmental	
Nitrogen use	Environmental	Nitrogen use in mineral and organic fertilizer for crop production, intake of nitrogen via feed by livestock, export in farm products, and nitrogen use efficiency. Includes protein intake by livestock also.
Phosphorus use	Environmental	Phosphorus use in mineral and organic fertilizer for crop production, intake of phosphorus via feed by livestock, export in farm products, and phosphorus use efficiency.
Potassium use	Environmental	Potassium use in mineral and organic fertilizer for crop production, intake of potassium via feed by livestock, export in farm products, and potassium use efficiency.
Energy use	Environmental	
Use of agrochemicals	Environmental	
Soil quality	Environmental	
Biodiversity	Environmental	
GHG emissions	Environmental	
Eutrophication	Environmental	
Acidification	Environmental	
Revenues	Economic	
Costs	Economic	
Profitability	Economic	Examples of indicators grouped under profitability are gross margin, net profit, and income.
Labour requirements	Social	
Off-farm labour opportunities	Social	
Job quality	Social	
Animal health and welfare	Social	Animal health and animal welfare were not separated because these topics are generally highly interconnected.

per theme may be preferred over models addressing a single indicator per theme, and models having indicators in the output rather than the input may be preferred to save time and efforts during the collection of input data. We could not assess the number of indicators per theme and whether indicators were in the input or output, because software, source code and documentation of models were often not available.

Models developed by multi- or interdisciplinary teams may include a larger number of sustainability themes, which could result in adoption and use in more scientific disciplines. The categories of disciplines from Web of Science were adopted to determine how often a first publication describing a model was cited in other publications from specific disciplines. The number of citations from the top-5 citing disciplines were used to determine whether a model was adopted broadly or narrowly over disciplines. The relative root mean square error (RMSE) from the average number of citations was calculated for the top-5 citing disciplines. If the relative RMSE is 0%, the number of citations for all top-5 disciplines is equal, which indicates a broad adoption over various disciplines. More skewed citation patterns increase the relative RMSE and indicate a more narrow adoption. The reverse of the relative RMSE was used as a metric for a disciplinary diversity (100% - relative RMSE). Furthermore, the percentage of citations from publications that are listed as multi- or interdisciplinary categories in Web of Science was calculated.

Adoption and further development of existing models is enhanced if source codes and software are available. In this review, a model was considered to be available if the source code or software could be downloaded for further use. We did not list models as available if publications did not explicitly indicate whether and how the model could be downloaded. It should be noted, therefore, that many more models might be available after contacting model developers. Three types of available models were distinguished. The first type is open source, where the source code of a model can be downloaded, accessed, used, modified and distributed without licensing fees. The second type is closed source without licensing fees. This means that the model can be downloaded and used, but the source code cannot or can hardly be accessed or modified. If the scope to modify the source code of a model was unclear, the model was assumed to belong to this type. The third type is closed source with license fees. Furthermore, the programming languages and the programs used to run the models were listed, because familiarity with specific languages and programs can be an important determinant for the adoption and further development of a model (Meyerovich and Rabkin, 2013).

3. Results

3.1. Livestock species and countries of origin

We found 215 models that met the selection criteria, which were published in the period 1974 to 2019. Only 61% of these models were obtained via search engines, and the rest was obtained via the snowball method, consultation of researchers, and existing literature reviews. This result confirmed the finding of Greenhalgh and Peacock (2005) that using search engines only may result in omission of relevant documents. Because several of the 215 models simulated more than one livestock species or type, a total of 256 livestock species and types were included (see Appendix). Most of the models focused on dairy cattle (35%), beef cattle (21%), pigs (18%), and sheep (15%), whereas models on goats and laying hens covered a relatively small proportion of the livestock models (Fig. 1). Nine models for cattle accounted for both milk and beef production (see Appendix). The seven models for goats all accounted for milk production, and two also focused on meat production. Out of the 39 models for sheep, 38 accounted for meat production, 12 models for wool production, and nine for milk production (see Appendix).

Models were developed in 23 European countries (see Appendix). The number of farm and livestock models developed per country was highest in the United Kingdom (46), France (33), the Netherlands (33), Spain (17), Germany (15), Denmark (9), Norway (9), and Ireland (8). Models were mainly developed in countries in Western Europe (Fig. 2). Dairy models were developed in 16 European countries. The highest number of models for dairy cattle was developed in the United Kingdom (Table 3). The highest numbers of models for beef cattle were found in the United Kingdom and France (Table 3). Models for sheep were developed in 12 European countries, and the highest number of models for sheep was developed in the United Kingdom. The highest numbers of models for pigs and broilers were found in the Netherlands (Table 3).

