Environmental and Sustainability Indicators 18 (2023) 100258

Contents lists available at ScienceDirect

Environmental and Sustainability Indicators

journal homepage: www.sciencedirect.com/journal/environmental-and-sustainability-indicators

Measuring sustainability at farm level – A critical view on data and indicators

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ARTICLE INFO

Keywords:
Agriculture
Data
Dairy farms
Economic sustainability
Environmental sustainability
Social sustainability

ABSTRACT

Measuring sustainability at farm level is a priority for both research and policy and requires sustainability indicators to track progress. Indicators make the sustainability concept more concrete and guide farm level decisions, playing a decisive role in determining food system impacts on societies and the environment. Data availability is often a limiting factor when choosing indicators, but not enough attention is paid to the role of data in indicator construction and assessment results. This paper assessed the critical role of data in indicator construction and the potential limitations that current data availability imposes on farm-level sustainability assessments, using the example of dairy farms in Sweden. To do so we used a five-step approach consisting of a literature review, an inventory of data sources, an expert consultation, a matching and gap analysis, and a critical assessment. We found that 20 indicators categorized under 12 out of 20 sustainability themes had measurement issues due to missing scope, temporary data, or additional data requirements. At least some indicators within all themes in the social and economic dimensions were measureable, while all indicators for pesticides, non-renewable energy, and soil quality in the environmental dimension had measurement issues. In the critical assessment, we argue that for some indicators, there are trade-offs between data availability and issues of comprehensibility and analytical validity. Furthermore, we found that no single data source could be used to measure all themes; which means that merging of different data sets is needed for a broader on-farm sustainability assessment. Our findings are relevant for the discussion on sustainability indicators and will also inform future programs aimed at collecting sustainability data at farm level, which should consider the broad data needs identified, and the potential to merge data to enable holistic sustainability assessments.

1. Introduction

A sustainable food system is one "that delivers food and nutrition security for all, in such a way that the economic, social and environmental bases to generate food security and nutrition for future generations are not compromised" (United Nations 2015). Thus, the capacity of socially just and resilient food systems to provide nutritious food without exceeding earth's ecological capacity lies at the heart of sustainable development, clearly relating to all Agenda 2030 sustainable development goals (SDGs) (DeClerck et al., 2016; Rockström and Sukhdev 2016; Wood et al., 2019; United Nations 2021). Since agriculture is a driving force behind many global environmental and social challenges, decisions made at farm level, such as specialisation, allocation of resources and management of production processes, are crucial in determining food system impacts on societies and the environment (Foley et al., 2011; Le Gal et al., 2011; Schader et al., 2016). The possibility to measure and evaluate farm level agricultural sustainability, in order to track developments and support evidence-based policymaking, is therefore a cornerstone in supporting a transition to a sustainable food system (Arulnathan et al., 2020; Fanzo et al., 2021).

For the purpose of monitoring progress towards a sustainability transition, adequate measurement is an important priority for research, policy, as well as the private and public agriculture and food sector. As a consequence, sustainability indicators have gained importance at all scales (Blay-Palmer et al., 2020). Indicators that can concretize and operationalize sustainability and provide transparency on its key features are of particular importance in a setting where different actors have differing perceptions of the concept (Rigby et al., 2001; Röös et al., 2022). Using indicators to measure sustainability in agriculture has thus become common practice and several literature reviews on

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https://doi.org/10.1016/j.indic.2023.100258
Received 30 September 2022; Received in revised form 27 April 2023; Accepted 29 April 2023
Available online 1 May 2023
2665-9727/

sustainability indicator frameworks demonstrate that a large variety of approaches are used (e.g Marchand et al., 2014; Schader et al., 2014; de Olde et al., 2016; Latruffe et al., 2016; Tidåker et al., 2018; Arulnathan et al., 2020; Chopin et al., 2021).

Irrespective of approach, the specific framework and indicators chosen to represent sustainability aspects strongly influence the results of sustainability assessments (Schader et al., 2014; Latruffe et al., 2016). However, the basis on which indicators are chosen is seldom evident in research. Even when criteria used for choosing indicators are explicitly stated, there are often important limitations in indicator construction, such as measurability and practicability, relating to the availability of data (Lebacq et al., 2013). In particular, data-driven sustainability assessments require readily available, relevant and reliable data for indicator construction, and lack of suitable data severely limits the analysis (Latruffe et al., 2016; Lynch et al., 2018; Béné et al., 2019). Within the literature on sustainability indicators in agriculture, limited attention has previously been paid to potential consequences of this essential role of data availability for indicator construction and sustainability assessment results. Since indicators for sustainability assessment are inevitably selected based on the available data, data sources for indicator construction and their implications for the explanatory power of indicators, warrant more research.

Accordingly, the aim of this paper was to assess the critical role of secondary data in constructing indicators for measuring sustainability and to explore the potential limitations posed by the availability of secondary data for conducting farm-level sustainability assessments. We had three sub-aims to achieve our main aim: first to identify environmental, social and economic sustainability indicators and themes at farm level, second to investigate data sources for constructing those indicators and third to assess consequences of secondary data availability for sustainability indicator construction and assessment at farm level.[1] As an illustrative example for the second and third sub-aim, we used the case of Swedish dairy farming, and hence assess data availability for Sweden. Dairy farming is interesting in this context as it provides an example of a sector with high environmental impact, which struggles with poor profitability while socially being a provider of consumer products with high demand (Robert Kiefer et al., 2015; Röös et al., 2018; FAO 2019). Given this interrelation between sustainability dimensions, assessment integrating the three pillars of environmental, social and economic sustainability is crucial in dairy farming. In addition, Sweden has stringent legislation on animal welfare and ambitious sustainability targets set by the industry, creating societal interest in monitoring farm-level indicators, making Swedish dairy farming a suitable case to study (HKScan et al., 2021; Jirskog 2022).

While sustainability indicators can be constructed from a variety of information sources, we focused on secondary data sources. Secondary data refers to data that has been previously collected, processed and published by individuals or organizations other than the user for a different purpose than the one currently being considered. As such, secondary data are not collected directly from farmers for the purpose of indicator construction, but is nevertheless widely used with that purpose. Use of secondary data is resource-efficient, as it exploits existing administrative procedures and existing data (Rasmussen et al., 2017). Furthermore, national register data for administrative purposes often include large samples of longitudinal data, which allows for repeated measures over time and increases the representativeness of results (Westergaard-Nielsen 1989). Such data are essential for efficient policy impact evaluation and for investigating the dynamic properties of agriculture (Dillon et al., 2010; Barnes and Thomson 2014). Sweden, known for good register data availability and quality, provides a good case for examination of the potential of such data in terms of sustainability indicator construction. Therefore, our results may be used to design more efficient data sources and collection strategies for farm-level sustainability measurement both in Sweden and beyond.

This study makes two significant contributions to existing literature. First, we contribute to the scholarly debate on sustainability indicators for farm-level sustainability assessment by highlighting the critical role of secondary data availability in indicator construction, identifying data gaps and measurement issues for farm level sustainability assessment, and by highlighting the trade-off between data availability and the comprehensibility and analytical validity of some indicators. In particular, we found that in our case study, 20 indicators categorized under 12 out of a total of 20 identified sustainability themes, had measurement issues due to missing scope, temporary (non-longitudinal) data or the existence of additional data requirements. In the social and economic dimensions, at least some indicators were measurable within all themes, while all indicators for pesticides, non-renewable energy and soil quality in the environmental dimension had measurement issues. Additionally, we found that 16 indicators within 8 themes had issues with comprehensibility and analytical validity and argue that some indicators experience a trade-off between such issues and data-availability. As such, our findings informs researchers and stakeholders on current issues, potential pitfalls and risks in farm level indicator construction from secondary data sources, using our case study area as an example. By highlighting data issues for dairy indicators in general and our case study area in particular, our study contributes to a much needed discussion on how to improve the quality of future data-driven sustainability assessment at the farm-level. By doing so, our study is also useful for developing and coordinating large-scale routine data collection for sustainability assessments. Second, at a national level, we make a contribution by providing a detailed description of indicators for essential sustainability themes in dairy farming, available secondary data, as well as information necessary for merging data sets, which is crucial for facilitating farm-level sustainability assessment in Sweden.