The number of models published increased after the year 2000 (Fig. 3A). Primary aims of models at the time of the first publication were most frequently (economic) farm optimization and management (18% of the models), herd and flock management (17%), acquiring insight in animal physiology (16%), assessment of environmental impacts (15%) and policy assessments (13%). Models mainly aimed at getting insight in animal physiology and optimizing herd or flock

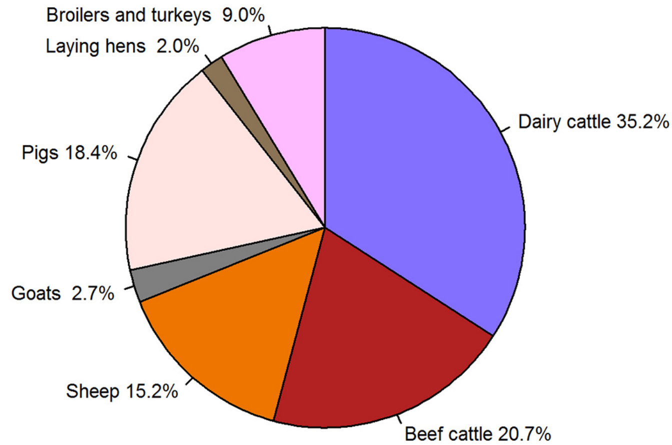

Fig. 1. Percentages of livestock species and types covered by the selected animal, herd or flock, and farm models.

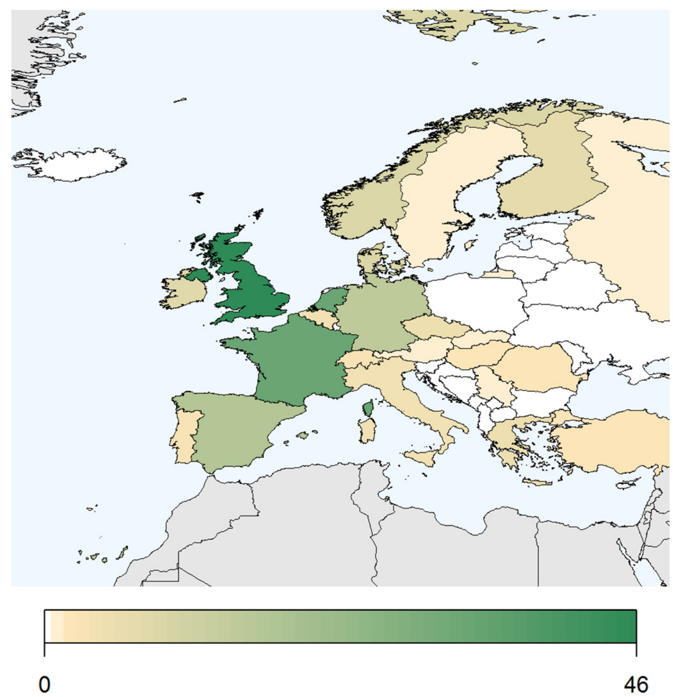

Fig. 2. Total number of models developed in European countries for all livestock species and types (dairy and beef cattle, sheep, goats, pigs, laying hens, broilers and turkeys).

Table 3
Overview of European countries where the highest numbers of models (top-4 or top-5) for dairy cattle, beef cattle, sheep, pigs, and broilers were developed.

Dairy cattle			Beef cattle			Sheep			Pigs			Broilers		
Rank	Country	Models	Rank	Country	Models	Rank	Country	Models	Rank	Country	Models	Rank	Country	Models
1	United Kingdom	22	1	United Kingdom	14	1	United Kingdom	16	1	Netherlands	7	1	Netherlands	7
2	Netherlands	20	2	France	10	2	France	5	2–4	Germany, Spain, United Kingdom	6	2	United Kingdom	4
3	France	11	3–4	Germany, Spain	4	3	Spain	4	5	France	5	3–4	France, Germany	3
4	Denmark	7				4	Greece	3						
5	Germany	6												

management in the 1970s and 1980s (Fig. 3B). Later, models also aimed at assessing environmental impacts, optimizing farm management and improving animal health and welfare. The disciplinary diversity for all models increased significantly over time ($P = .003$), but the percentage citations from multi- or interdisciplinary journals did not increase significantly ($P = .357$).

3.2. Sustainability dimensions and themes addressed

The environmental, economic, and social dimension of sustainability are commonly addressed in sustainability assessments of livestock farms. Environmental themes were included in 67% of the total number of models, economic themes in 67% also, and social themes in 52%. In total, 33% of the models addressed all three sustainability dimensions, 27% addressed two dimensions and 33% addressed one dimension. In this review, 7% of the models did not include any sustainability theme, because none of their inputs, variables or outputs could be classified under a sustainability theme. Some of these models focused on biophysical aspects of livestock production, and simulated animals based on dry matter intake or energy intake. Others focused on herd or flock management to optimize slaughter weights and replacement rates. The percentage of models addressing all three dimensions was higher for ruminants (35% for dairy cows up to 54% for sheep) than for monogastrics (0% for laying hens up to 17% for broilers and pigs).

Environmental sustainability themes that were addressed most frequently in the models were nitrogen use (40% of the models), land use (36%), GHG emissions (20%), and energy use (18%) (Fig. 4). The economic sustainability themes costs (66%), revenues (62%), and profitability (53%) were frequently addressed. On the social dimension, labour requirements (39%) and animal health and welfare (31%) were most often addressed in the models (Fig. 4). Models covered up to 14 themes out of the 19 themes (Fig. 5). The average number of sustainability themes addressed was 4.3, and the median was 4. For the models that addressed all three sustainability dimensions (33% of the total models), the average number of sustainability themes was 7.0, the median was 6 themes and the number of themes ranged from 3 up to 13.

Using linear regression, the average number of sustainability dimensions addressed by models did not show a significant increase or decrease over time ($P = .399$, Fig. 6A). The average number of sustainability themes addressed by models, however, increased significantly by 0.05 themes per year ($P = .013$, Fig. 6B). The percentage of economic themes within all 19 themes addressed decreased

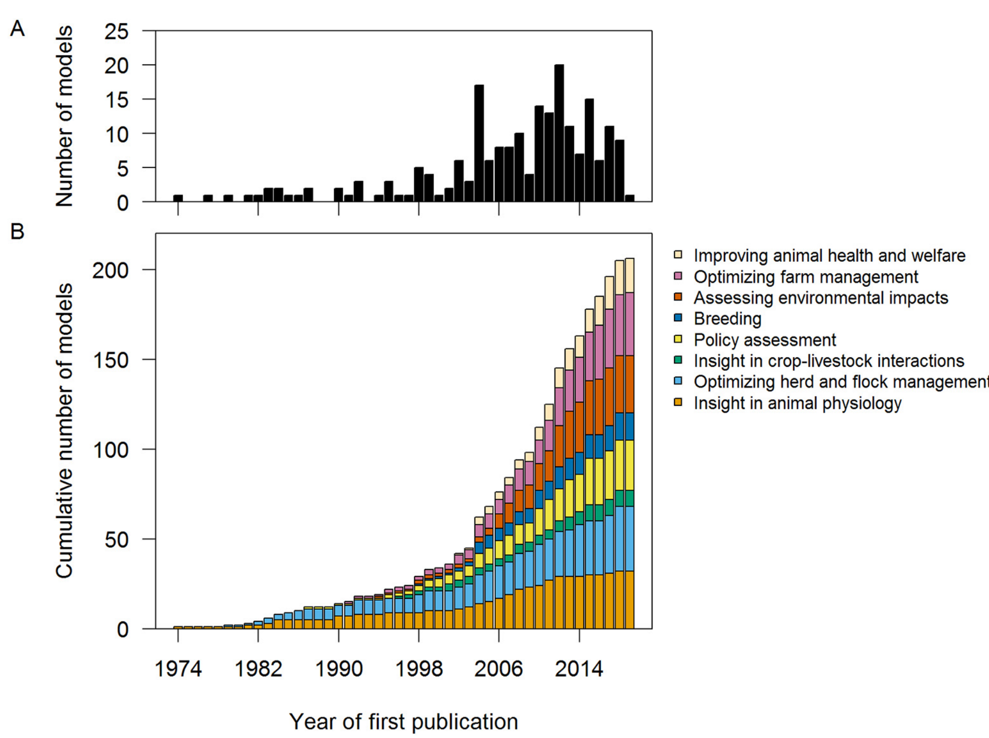

Fig. 3. Numbers of models published over time (A) and their primary aim at first publication (B). The year of first publication could only be identified for 207 out of the 215 models.