2. Approach

The United States Environmental Protection Agency defines a sustainability indicator based on the three pillars concept as "a measurable aspect of environmental, economic or social systems that is useful for monitoring changes in system characteristics relevant to the continuation of human and environmental well-being" (Fiksel et al., 2012:6). Also, to concretize an indicator "it is necessary to add a unit of measurement, period of measurement, and boundaries" (Veleva and Ellenbecker, 2001). Regarding the hierarchical structure and terminology of sustainability indicator frameworks, we followed the Sustainability Assessment of Food and Agricultural Systems (SAFA) guidelines from (FAO (2013) in labelling sustainability dimensions, themes, sub-themes and indicators.

Our analysis comprised five distinct steps (Fig. 1). 1) In a comprehensive literature review, we identified indicators as well as a set of indicator themes and sub-themes, considered necessary for a holistic sustainability assessment on dairy farms. 2) We mapped available secondary data sources for constructing indicators for dairy farms in Sweden in an inventory. 3) We validated the results of the literature review and data source inventory with a group of dairy sustainability experts. 4) We assessed whether the secondary data sources in the inventory can be used to measure indicators within all the themes at farm level. 5) We identified data gaps and critically appraised the indicators, as well as the potential of the data sources in the inventory to support holistic sustainability assessment.

2.1. *Step 1: literature review on sustainability indicators in dairy farming and identification of indicator themes*

To identify relevant sustainability themes and previously used indicators, we reviewed the literature on indicator-based sustainability assessment of dairy and livestock farming. Previous reviews have

[1] It should be clear to the reader that proposing a new framework for dairy sustainability assessment is not within the aim and scope of this paper.

Fig. 1. Illustration of the five-step approach.

covered the three dimensions of sustainability in dairy farming (Arvidsson Segerkvist et al., 2020) and the use of the Farm Accountancy Data Network (FADN) database for sustainability indicator construction, including for dairy farming (Kelly et al., 2018b). These papers were an important starting point for our review; together with the evaluation of Sweden's food strategy with corresponding sustainability indicators (Burman et al., 2021). We also conducted a narrative literature search in Web of Science full collection, which included results from CAB Abstracts, Current Contents Connect, BIOSIS Citation Index, MEDLINE and SciELO Citation Index. A search conducted on *topics* using the search string *((sustainab* near indicator*) (dairy or milk) and (agriculture or livestock))* resulted in 178 articles. In a second step, articles were selected based on title and abstract relevance, where preference was given to assessments at farm level containing more than one indicator in more than one sustainability dimension, and studies explicitly reporting use of at least one secondary data source for indicator construction. Assessments of agricultural systems with little resemblance to a Swedish setting, such as subsistence farming in developing countries, were excluded. The papers that remained (n = 40), were scrutinised for examples of indicators in the three dimensions of sustainability (Tables 1–3). Indicators based on on-farm measurements, rather than secondary data, are reported in italics in column 3 of Tables 1–3. While not all indicators have been used exclusively on dairy farms, only indicators that are relevant for dairy farms were listed. To categorise indicators into themes and sub-themes, we used the RISE 2.0 parameter framework as a reference point (Grenz et al., 2011).[2]

Our approach was to identify an extensive set of indicators to measure all relevant sustainability themes, while at the same time include a manageable amount of indicators for the subsequent analysis. While this was a choice of convenience for us, it implies that there are many indicators both from sustainability assessments and from other areas of research that have not been considered in this paper. Since our aim was not to identify the most suitable indicators in a particular case, but rather to investigate the capacity of current data availability to construct indicators, we considered this an acceptable limitation of the literature review.

2.2. Step 2: developing an inventory of secondary data sources for indicator construction

We developed an inventory of secondary data sources for sustainability indicator construction for Swedish dairy farms. Schader et al. (2014) identified different levels for sustainability assessments in the agriculture sector, with the scope and purpose of an assessment determining the level of analysis requiring data. Since our investigation considered the farm as the level of analysis, the inventory necessarily included Swedish sources of farm-level data, such as farm economics survey (FES) and FADN. Data sources with other units of analysis on a micro-level,[3] listing variables for individuals, animals, firms or fields, were included if they likely could provide information about sustainability aspects at farm level, through for example a farm ID or organizational number. By using such a farm level identifier, different data sources can technically be merged at the farm level and provide basis for broader indicator analysis. Another criterion for inclusion in the inventory was that information on population, sampling and availability of underlying data was somehow provided.

Data on individuals, useful in constructing social sustainability indicators, such as education, age, gender, wages and working conditions, were found in the Longitudinal Integrated Database for Health Insurance and Labour Market Studies (LISA) and Labour Statistics Based on Administrative Sources (RAMS). Data on firms, which are useful for constructing indicators of economic sustainability, such as value added and labour productivity, were found in Structural Business Statistics (FEK). Other firm data for constructing indicators relating to environmental sustainability, such as taxes paid for different energy types, were taken from the Firm Register and Individual Databases (FRIDA). The farm support payments for rural development (RDP) lists subsidies received for activities related to all three dimensions of sustainability. Data on fields or agricultural blocks, useful for constructing indicators such as agricultural land type, natural values and signal species, were found in the National Inventory of Meadows and Pastures (TUVA) and the Land Parcel Identification system (LPIS). Data on animals, useful for constructing indicators related to their health, welfare and productivity were obtained from milk recording schemes (KK). Additional data sources included Sweden Food Arena's (SFA) innovation survey, capturing variables relating to succession, innovation and external cooperation of agricultural firms. Based on recommendations from dairy sustainability experts at the expert consultation workshop (see section 2.3), data sets compiled from a calculation tool for farm level environmental impacts administered by the Swedish Board of Agriculture (SBA) was included in the inventory. The tool, named VERA, contains farm level data on several environmental aspects for individual farms as well as an "example farm", however only data on nutrient balances have been compiled and made available for research purposes. The appendix contains information on the unit of analysis, population, sample, register base, availability as well as ownership and management for all the data sources included in this study.

2.3. Step 3: expert consultation

A consultative workshop with seven dairy sustainability experts was held. Three additional experts, who could not participate in the workshop, were interviewed in separate meetings. The expert group covers broad scientific knowledge in ecology and biodiversity, ecosystem services, life cycle analysis, rural development, veterinary medicine, animal science, work science, agricultural economics and economic sustainability. As such, they represent knowledge for a holistic sustainability assessment of dairy farms and the purpose of the expert

[2] RISE (Response-Inducing Sustainability Evaluation) is an interview-based method for assessing sustainability of farming operations across economic, social and environmental dimension developed by the Swiss College of Agriculture (Grenz et al., 2011).

[3] By micro-level data we mean unit level data obtained from for example sample surveys, censuses and administrative systems, providing information about characteristics of individuals, entities or geographical areas (World Bank 2020).

consultation was hence to validate the relevance of the sustainability themes identified from step 1. Furthermore, the group provided recommendations on additional data sources to be included in the data inventory.