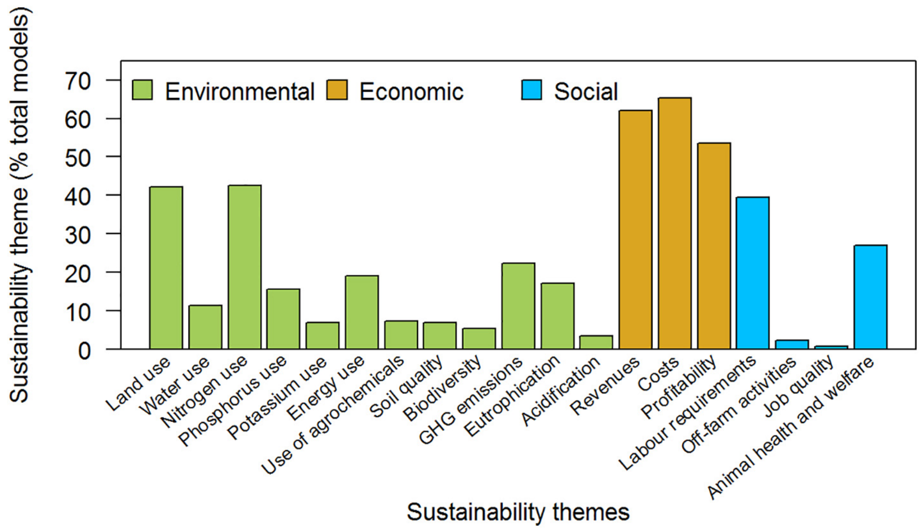

Fig. 4. Environmental, economic and social sustainability themes addressed in the models. GHG = greenhouse gas.

significantly by 1.0% per year ($P < .001$), whereas no significant increase or decrease over time was observed in the percentages of environmental and social themes (Fig. 6C). The number of sustainability themes addressed per model increased significantly with an increasing disciplinary diversity ($P = .002$), but not with the percentage of citations in multi- or interdisciplinary journals ($P = .373$). The number of sustainability themes, however, increased with an increasing percentage of citations in multi- or interdisciplinary journals for models developed to assess policy consequences ($P = .031$).

3.3. Model availability and ease of use

Additional information on models (source codes, software, documentation, examples, and applications) was provided on web pages for 26% of the models. The source code or software was available for 39 models, which corresponds to 18% of the total number of models. Thirteen out of the 39 models were open source (6% of the total number of models). Twenty models were closed source without licensing fees (9%) and six models were closed source with license fees (3%). Models published up to 1992 were not available. Available models were found in the years 2001–2018, except for 2007. The percentage of available models published per year in this period, however, did not increase or decrease significantly. At least thirteen of the available models could be downloaded after providing user information and/or information on the intended purpose of model use.

Programs and programming languages used for model simulation were listed for 69% of the models. The programs used most frequently were Excel, GAMS, and ModelMaker. Excel was used in 47 models, from which 11 times in combination with the add-in @risk. Contrary to the other programs, Excel is a spreadsheet program that could be considered to be a distinct program category. MATLAB, which is referred to as a scripting language, was used five times in model development. The programming languages most frequently used were R, Visual Basic for Applications, C or C++, Fortran, Pascal, and Python (Fig. 7).

4. Discussion

4.1. Livestock species and countries of origin

This review provided an overview of 215 European livestock models, and described the livestock species and types included, the countries models were developed in, the models' aims, the sustainability themes addressed, and their availability. The share of models developed for a livestock species or type was largest for dairy cattle and beef cattle, whereas it was smallest for laying hens and goats (Fig.1). Differences in shares of livestock species and types may be explained by a combination of the economic value of their products, their impact on the environment, the share of agricultural area used, and provision of ecosystem services.

Countries where most models were developed were mainly located in Western Europe (Fig. 2). This result broadly corresponds to the study of Reidsma et al. (2018), who found that agricultural models used in policy making were mainly applied in Western Europe, with few applications in Eastern Europe. The development and application of

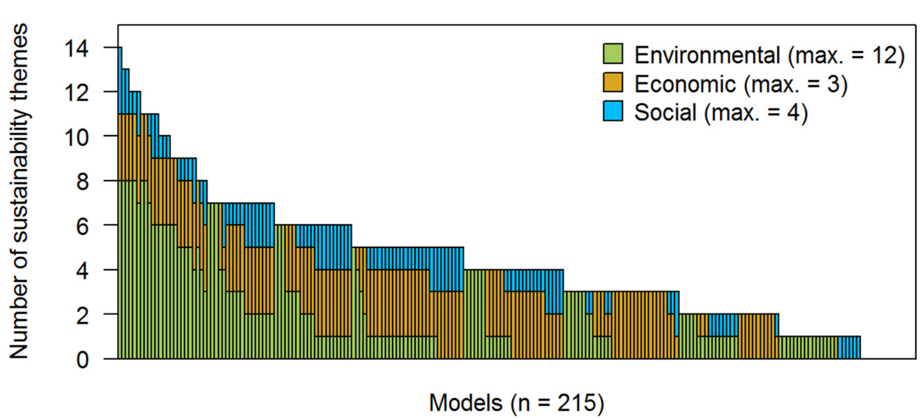

Fig. 5. Numbers of environmental, economic and social sustainability themes addressed per model. Each bar represents one model.