2.4. Step 4: matching indicator themes and data

The sustainability themes were matched with variables in the available data sources through the example indicators from the literature. If at least one variable in the data source could be used to construct an indicator, for at least one theme and at least one point in time, the source and variable were matched to that indicator. For example, in the environmental dimension, the first theme was nutrient flows and the first sub-theme was eutrophication (Table 1). An indicator identified for eutrophication was nutrient balance or surplus, expressed in kg phosphorus (P), nitrogen (N) and/or potassium (K) per hectare farmed land or per kg fat- and protein-corrected milk (FPCM) produced (Ehrmann 2008; Oudshoorn et al., 2012; Klootwijk et al., 2016). VERA-variables for kg surplus P, N and K per hectare can be directly used as an indicator for eutrophication. FADN-variables for P, N and K in fertilizer input quantities in decitonne (dt), coupled with milk output in kg need additional data on P, N and K in other inputs and outputs to construct such an indicator. Fertiliser and feed purchases, manure and milk sales in Swedish Kronor (SEK) in FES, also requires additional data for indicator construction, such as a conversion factor from currency to quantity units. FADN and FADN/FES are therefore written in bold in column 5 in Table 1. Another indicator identified for the eutrophication sub-theme was eutrophication potential expressed as g nitrate (NO_3)-equivalents per kg FPCM produced (Dolman et al., 2014). This indicator was previously measured by primary data and is therefore written in italics. Since no data source in the inventory contained variables to construct this indicator, the indicator scope was not covered and the Data source and Variable columns are left blank in Table 1. Even though the eutrophication potential indicator had measurement issues, the theme 'nutrient flows' could still be measured through the indicator for nutrient balance/surplus, for which data were available.

2.5. Step 5: gap analysis and critical assessment

We conducted a gap analysis to identify indicators without a match in the data and then compiled a table of sustainability indicators (Table 4) with measurement issues, be they in terms of missing scope, additional data requirements, or temporary data. Missing scope implies that secondary sources do not cover the data needed for indicator construction at all; additional data requirements implies that there are some data available, but there is a need for additional data, such as reference data or a unit conversion factor; temporary data implies that the data is not longitudinal but collected only at a single point in time. Additionally, we used the review of indicator criteria for agri-sustainability as described by Bonisoli et al. (2018) to critically asses the comprehensibility and analytical validity of the indicators from the literature review. High comprehensibility or transparency of an indicator means that it should be easy to seize, clear, simple and unambiguous (Sauvenier et al., 2005; Niemeijer and de Groot 2008; Lebacq et al., 2013). High analytical validity implies that the indicator depends only minimally on external factors (Niemeijer and de Groot 2008) and demonstrates a "obvious and well-defined relationship between the indicator and the phenomenon being monitored" (Meul et al., 2008 p.322). The result of the critical assessment is presented in Table 5. In Table 6, we summarized the findings in the gap analysis and the critical assessment for the identified sustainability themes.

In section 4, we discuss our findings in terms of consequences of the current data availability for indicator construction in the general and Swedish case, as well as scope for further research and future developments in sustainability data collection.

3. Results

Below, we present a typology of indicator themes, coupled with sub-themes, indicators and units from the literature, with each dimension of sustainability considered separately for clarity. Note, however, that there are no strict boundaries between sustainability dimensions, and similar indicators are sometimes used for different themes in the literature. Using indicators found in the literature, we matched the sustainability themes and sub-themes with available secondary micro-level data for Sweden, with the theoretical capacity to analyse activities at farm level.

Columns 1 and 2 in Tables 1–3 report the themes and sub-themes identified, and columns 3 and 4 report indicators (with units) from the international literature of dairy and livestock farming. If any of the Swedish secondary data sources was found to cover the scope of the indicator, column 5 reports the data source(s), with the corresponding variable(s) for indicator construction identified in column 6. Table 4 reports the indicators with measurement issues when using secondary data (missing scope, additional data requirements or temporary data). Table 5, show the result of the critical assessment and hence reports the indicators with issues of comprehensibility and analytical validity. Table 6 reports the findings of the gap analysis and critical assessment in terms of sustainability themes.

None of the secondary data sources could be used to measure all 20 identified themes jointly. For 17 out of 20 themes, we identified at least one indicator that was measurable from some of the available secondary data sources. However, 10 of 69 indicators identified were not covered in scope. An additional 10 indicators were covered in scope but lacked some additional necessary data (reference data, unit conversion factor, price information etc.) for construction (e.g. purchases of plant protection products (PPP) in SEK) or temporary data (e.g. SFA is a one-time survey, not permitting longitudinal analysis). Thus, in total, 20 of 69 indicators had measurement issues. For 3 themes within the environmental dimension ('pesticides, 'non-renewable resources', 'soil quality'), *all* indicators had measurement issues. Further, for 8 out of 20 themes, we found that 10 indicators had issues with comprehensibility and 6 indicators exhibited issues of analytical validity. There was no theme however, for which all indicators exhibited these issues. Note that Tables 1–3 show the potential of secondary data sources to support indicator construction within each sustainability theme, this does not automatically mean that the theme is adequately represented in terms of sub-themes, nor that the indicator for is suitable for any scope and type of assessment conducted.

3.1. Indicators and data for measuring environmental sustainability

The literature review from step 1 revealed that long-term research on indicator-based environmental assessment of agriculture has resulted in relative consensus on themes relevant for environmental sustainability, although these are categorized and named differently in different studies (see e. g van Calker et al., 2006; Latruffe et al., 2016; Chopin et al., 2021) and the underlying indicators vary. The environmental themes in Table 1, Column 1 therefore relate to nutrient flows (N, P, K), plant protection products (PPP) (including herbicides, fungicides, insecticides), non-renewable resources (energy, water), land use, land/-ecosystem management, emissions of greenhouse gases and acidifying substances, biodiversity, and physical, chemical and biological soil quality (Lebacq et al., 2013). Circularity/waste management is included as a sub-theme for the 'nutrient flows' theme, since the most relevant waste flows from dairy farms relate to nutrients (Coteur et al., 2018; Burggraaf et al., 2021).

The 'nutrient flows' theme has three sub-themes: eutrophication, circularity and acidification (Table 1, column 1 and 2). Nutrient balance/surplus and a material circularity indicator have previously been measured using data on fertiliser and feed inputs and milk and manure outputs (column 3 and 4). VERA contain data on individual nutrient

Table 1
Themes, sub-themes, indicators, units, data sources and variables for environmental sustainability measurements[a b].

Theme	Sub-theme	Indicator (references)	Units/factor measured	Secondary data source	Variable
Nutrient flows	Eutrophication	Nutrient (Phosporus (P), Nitrogen (N) ,Potassium (K)) balance/surplus per hectare farmed area and/or per kg Fat and Protein Corrected Milk (FPCM)[c] (Oudshoorn et al., 2012; Klootwijk et al., 2016)	Kilo (Kg) N,P,K input/ kg output	VERA **FADN** **FADN/FES**	N,P,K surplus, kg/ha N,P,K input quantities (in fertilizer), dt[d]/kg milk output Fertiliser and feed inputs, manure and milk sales, Swedish Kronor (SEK)
		Eutrophication potential (g NO_3-eq/FPCM). (Dolman et al., 2014)	grams Nitrate equivalents (g NO_3-eq)/kg/hectare (ha)	–	–
	Circularity	Material circularity indicator: 1-(P,N virgin feedstock + N,P waste/2* Total P,N inputs) (Burggraaf et al., 2021)	Kg/ha/year	VERA **FADN**	N,P surplus, kg/ha N,P input quantities (in fertilizer), dt/kg milk output
	Acidification	*Acidification potential (g SO_2-eq/FPCM).* (Dolman et al., 2014)	grams Sulphur dioxide equivalents (g SO_2-eq)/kg/ha	–	–
Pesticides	Non-toxic environment	Yearly Plant Protection Products (PPP) use (Burman et al., 2021)	Kg/ha or Kg/FPCM	**FADN/FES**	PPP inputs, SEK
Non-renewable resources	Water management	Yearly irrigation/water use (Marton et al., 2016)	Litre (L)/ha	**FES**	Irrigated area, ha
	Energy use	Non-renewable energy use (Dolman et al., 2014)	% of total energy	**FADN/FES**	Total fuel purchases, SEK
		Energy use efficiency (electricity, heating, fuel) (Hennessy et al., 2013)	Carbon dioxide equivalent (CO_2-eq) from energy/kg output	**FRIDA** **FADN/FES**	Energy tax per fuel type, CO_2 tax; SEK Electricity, heating, SEK
Land and ecosystem use and management	Land cover	Grasslands, meadows (Marton et al., 2016)	Ha	FADN/FES TUVA LPIS	Temporary grass, permanent pasture, meadow, rough grazing, ha Summer pasture, forest grazing, meadows, blocks and ha Pasture, wetlands, arable land, blocks and ha
	Land use	Total area used for dairy farming (Van Passel et al., 2007; Meul et al., 2012)	Ha	FADN/FES	Farmed area, ha
	Land use intensity	Livestock intensity (Gonzalez-Mejia et al., 2018)	Number of dairy cows/ ha non-cash crop area	FADN/FES	Farmed area, ha Total livestock units (LU)
Climate impact	CO_2-equivalents	Yearly emissions of CO_2-eq (Ryan et al., 2016)	CO_2-eq/ha/kg	–	–
	Carbon sequestration and storage	Permanent to temporary grass area (Barnes and Thomson 2014)	Ha, %	FADN/FES	Permanent pasture and meadow/temporary grass, ha
Biodiversity	Habitats/biotopes/ signal species	*Amount and area of biotopes with nature value* (Oudshoorn et al., 2012)	Number, ha	TUVA	Positive/negative signal species and occurrence by species, number. per block Natura 2000, classification y/n
	On-farm/functional diversity	*Number. of plant species per hectare pasture* (Oudshoorn et al., 2012)	Number, ha	–	–
		Rough grazing area to total area (Barnes and Thomson, 2014)	Ha, %	FADN	Rough grazing, farmed area, ha
Soil quality	Physical, chemical and biological soil degradation	*Soil organic matter* (Dolman et al., 2014)	g/100g soil	–	–