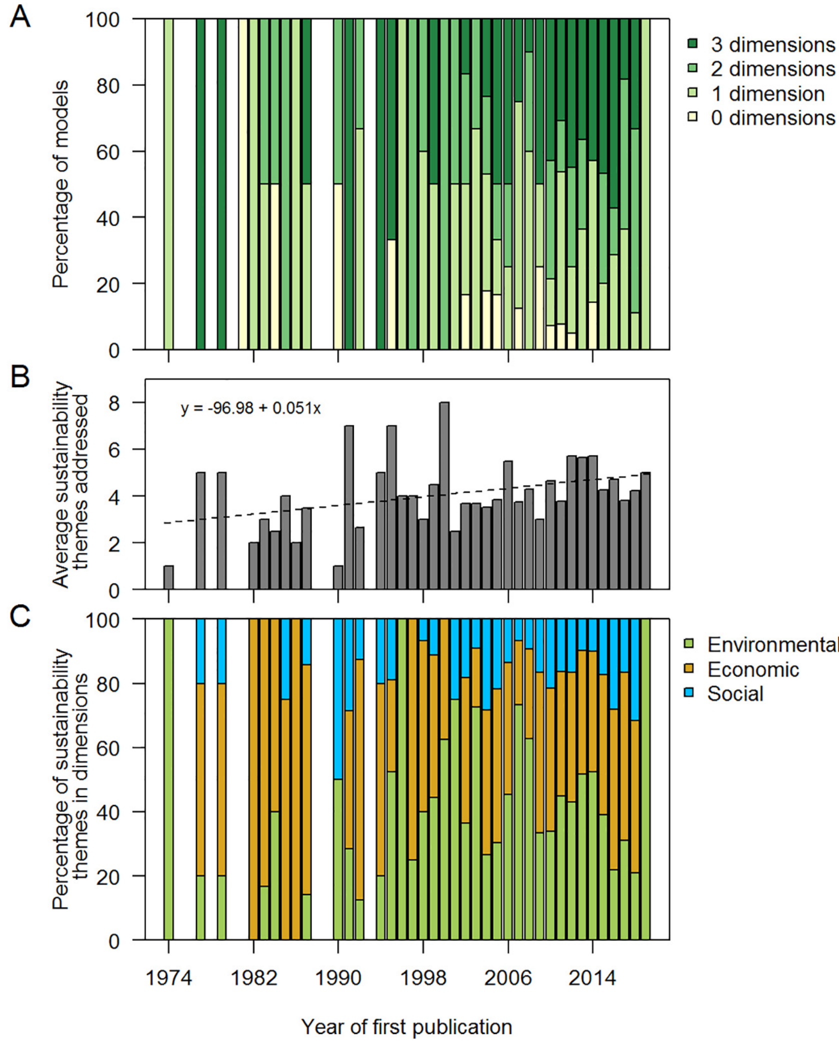

Fig. 6. Percentage of models addressing three, two, one, or none of the sustainability dimensions (i.e. environmental, economic and social) (A), the average number of sustainability themes addressed per model (B), and the percentages of sustainability themes within the sustainability dimensions (C).

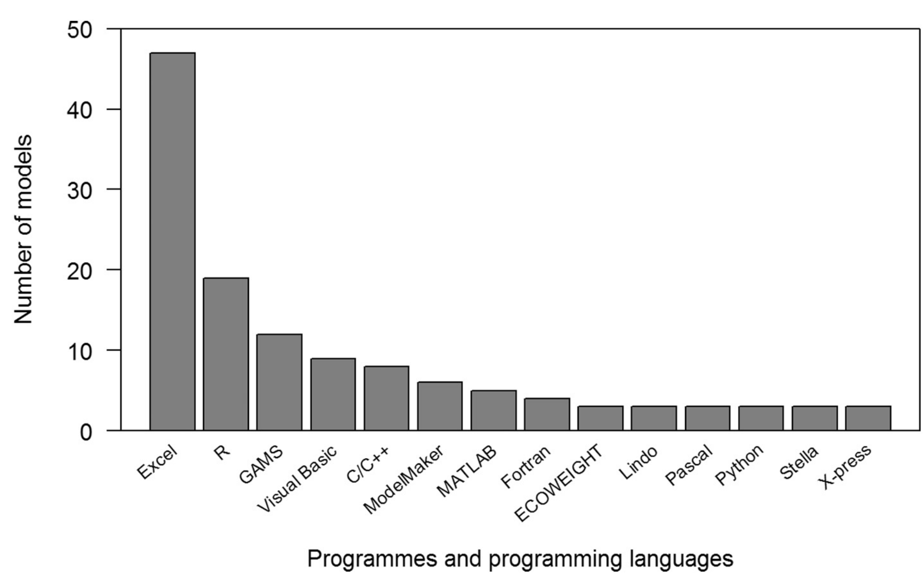

Fig. 7. Number of models using particular programs (e.g. Excel, GAMS and ModelMaker) and programming languages (e.g. R, Visual Basic, C or C + + and Fortran). Note more than one programme or programming language can be used to run a model.

multiple models in Western Europe is in line with expectations, because the analysis of livestock farming systems has emerged in this geographic area (Gibon et al., 1999). Hence, many of the existing models have not been designed to simulate livestock production in regions other than Western Europe. This implies that effects of innovations and policies on the sustainability performance of farms outside Western Europe might be assessed with a lower accuracy and precision. This possibility is to be kept in mind by policy makers and other stakeholders that make decisions based on model output.

The first modellers that aimed to simulate livestock production in the 1970s and 1980s focused on physiological processes of individual animals, and on herd or flock dynamics. Models for farm optimization were introduced in the 1990s (Fig. 3). This corresponds to the notion of Gibon et al. (1999), who indicated that most models dealt with herd management strategies around that time, and that simulation of farm management strategies was an important challenge. Models for animal health and welfare were introduced around the start of the 21st century, possibly as a result of increasing societal concerns about animal health and welfare (Boogaard et al., 2011; Busch et al., 2018; Gibon et al., 1999). Our results, however, are too narrow to support the hypothesis that concerns on animal health and welfare impelled model development, because models focussing primarily on transmission of pathogens were excluded in this study. The increasing disciplinary diversity over time might suggest that model developers have reached a more and more diverse group of scientists with their publications. Nevertheless, the percentage of papers cited in multi-or interdisciplinary journals did not increase. These contradicting and explorative results thus cannot be used as evidence for more interaction and collaboration among disciplines over time.

4.2. Sustainability dimensions and themes addressed

Our review indicates that environmental and economic sustainability dimensions are addressed in approximately two-thirds of the models, whereas the social dimension of sustainability is addressed in approximately half of the models. Contrary to environmental and economic sustainability indicators, social indicators are often based on information from surveys and interviews, which is often difficult to quantify (De Olde et al., 2018; Latruffe et al., 2016). The difficulty to quantify social indicators may be explained by difficulties to define social goals by society also (Rossing et al., 2007). Other explanations why the social dimension was addressed in fewer models are the lower degree of consensus among stakeholders on social themes than on environmental and economic themes, the variety of approaches used in research to evaluate social impact, and the relatively late addition of social themes to sustainability assessments (De Olde et al., 2018). More efforts have to be paid, therefore, to integrate the social dimension in livestock models, because synergies and trade-offs important to stakeholders may not be captured or may not be captured adequately, thereby reducing the relevance of model results.

A novelty of this model review is the specification of 19 sustainability themes within the three sustainability dimensions. The three environmental themes most frequently addressed in models were nitrogen use, land use, and GHG emissions (Fig. 4). These three themes are in line with key issues presented in global and European policies and in the scientific debate. The economic sustainability themes revenues, costs, and profitability were addressed frequently (Fig. 4). Many of the linear programming models included in this review are designed to maximize the gross margin of a product or a farm, which partly explains why the theme profitability is frequently addressed. Profitability was included in fewer models than revenues and costs, since not all models addressed revenues and costs in sufficient detail to calculate profitability. Labour requirements was the social sustainability theme most frequently included in models (Fig. 4), which corresponds to the study of Rossing et al. (2007). Labour requirements is a social theme that is often linked to the economic theme costs, due to the costs of labour. Hence, one can wonder whether the primary intention of including labour requirements was to get insights in the social sustainability of farms or to assess their economic sustainability.

Our study shows that most models addressed only a limited number of sustainability dimensions and themes (Figs. 5 and 6). Approximately one-third of the models addressed all three sustainability dimensions. The median number of themes addressed was 4, and the maximum number was 14, so none of the models addressed all 19 themes (Fig. 5). The more sustainability dimensions and themes included in a model, the more synergies and trade-offs can be identified and taken into account by decision makers and farmers. The results indicate that many models at the animal, herd or flock, and farm level do not suffice to assess sustainability based on a wide array of dimensions and themes, and have been developed for other purposes.