[a] Indicators in *italics* indicate the indicator was measured with primary data in the reference literature. Secondary data sources in **bold** indicate that the data source is temporary and/or requires additional data to measure the indicator.
[b] VERA-farm level environmental impacts tool administered by the Board of Agriculture, FADN-Farm Accountancy Data Network, FES - Farm Economic Survey, FRIDA – Firm Register and Individual Data Bases, TUVA - National Inventory of Meadows and Pastures, LPIS - Land Parcel Identification system. See section 2.2 and appendix for full description of the data sources.
[c] In general, all indicators calculated per hectare could also be calculated per kg Fat and Protein Corrected Milk (FPCM) produced and vice versa, as long as data for production volume and farmed land is available.
[d] 1 dt = 100 kg.

balances (kg surplus/ha) calculated at farm level, while FADN and FES contain fertilizer and feed inputs, manure and milk output in currency units, and FADN contains amounts of N,P,K inputs only in fertilizer (column 5 and 6). Eutrophication and acidification potential have been calculated previously from site-specific measurements of Nitrate (NO_3), ammonia (NH_3) and sulphur dioxide (SO_2), which are not listed in any of the data sources in our inventory.

For the ‘pesticides’ theme, yearly consumption of PPP (kg/ha) is used at national level to evaluate the environmental target “a non-toxic environment” (Burman et al., 2021). Yearly spending on PPP at farm level is listed in FADN and FES, but apart from the currency unit complicating interpretation of the indicator in amounts, the value may also include non-chemical plant protection which complicates the interpretation of an indicator based on this data (European Commission, 2020).

The ‘non-renewable resources’ theme has sub-themes on energy use (non-renewable energy use, energy use efficiency) and water management. Water management has been measured previously as yearly irrigation. FES contains data on irrigated area, but not water use expressed in litres. FADN and FES contain data on total fuel, electricity and heating costs, but with no distinction between renewable and non-renewable energy. FRIDA contains variables for energy taxes paid by fuel type, but no information on total energy use on-farm. Consequently, all indicators within this theme have measurement issues.

The ‘land/ecosystem use and management’ theme has interrelated sub-themes of land cover, land use and land use intensity. Livestock intensity has been used previously as an indicator of land use intensity. It can be constructed through variables on farmed area and total livestock units in FADN and FES. Land use has been measured as ratio of grassland to cropland area (ha), data that are also present in FADN and FES. A land cover indicator is area of beneficial cover, such as grasslands and meadows. More detailed data on land use and land cover, such as wetlands and forest grazing, in agricultural fields (blocks) are available in LPIS and TUVA.

The ‘climate impact’ theme is most commonly measured as yearly emissions of CO_2-eq, an indicator for which no adequate Swedish secondary source data was identified at the farm level, even though numbers of animals, as well as the data needed to compute nutrient balances also comprise important data needs to compute CO_2-emissions. Another indicator in this theme is illustrated by Barnes and Thomson (2014) who used the ratio of permanent to temporary grass area, reflecting maintained soil structures and preserved carbon sink effects, as an indicator of carbon capture on beef farms. Variables to construct this indicator are currently listed in the Swedish FADN.

The ‘biodiversity’ theme in this representation has two sub-themes, habitats and functional diversity. Oudshoorn et al. (2012) recorded biotopes with nature value and plant species in pasture fields by primary sample. TUVA contains similar information for agricultural blocks, plus occurrence of negative and positive signal species. Barnes and Thomson (2014) used data available in FADN and calculated rough grazing area to total area since “higher levels of rough grazing per total area lead to increased biodiversity and related improvements” (p. 215).

‘Soil quality’ has been measured previously through sampling of soil organic matter content, or by estimation of soil carbon stocks, to determine soil organic carbon (Dolman et al., 2014; Mosnier et al., 2017). Soil organic carbon is strongly affected by soil type, drainage level and land use history (Schulp and Verburg 2009), which are site-specific factors not generally covered in secondary data available for Swedish dairy farms. Piikki and Söderström (2019) constructed a digital soil map of 90% of Sweden’s arable land showing clay content at agricultural block level with high accuracy. To our knowledge, clay content has not yet been used but could potentially be suitable as a soil quality indicator for dairy farms.

3.2. Indicators and data for measuring social sustainability

Lebacq et al. (2013) identified education, working conditions and quality of life as main themes for *internal* social sustainability on a farm, i.e. related to human and animal wellbeing. Since more intangible factors such as experience and knowledge of the land and surroundings are also highly relevant in agriculture, we re-named this theme ‘human capital and education’ (Table 2, column 1). Apart from education and training, demographic viability has been measured through age structure and succession potential (Van Passel et al., 2007; Ryan et al., 2016). The theme working conditions captures the physical work environment, such as fatal accidents on the farm (Chen and Holden 2017), yearly wages (Ehrmann and Kleinhanss 2008) and gender balance (Burman et al., 2021). Psychological issues, such as work-life balance (Ryan et al., 2016), household vulnerability and isolation (Hennessy et al., 2013) affect the wellbeing of the farmer and hence the theme quality of life. Social sustainability themes also contain issues that matter “on the level of society” (Latruffe et al., 2016, p. 125) and hence concern the societal contribution of the dairy business. Lebacq et al. (2013) identified multi-functionality (contribution to rural employment, involvement in the rural community and ecosystem services), acceptable agricultural practices (including animal welfare and health) and quality of products (including food safety, nutrition and human health) as main themes for such *external* social sustainability. Additional themes within the social dimension are cultural heritage (Chen and Holden 2017) and antibiotics use (Burman et al., 2021). In the dairy farm context, cultural values are included as part of landscape features and antibiotics use is mainly considered an issue of animal health and welfare, but could also be considered a human health issue.

The ‘human capital and education’ theme has the sub-themes general education level, specific agricultural training and knowledge accumulation through demographic viability. Education (general or specific), is a commonly measured indicator for dairy farms. FADN contains data on agricultural training and farm manager age, while LISA records age and level, years and specialisation in education for individuals. The SFA survey contains information on share of the workforce below 30 and over 60 years old and, in addition, whether a generational change is expected within the coming three years. This can be used for constructing indicators relating to demographic viability.