Models addressing a relatively large number of sustainability dimensions and themes are generally preferred to assess the sustainability performance of farms with livestock. The number of dimensions and themes included in models is expected to increase over time, because sustainability assessments have broadened throughout history (De Olde et al., 2018). Although our study did not show a significant increase in the number of sustainability dimensions over time, the number of sustainability themes addressed in models increased (Fig. 6A and B). This increase might stem from an increased collaboration between scientific disciplines in model development. Models with a higher number of sustainability themes had a higher disciplinary diversity in citations. Their development teams might also have had a higher diversity, although this was not assessed in this study.

Development of livestock models that can assess the sustainability performance of farms based on multiple dimensions and themes is facilitated by collaboration among disciplines. Solutions for more and closer collaboration can be fostered by providing extra resources for multi- and interdisciplinary projects to develop shared visions, objectives, frameworks and protocols. In addition, research institutes may include multi- and interdisciplinary collaboration in their performance metrics, which is often not done yet. Funding in research on sustainability in agriculture could be directed more towards multidisciplinary consortia that indicate clearly how expertise from different academic fields will be integrated. Finally, editors of disciplinary journals may broaden the scope of their journals to provide more opportunities to publish results of interdisciplinary projects (Kragt et al., 2016).

The overview of livestock models in our study can assist in selecting models for assessing impacts of specific technological innovations, changes in farm design, or policies on the sustainability performance of European farms with livestock *ex ante* (see Appendix). This selection can be based on several criteria. Ideally, livestock species or type and the (geographic) application domain of the selected models should correspond to those of the actual farm systems. In addition, this overview allows to select for the year of first publication, where more recent models may be preferred over older ones. The overview may provide direction whether any of the existing models suffices, whether existing models have to be adapted, extended, or combined, or whether new models need to be developed to meet certain aims.

In general, models for monogastrics addressed fewer sustainability domains than models for ruminants. Priority may thus be given to models for monogastrics to increase the number of models that integrate and address all three domains. Development of more integrative models involves an increase in model complexity. In our opinion, the most efficient strategy to deal with increasing complexity is to adapt, combine and extend existing models, and to avoid starting model development from scratch as much as possible. Following this strategy, development of more integrative models requires existing models that are freely available, and that allow to modify the source code or software (i.e. open source).

4.3. Model availability and ease of use

The source code or software was classified as available for 18% of the models. In comparison, a review by Kremmydas et al. (2018) on agent-based models used in agricultural policies indicated that 31% of the models (10 out of 32 models) was available, and their results could possibly be reproduced. Reidsma et al. (2018) found that 37% of the models included in their review could be re-used and/or was described in much detail. Although the methods to quantify the percentage of available models differed slightly among studies, this study adds to the notion that only a minority of the agricultural models is available.

The low percentage of available models does not imply that other models are necessarily unavailable for those interested in using them. Some authors state explicitly that the source code or software is available upon request (e.g. Ramsden et al., 1999). Despite this statement, models may not be available anymore because the developers might have retired or moved to another institute, which may apply especially for the older models included in this review. Even if not stated explicitly, models might be available after contacting the developers. In addition, several models in this study were described in much detail in papers, appendices, or manuals. Complete lists of equations and parameters might allow to reproduce some of these models. It should be kept in mind also that available models may not work as expected due to bugs in the source code and software.

Major advantages of making models available are the ability to reproduce the models' results and to investigate new research questions (Joppa et al., 2013). Next to the software or source code, model inputs should be available also to allow reproduction of model results. Within the available models, the open source models serve the research community most, because they allow anyone to adapt and extend the source code or software. Open source models allow researchers to investigate what code is already available for particular purposes, which is helpful to decide whether (components of) an existing model can be used or not for the development of more integrative models.

Several models for particular livestock species in the overview appear to be similar (see Appendix). Some of the apparent similarities may not be actual similarities after close inspection of software and source code. Nevertheless, the similarities suggest that European modellers work at cross purposes at some instances and are at risk to reinvent the wheel, a concern that has already been expressed in the literature (Janssen et al., 2010; Janssen et al., 2017; Reidsma et al., 2018).

The decision of modelling groups to develop their own models might be related to several causes that have to be addressed in future. First, the low percentage of available models, and open source models in particular, blocks adaptation and extension towards more integrative models. The results of this study highlight the need to improve the scope to re-use source code and software in the agricultural sciences, as has been argued before (Janssen et al., 2017; Jones et al., 2017a; Kremmydas et al., 2018). Still, many journals do not require the source code to be reviewed for publication, nor promote open source publication of models (Joppa et al., 2013; Stodden et al., 2013). In our opinion, journals and authors should, therefore, impose stricter rules on the availability of models and input datasets to ensure reproducibility of results and re-use of models. Furthermore, commercial licenses might hamper model adoption and re-use by less endowed institutes and other stakeholders, such as farmers. The programs listed in Fig. 7 generally require commercial licenses, whereas the programming languages can be used for free. Research institutes generally provide commercial licenses, so the purchase of licenses may hardly hamper model adoption in most institutes (Ince et al., 2012). Some models can be downloaded after providing user information to the model developers. Although this condition may not be in line with open source publishing, it allows model developers to keep track of model adoption and use, which may open up ways for collaboration.