The ‘working conditions’ theme has the sub-themes wages, gender balance and labour accidents. Data on wages and social fees are provided in FADN, but there is need for additional data on reference wages for the indicator to be defined as in Ehrmann and Kleinhanss (2008). In RAMS, an individual’s gender can be connected to firm/employment site. Payments for work-related injuries and rehabilitation are listed in LISA, but not the actual incidence of injuries at farm level. LISA and FES also contain data for other indicators related to working conditions, e.g. social security payments, pensions, other social costs etc.

‘Quality of life’ has the sub-themes work-life balance, farm household vulnerability, isolation and succession potential. Indicators of work life balance are total workload in hours or annual working units, while weekly-unpaid labour input, as well as farm viability and off-farm employment are indicators of farm household vulnerability. FES and FADN contain data required for constructing indicators for workload and unpaid labour input and farm viability, apart from a reference wage, which must be found elsewhere. LISA contains data on primary, secondary and tertiary income source useful for determining the existence of an off-farm income. Additionally, a single-household farmer is an indicator of isolation and the presence of a successor or doubts about succession are indicators of the farm’s succession potential. LISA also contains data on civil status for individuals, including cohabitation and children of different age spans residing on the same address, which can be used to measure isolation as well as the presence of a successor within the family. Regarding succession doubts however, this indicator was based on primary data and captures subjective feelings of doubt, which are hard to measure through secondary data.

The theme ‘landscape/cultural and recreational values’ relates to aesthetic values of an open agricultural landscape, measured as presence of grazing land, pastures and meadows. TUVA contains data on field type, summer pasture and forest grazing and LPIS contains data on land type, such as wetlands and arable land (for agricultural blocks in both cases), while FADN reports pasture and meadows for individual farms. The Swedish FADN does not contain data on grazing time of animals, and for yearly share of fresh grass versus concentrates intake, FADN contains data on ruminant feed production and purchases but additional data on the share of fresh grass is needed for constructing the indicator as defined in Oudshoorn et al. (2012) .

‘Animal health and welfare’ have been measured by many different indicators, most of them which can be found in KK, such as average somatic cell count per mL milk as an indicator of mastitis incidence risk. Veterinary costs (SEK) are presented in FADN and FES, which also list additional variables useful for animal health and welfare indicators, such as costs for animal advice and control, animal care, straw and bedding. However, on farm-measures related to animal appearance, such as proportion of thin, dirty, lame cows or lesions, are not present in the inventoried secondary data.

The ‘multi-functionality and regional development’ theme has sub-themes relating to rural employment, development and livelihoods

Table 2
Themes, sub-themes, indicators, data sources and variables for social sustainability measurements[a b].

Theme	Sub-theme	Indicator (references)	Units/factor measured	Data source	Variable
Human capital and education	General education level	Higher education/diploma of farm manager (Van Passel et al., 2007)	y/n	LISA	Level, years and specialisation of education for individuals.
		Employees with education (Ryan et al., 2016)	%	LISA	
	Specific agricultural training	Agricultural training received (Hennessy et al., 2013)	y/n	FADN	Agricultural training: farm manager, practical, basic, full
	Demographic viability	Age of farm manager (Van Passel and Meul, 2012)	Years	FADN	Year of birth of farmer/manager
		Age of farm manager and closest successor (Ryan et al., 2016)	Years	LISA	Age, year of birth for individuals, children, position in firm
				SFA	Share of workforce <30 and >60, %
Working conditions	Labour accidents	Yearly fatality rate on-farm (Chen and Holden 2017)	%	–	–
		Yearly work-related injuries (Burman et al., 2021)	Relative incidence	**LISA**	Payments for work-related injuries, Swedish Kronor (SEK)
	Wages	Yearly wages for hired workers in comparison to a reference wage (Ehrmann and Kleinhanss 2008)	Currency units (CU)/year	**FADN/ FES**	Wages, social fees, SEK
				FEK	Wages and other remuneration, SEK
	Gender balance	Share male/female labour (Burman et al., 2021)	%	RAMS	Gender, individuals
				FADN	Gender, farm manager
Quality of life	Work-life balance	Yearly working hours (Burman et al., 2021)	Annual Working Hours (AWH)	FADN/ FES	Manager, hired, family, rented, labour, Annual Working Units (AWU), AWH
		Total workload (Marton et al., 2016)	Hours/week/ month/year	FADN	Paid/unpaid labour, farm household labour/hired labour, H/AWU
	Farm household vulnerability	Unpaid labour input per week (Reidla and Nurmet 2017)	CU/week	FADN	
		Farm viability[c] +off-farm income (Ryan et al., 2016)	CU/year + CU	**LISA**	Primary, secondary, tertiary source of income, Industry code (SNI)
				FADN/ FES	Wages, assets, investments, debt, SEK
				FEK	Wages, assets, investments, SEK
	Isolation	*Farmer lives alone.* (Ryan et al., 2016)	y/n	LISA	Single, with or without children, y/n
	Succession potential	*Successor on farm.* (Van Passel et al., 2007)	y/n	LISA	Children in certain age span, tenure on family farms, y/n
				SFA	Generational change within three years, y/n
		Doubt about succession (Van Passel et al., 2007)	y/n	**-**	–
Landscape, cultural and recreational values	A rich agricultural landscape	Pastures and meadows (Burman et al., 2021)	Hectares (ha)	TUVA	Field type, summer pasture, forest grazing, blocks
				LPIS	Pasture, wetlands, arable land, blocks/ha
		Grazed land. (van Calker et al., 2006)	Ha	FADN	Permanent pasture, meadows, ha
Animal welfare and health	Grazing	Yearly grazing time (Oudshoorn et al., 2012; Dolman et al., 2014)	Hours/day/cow, days/year	–	–
		Yearly share of fresh grass intake/concentrate intake (Oudshoorn et al., 2012)	%/year	**FADN**	Ruminant feed purchases and production (coarse, concentrates) SEK
	Appearance	*Thin/dirty/lame cows, lesions* (Meul et al., 2012)	%	–	–
	Risk of mastitis incidence	Yearly-weighted average bulk tank somatic cell count (BTSCC) of milk produced (Balaine et al., 2020)	Cells/millilitre (mL)	KK	Average somatic cell count, cells/mL/ Livestock Unit (LU)
	Treatments	Total and disease-specific treatment per 100 cows (Oudshoorn et al., 2012)	Amount/100 cows	KK	Disease frequency and type
	Antibiotics	Sales of antibiotics for farm animals (Burman et al., 2021)	CU (national)	KK	Treatment incidence per antimicrobial substance per milking cow and heifer, no./ herd
	Culling rate	Culled cows/year (Oudshoorn et al., 2012)	Number./year	KK	Culling, culling age, culling reason, no./ month/herd
	Veterinary costs	Yearly veterinary costs (Oudshoorn et al., 2012)	CU/year	FADN	Veterinary costs + other livestock costs, SEK
				FES	Animal advice and control, veterinary/ medicine, insemination, animal care, straw, cleaning, SEK
Multi-functionality and rural development	Rural employment opportunities	Yearly hired labour (Klootwijk et al., 2016)	H/year	FADN/ FES	Hired, rented, labour, AWU and H
	Regional development	Yearly working hours + value added + employment sites. (Burman et al., 2021)	Regional breakdown, % of total	**FADN/ FES**	Labour, AWU production, costs, SEK
				FEK	Value added, SEK
					Workplaces, number
	Rural livelihoods	Number of farmers. (Reidsma et al., 2015)	Number in a geograpical area.	FEK/ LISA	Firm/workplace location geocoded 250*250 m squares, municipality
				PPR	Production facility location, postal code
	Eco-system services	Agro-environmental measures payments (Dolman et al., 2014)	CU/ha	RDP	Support received for agri-environmental measures, SEK

(*continued on next page*)

Table 2 (*continued*)

Theme	Sub-theme	Indicator (references)	Units/factor measured	Data source	Variable
Quality of products	Nutrition	Milk nutrients content (Oudshoorn et al., 2012)	Fat, protein %	KK	Fat and protein content, %
	Food safety	Penalties for aberrant milk composition (high SCC or bacterial count) (Dolman et al., 2014)	% milk output	KK	Average somatic cell count, cells/mL/LU

[a] Indicators in *italics* indicate the indicator was measured with primary data in the reference literature. Secondary data sources in **bold** indicate that the data source is temporary and/or requires additional data to measure the indicator.
[b] LISA - Longitudinal integrated database for health insurance and labour market studies, FADN-Farm Accountancy Data Network, FES - Farm Economic Survey, SFA- Sweden Food Arena, RAMS - Labour statistics based on administrative sources, TUVA - National Inventory of Meadows and Pastures, FEK - Structural Business statistics, KK - milk recording schemes, RDP – Support payments for Rural Development. See section 2.2 and appendix for full description of the data sources.
[c] See indicator definition in Table 3 in theme "Farm viability".

and ecosystem services. Data on hired labour, value added and employment sites can be found in FADN, FES and FEK. Number of farmers in an area has been used previously as an indicator of contribution to rural livelihoods and potential to network and cooperate with others. Data required for construction of this indicator are present in FEK and LISA at municipality level and geocoded by 250*250 m squares, or in PPR at postal code level. Subsidies received for agro-environmental measures, as an indicator of ecosystem services, are listed in RDP.

'Quality of products' relating to sub-themes of nutrition and food safety have previously been measured using information on milk nutrient content and the presence of penalties for aberrant milk consumption. Data on fat and protein content in milk, as well as somatic cell count, which can be used to evaluate food safety (equivalent to penalties for aberrant milk consumption according to Kelly et al. (2018a)) is available in KK.

3.3. Indicators and data for measuring economic sustainability

The economic dimension of sustainability is commonly assessed as production of goods and services, measured through indicators reflecting annual farm profitability and productivity (Meul et al., 2012; Lehtonen 2015; Mosnier et al., 2017). Productivity in use of production factors, i.e. natural, human and animal resources, is a measure of efficiency (Dillon et al., 2016). Following the notion of strong sustainability defined by (Ayres et al., 2001) we chose the term efficient use of resources rather than productivity (Table 3, column 1). Economic viability of a dairy farm is defined as the ability to balance expenditures and revenues so that a business can be sustained and grow (Barnes et al., 2015; Wilczyński and Kołoszycz 2021). The National Food Strategy defines economic sustainability of Swedish agriculture as its competitiveness, measured as the level of productivity and value added (Burman et al., 2021), while other studies use different measures for competitiveness, for example related to innovation and market orientation (Hennessy et al., 2013) or investment (Ehrmann 2008).[4] Three additional themes to measure economic sustainability at farm level are: 1) Farm autonomy, with regard to external financing most notably subsidies but also inputs of fertiliser or feed concentrates; 2) diversification of income, through off-farm income, non-food production income, other production etc.; and 3) farm durability, measured with indicators relating to succession and economic transmissibility (Lebacq et al., 2013). Economic transmissibility is here included in the economic viability theme. Other durability issues, such as demographic viability and succession potential, are included in the social sustainability dimension (section 3.2). To avoid redundancy, they are not included again here.

The 'profitability' theme has sub-themes of yields, farm gross income and market-based profits. Data to construct indicators for these, e.g. total production, output (including all sales and use, other gainful activities, change in stocks and valuation) and expenses are listed in farm accounts (FADN, FES). Total and average yield per herd, animal and year can be found in KK.

'Efficient use of resources' relates to use of factors such as land, labour, capital and animals in production. Profitability data and other data (total farmed area, number of dairy cows, balance of all subsidies and taxes, depreciation, annual labour requirements) needed to construct such indicators are generally available in FADN and FES. FEK has some similar data but variables based on currency units (CU) which are not suitable for constructing indicators based on hectares farmed or quantity produced.

'Farm viability', defined here as dairy farm survival and growth ability, has previously been measured as the capacity to remunerate all labour units above a certain threshold (e.g. average or minimum national, regional or agricultural wage) and provide an additional minimum investable return on non-land assets. Useful variables for these indicators, such as net farm income and non-land assets, are listed in FADN and FEK, but FEK makes no specification on land assets. In both cases, additional data are needed to construct the remuneration threshold.

'Competitiveness' has the sub-themes value added, innovation, investment and market orientation. Data on value added are available in FADN and FEK, but data on agricultural land for value added per hectare are only available in FADN. For innovation, data on milk recording program participation is present in KK, but membership in dairy discussion group is not. Investment data in currency units are available in both FADN and FEK. Data on subsidies, needed to construct indicators on market orientation such as share of market-based income, are available in FADN/FES and RDP, but RDP does not include product-related payments such as national milk support payments.

'Autonomy' includes the sub-themes financial stress, financial resilience and solvency, all measured with indicators constructed from data on debts and subsidies. Data on debts are available in FEK and FADN, but data on subsidies are mostly covered in FADN/FES.

The 'Income diversification' theme can be related to off-farm employment and on-farm income diversification. Both LISA and FADN/FES contain data on variables needed to measure alternative income sources for dairy farms, but the Swedish FADN only contain variables for non-production activities on the farm, such as renting out machines, while LISA contain information on primary, secondary and tertiary income source by industry (SNI) code, which can determine the presence (but not the level or value) of off-farm employment. Incomes from other employment outside the farm is hence not listed in any of the secondary data sources. Income from other production than milk on the farm such as crops, beef or other sales can be measured through non-dairy sales data in FADN.

3.4. Gap analysis and critical assessment

Table 4 shows indicators with missing scope in Swedish secondary data, only temporary existing data or indicators that require additional data for its construction. In total 20 indicators out of which 9 in the

[4] see e.g. Cele et al. (2021) for an economic definition of dairy competitiveness.

Table 3
Themes, sub-themes, indicators, units, data sources and variables for economic sustainability measurements[a b].