Second, a lack of overview and awareness of the existing models might result in isolated development of models. The objective of this review is to provide an overview of the existing livestock models developed in Europe. Future research may focus on creating overviews of models developed outside Europe. Next to model overviews, establishing and maintaining networks and overarching platforms contributes to more awareness and more connections between researchers. For example, the European modelling knowledge hub MACSUR (Modelling European Agriculture with Climate change for food SecURity) has been instrumental in connecting researchers that focus on modelling ruminant production on grasslands under climate change (Kipling et al., 2016a; Kipling et al., 2016b). More funding may be directed to overarching platforms such as MACSUR to induce collaboration and coordinate model development.

In addition, priority may be given to the joint development of generic and modular models, which reduces time and funding required by the modelling community as a whole (Janssen et al., 2010; Janssen et al., 2017; Jones et al., 2017b; Reidsma et al., 2018). Another advantage of generic models with large application domains is the scope to benchmark and compare results of different studies using the same model. The generic models can be specified further by individual research groups, depending on the purpose of the sustainability assessment. Advantages of more specific models are a better coverage of the local context of livestock farming and generally a larger engagement of stakeholders (Gasso et al., 2015). Modellers thus have to deal with the trade-off between efficiency and the scope for benchmarking against other results on the one hand, and coverage of the local context and stakeholder engagement on the other hand.

Third, some model publications provide little guidance to researchers that consider adapting and extending existing models. This review indicated that only 65% of the models specified what programming languages or programs were used. Programs and programming languages are to be specified, because they are important determinants for adoption and further development of models (Meyerovich and Rabkin, 2013). Researchers might be inclined to select models that run with programs and programming languages they or their colleagues are already familiar with, because getting acquainted to a new program or programming language may require a considerable amount of time. The overview of models, therefore, allows to assess which models require specific programs or are written in a specific programming language (see Appendix).

Another reason to select particular programs or programming languages is the likelihood of making errors, which affects the reliability of model output (Ray et al., 2017). Programs and programming languages facilitate the prevention, identification and correction of errors to different degrees. Especially models developed in spreadsheet programs such as Excel are known to be prone to errors (Panko and Sprague, 1998). Keeping the overview tends to be harder when using spreadsheet programs, because equations are hidden in cells. In addition, risks on errors related to copying and pasting information tend to be higher with spreadsheet programs. Hence, the programming language used for model operation has to be specified clearly to facilitate model adoption.

Besides programs and programming languages, many of the publications are not explicit about stakeholder involvement and model specificity. Stakeholder involvement is essential to develop models that fit to the specific context of stakeholders (de Olde et al., 2016). Future publications on livestock models should specify better which stakeholders were involved, how they were involved, when, and what their contribution to model development was. This review focussed on the first publications describing a model. These first publications generally exclude the evaluation, adoption and use of a model by stakeholders, and its long term impact on livestock farming. Future research could link, therefore, the degree of stakeholder involvement to the adoption, use and impact of models and model results.

5. Conclusions

This review provides an overview of 215 European models that assess livestock production at the animal, herd or flock, and farm level. The majority of models was developed in Western Europe, which may imply that model results may be less accurate when applied to other regions than Western Europe. All three sustainability dimensions were included in 33% of the models. The median number of sustainability themes addressed was 4 out of the total of 19 themes. Hence, most models do not allow to simulate synergies and trade-offs among a diverse array of sustainability themes within the three sustainability dimensions. To increase the number of models capable to do so, adaptation and extension of existing models is required, especially towards the social dimension and for monogastric species. To facilitate adaption and extension, the availability of livestock models and their open source publication is to be improved, since the software or source code was available for only 18% of the models. In addition, future efforts may focus on development of generic models in multi- and interdisciplinary consortia, which can be made more specific by individual research groups. Furthermore, publications describing models should be more specific about the programming languages and programs used, and should describe stakeholder involvement better. The overview of livestock models presented in this paper can be used to decide which of the existing models are best suited to assess effects of specific innovations and policies on the sustainability performance of farms, or whether existing models are to be combined, adapted, extended or new models are to be developed.

Declaration of Competing Interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

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