Theme	Sub-themes	Indicator (references)	Units	Data source	Variable (units)
Profitability	Yields	Total/average milk yield per farm & year (Marton et al., 2016; Mosnier et al., 2017)	Litre (L)/farm/year	KK	Average yield (Kilo Energy Corrected Milk (kg ECM) per cow/herd/year)
				FADN/FES	Milk production (Decitonne (dt)[c])
	Farm gross income	Gross output + subsidies (Dillon et al., 2010)	Currency unit (CU)/farm		Output, subsidies, costs, wages (Swedish Kronor (SEK))
	Market Profits	Market-based gross margin per hectare (Ryan et al., 2016; Hennessy et al., 2013)	CU/hectare (ha)		Milk/other sales, intermediate consumption (SEK) Farmed area (ha/ares[d])
Efficient use of resources	Productivity of land	Output value per hectare (Ryan et al., 2016)	CU/ha		Total output, balance all subsidies and taxes, costs, depreciation, yearly paid/unpaid working units (SEK, AWU)
	Productivity of labour	Farm income per paid/unpaid labour unit (Dillon et al., 2016)	CU/Annual Working Units (AWU), paid/Unpaid	**FEK**	Operating profit/loss, employees (SEK, AWU)
		Milk production per labour input (Meul et al., 2012)	Kg-L/AWU	FADN/FES	Milk production, family, permanent, temporary labour (dt, AWU)
	Capital productivity	Value added per total capital (Meul et al., 2012)	CU	FADN	Farm net value added, assets, (SEK)
				FEK	Value added, assets, debt, (SEK)
	Productivity of dairy cows	Output quantity per livestock unit (Barnes and Thomson, 2014)	Kg/Livestock Unit (LU)	FADN/FES	Milk production, milking cows (dt, LU)
				KK	Average yield per dairy cow (kg ECM)
Farm viability	Survival and growth ability	Farm net income > average wage per AWU (Dillon et al., 2010)	CU/AWU	**FADN/FES**	Farm net income, labour input (SEK, AWU)
		+ minimum 5% return on non-land assets (Ryan et al., 2016, Wilczyński and Kołoszycz, 2021	CU	FADN/FES	Farm net income, land, permanent crops and quota-assets (SEK)
Competitive-ness	Value added	Output value - total costs per hectare (Ehrmann 2008)	CU/ha Used Agricultural Area (UAA)	FADN	Output, costs, agricultural land (SEK, ha/ares)
				FEK	Value added, assets (SEK)
		Milk recording programme participation (Hennessy et al., 2013)	y/n	KK	All cows in KK are included in milk recording scheme, with production place
		Membership of dairy discussion group (Hennessy et al., 2013)	y/n	–	–
	Investment	Net investments (Ehrmann 2008)	% of profits	FADN/FES FEK	Net investments (SEK)
	Market orientation	Share of output derived from market rather than subsidies (Hennessy et al., 2013)	CU, %	**FEK**	Net turnover (SEK)
				RDP	Single farm payments, regional development payments (SEK)
				FADN/FES	Output, subsidies (SEK)
Autonomy	Financial stress	Total debt as share of income (Barnes and Thomson, 2014)	CU, %	FADN/FES	Farm net income, debt (SEK)
				FEK	Operating profit/loss, long-term/short-term debt (SEK)
	Financial resilience	Subsidies to farm gross margin (Barnes and Thomson, 2014)	CU, %	FADN/FES	Milk/other sales, other gainful activity (OGA), subsidies, intermediate, consumption (SEK)
				RDP	Single farm payments, regional development payments, SEK
	Solvency	Share of own capital/total capital (Van Passel et al., 2007)	CU, %	FADN/FES	Own capital, total capital (SEK)
				FEK	Own capital, debt[e] (SEK)
Income diversification	Off-farm employment	Farm households where famer and/or spouse have other employment (Ryan et al., 2016; Hennessy et al., 2013)	y/n	LISA	Primary, secondary, tertiary source of income, industry of farm manager if own firm (SNI code)
	On-farm income diversification	Income from crop production/beef production/other production (Marton et al., 2016)	CU, %	FADN	Crop sales, other sales (SEK)

[a] Indicators in *italics* indicate the indicator was measured with primary data in the reference literature. Secondary data sources in **bold** indicate that the data source is temporary and/or requires additional data to measure the indicator.
[b] LISA - Longitudinal integrated database for health insurance and labour market studies, FADN-Farm Accountancy Data Network, FES - Farm Economic Survey, SFA- Sweden Food Arena, FEK - Structural Business statistics, KK - milk recording schemes, RDP – Support payments for Rural Development. See section 2.2 and appendix for full description of the data sources.
[c] 1 dt = 100 kg.
[d] I hectare = 100 ares.
[e] In FEK total capital is defined as own capital + debt.

environmental dimension, 9 in the social dimension and 2 in the economic dimension exhibited such measurement issues.

Within the *environmental dimension*, available secondary data do not cover five indicators (eutrophication potential in NO_3-eq/FPCM, acidification potential in g SO_2-eq/kg FPCM/ha, yearly emissions in CO_2-eq, number of plant species per hectare and soil organic matter) at farm level, while indicators for pesticides and non-renewable energy need additional data for construction. Within the environmental themes “nutrient flows”, “climate impact” and “biodiversity”, there are alternative indicators which can be measured through available secondary data, but within the themes ‘pesticides’, ‘non-renewable resources’ and ‘soil quality’, all indicators have measurement issues.

Table 4
Indicators with measurement issues[a] when using secondary data.

	Environmental	Social	Economic
Missing scope	Eutrophication potential	Yearly fatality rate on farm	Membership of dairy discussion group
	Acidification potential	Doubt about succession	
	Yearly emissions of CO_2-equivalents	Yearly grazing time	
	No. of plant species per hectare pasture	Thin/dirty/lame cows, lesions	
	Soil organic matter		
Requires additional data/ temporary data source	Yearly PPP use	Yearly work-related injuries	Viability: Farm net income covers average agricultural wage
	Yearly irrigation/ water use	Yearly wages for hired workers in comparison to a reference wage	
	Non-renewable energy use	Farm viability + off-farm income	
	Energy use efficiency	Yearly share of fresh grass intake/ concentrate intake	
		Regional development indicator	

[a] Measurement issues means we have at least 1 of 3 of the following issues: 1) Missing scope meaning that secondary sources does not cover the data needed for indicator construction at all, 2) additional data requirements implies that there is some data, but there is need for additional data such as a unit conversion factor, 3) temporary data meaning that the data is not longitudinal. See further section 2.4.

Within the *social dimension*, secondary data at farm level are missing for four indicators (fatality rates, doubt about succession, grazing days and thin/dirty/lame/injured cows). Indicators on work-related injuries, wages in comparison to reference wage, farm viability + off-farm income, yearly share of fresh grass intake/concentrate intake and regional development indicators need additional data, although for the wage and viability indicator the required reference wage should be easily attained from another source. However, all seven themes of social sustainability can be measured using other indicators for which data from different sources are available.

In the *economic dimension*, indicators within all themes can be measured using secondary data. We only identified a gap for one specific indicator of innovation (Hennessy et al., 2013): membership of dairy development group. However, as above, to construct a reference wage to measure viability (see e.g. Ryan et al., 2016), additional data on average (national, regional or agricultural) wages are needed.

Table 5 reports indicators that were identified with issues regarding the comprehensibility and analytical validity in the critical assessment. In total 16 indicators out of which 6 in the environmental dimension, 6 in the social dimension and 4 in the economic dimension exhibited such issues.

Within the *environmental* dimension significant differences between studies, countries and data sources in the definition of grasslands, and grazing complicates the interpretation (Beardmore et al., 2019). The indicators therefore have issues with comprehensibility when used to measure environmental benefits such as carbon sequestration and biodiversity. Furthermore, for biodiversity appropriate indicators should reflect occurrence of long-term degradation, fragmentation and loss of habitats, invasive species and viable populations of native organisms. The indicators counting single areas or species today merely provide a snapshot of current diversity, which rather reflects activities

Table 5
Indicators with issues of comprehensibility and analytical validity.[a].

	Environmental	Social	Economic
Comprehensibility	Grasslands, meadows	Farmer lives alone.	Milk recording programme participation
	Permanent to temporary grass area	Sales of antibiotics for farm animals	Membership of dairy discussion group
	Rough grazing area to total area	Culled cows/ year	
		Yearly veterinary costs	
		Number of farmers	
Analytical validity	Yearly irrigation/ water use	Successor on farm.	Total/average milk yield per farm & year
	Amount and area of biotopes with nature value		Gross output + subsidies
	No. of plant species per hectare pasture		

[a] Issues of comprehensibility implies a lack of transparency, i. e that the meaning of an indicator is not easy to seize, unclear, overly technical and/or ambiguous (Sauvenier et al., 2005; Niemeijer and de Groot 2008; Lebacq et al., 2013). Issues of analytical validity implies that there is not an obvious and well-defined relationship between the indicator and the monitoring phenomena and/or the indicator heavily depends on unmeasured factors (Meul et al., 2008; Bonisoli et al., 2018).

taking place 5–20 years ago.[5] Hence, indicators are depending on external factors and thereby exhibit issues related to analytical validity. Additionally, the analytical validity of irrigation as an indicator for sustainable water management can be questioned as it depends heavily on whether there is local water scarcity or not.

In the *social dimension*, several indicators were found to be somewhat ambiguous or vague. The fact that the farmer lives alone may be self-selected or not and therefore only ambiguously indicate isolation. Low antibiotics sales and veterinary costs could theoretically reflect either low disease occurrence or low animal welfare (in that veterinary is not appointed or antibiotics are not given) and culling may be due to several reasons that are positive or negative for animal welfare. The number of farmers as an indicator for rural livelihoods is quite vague, especially if the indicator is not measured in relation to the total population in the geographical area. Even when referring to cooperation opportunities, the relationship to livelihoods may as well be negatively affected if the presence of more farmers lead to competition rather than cooperation. Finally, while the confirmed presence of a successor on the farm indicates that a farm has succession potential, the absence of a successor on the farm does not necessarily indicate no successor, as the farm may as well be sold to an external successor.

The *economic dimension* has few problems with indicator comprehensibility in this regard, although participation in a milk-recording programme as well as membership of dairy discussion group, however clearly connected to innovation practices in an individual case are too vague to indicate innovation for the general case. Profitability indicators focusing on gross output and gross incomes of the farm ignores that the effect on profitability will be heavily influenced by the costs induced, and therefore exhibits issues of analytical validity.

Table 6 summarises themes with issues connected to measurement, comprehensibility or analytical validity within each dimension of sustainability. Underlined themes have identified measurement issues relating to scope, additional data requirements or temporary data and themes in italics have issues connected to the comprehensibility or

[5] Personal communication, Åsa Berggren, 11 November 2021.

Table 6
Themes with identified indicator issues.[a]

Environmental	Social	Economic
Nutrient flows	Human capital and education	*Profitability*
Pesticides	Working conditions	Efficient use of resources
Non-renewable resources	*Quality of life*	Farm viability
Land and ecosystem use and management	Landscape, cultural and recreational values	*Competitiveness*
Climate impact	*Animal health and welfare*	Autonomy
Biodiversity	*Multi-functionality and rural development*	Diversification
Soil quality	Quality of products	

[a] The underlined sustainability themes include some indicators with measurement issues in terms of missing scope, additional data requirements and/or temporary data. The themes in italics have issues connected to the comprehensibility or analytical validity of the indicators.

analytical validity of the indicators.

Table 6 shows that the majority of the themes, 6 of 7 within the environmental dimension, 4 of 7 within the social dimension and 3 of 6 within the economic dimension, exhibit some sort of issue with measurability, comprehensibility and/or analytical validity of indicators, which in extension will affect the results of a sustainability assessment using these indicators. Trade-offs between data availability and comprehensibility can be identified, for example in the climate impact theme, for which one indicator (Yearly emissions of CO2-eq) is not covered in scope by the data and the other (Permanent to temporary grass area) exhibit issues of comprehensibility.

4. Discussion and conclusions

This study assessed the critical role of data in indicator construction and consequences of secondary data availability on farm-level sustainability assessment. The analysis primarily focused on identifying indicators that can be measured and indicators that have measurement issues by matching themes, sub-themes and indicators against available secondary data, using the case of Swedish dairy farming as an example. In this way, we could identify consequences of current secondary data availability for constructing indicators of environmental, social and economic dimensions in data-driven sustainability assessment at farm level in our case study area. Furthermore, indicators previously used in farm level sustainability assessments were critically evaluated in terms of comprehensibility and analytical validity. Indicators identified from the literature ($n = 69$) were categorized into 55 sub-themes and 20 themes and matched with Swedish secondary source data. Gap analysis of the Swedish data sources and critical assessment of the indicators then identified issues of measurement, comprehensibility and analytical validity within 13 of these 20 themes. While the presence of a measurement issue means that a particular indicator cannot be *directly* derived from currently available secondary data sources in the Swedish case, the presence of comprehensibility and analytical validity issues raise more general concerns regarding the use of secondary data for sustainability indicator construction. Issues as the ones described in this study will inevitably have an effect on sustainability assessment results and potentially cause serious problems for the explanatory power of the analysis. This has consequences both for efficient farm-level sustainability analysis as well as for rigorous policy impact evaluation, which typically has to be based on appropriate longitudinal data like most of the data included in our analysis.

In the *environmental* dimension, there were clear measurement issues for some indicators within the climate impact and biodiversity themes, and for the pesticides, non-renewable resources and soil quality themes, *all* indicators identified had measurement issues. For example, in Sweden it is currently not possible to directly observe CO_2 emissions at farm level from any of the secondary data sources in the inventory, in contrary to other countries (for example Teagasc National Farm Survey in Ireland, see e.g. Ryan et al., 2016). Another example is the use of non-renewable versus renewable energy, which is not specified at the farm level in any of the data sources. Even though there is data on fuel expenses and energy taxes per fuel type, this is still not sufficient to construct an indicator on the share of non-renewable energy. Very site specific measures such as soil quality are generally hard to measure through secondary data.

Within the *social* sustainability dimension, there were measurement issues for individual indicators within four themes (working conditions, quality of life, animal health and welfare; multi-functionality and rural development), but it was still possible to construct at least one indicator for all themes from the secondary data sources inventoried. Thus, the plurality of indicators within the social dimension is beneficial with regard to data availability. However, secondary data sources will not be as precise as primary sources in measuring subjective indicators such as the appearance of animals or the farmer's psycho-social state such as his/her doubt about succession. For assessment of such aspects, secondary data may therefore not be an appropriate data source.

In the *economic* dimension, there were measurement issues for the sub-themes innovation and financial viability within the farm viability and competitiveness themes, but other measurable indicators compensated for this. For example, instead of measuring farm competitiveness through innovation, indicators to measure investment, value added and market orientation can be used (Ehrmann 2008; Hennessy et al., 2013). It is clearly an advantage for indicators in the economic dimension that many of the data sources in the inventory where based on administrative data expressed in currency units since this is how economic indicators from the literature have been measured.

We selected data sources based on an inventory of available secondary micro-level data and recommendations from experts on dairy farming and sustainability. Our selection of data sources was based on an inventory of available secondary micro-level data, as well as recommendations from experts in dairy farming and sustainability. We included data sources in the inventory that we and the expert group were knowledgeable and were able to obtain sufficient information about, regarding the unit of analysis, population, and sample at the time of the research. While there is a slight risk of relevant data sources being inadvertently omitted from the inventory, we believe this is relatively unlikely. We believe that the inventory covers all major relevant data sources for Sweden, that meet the requirements specified in section 2.2. Additional data sources could however be added in the future, for example digital maps, in particular as a basis for biodiversity and soil quality indicators could be considered (see e.g. (Piikki and Söderström 2019; Aguilera et al., 2020). In addition, there are initiatives developed by the industry, such as the Green Industry Index (variables related to farmer expectations, willingness to expand/diminish) and Lantbruksbarometern (data on experienced profitability, investment plans and general satisfaction) and other sources, which are interesting additional data sources for Sweden. However, for these sources we could not have access to information regarding population, sampling and availability of underlying data and they where therefore not included in this analysis. Additionally, the data sources included the inventory should be further explored in terms of indicator construction, for example, FES and LISA contain data on social security payments and pensions while RDP includes data on a range of subsidies received for farm measures with connection to sustainability. In summary, the Swedish dairy case shows that data availability is generally good, but there are still some significant data gaps and measurement issues with important implications for sustainability assessment results. Those should be remedied for assessments to provide a more adequate measurement of sustainability progress.

In the critical assessment, we identified challenges for sustainability indicator construction based on secondary data sources, relevant for the broader discussion on sustainability measurement. The indicators in this study were collected from international assessments of livestock and dairy farms, in which they were presumably selected based on data availability and on relevance in the specific study context. While this have resulted in convenient and measurable indicators, several of the indicators exhibit issues of comprehensibility or analytical validity, which means they are not easily interpretable in sustainability terms, nor are they robust to changes in external factors. Such indicators may therefore even be misleading in a general context, but are nevertheless used. Assuming that available data to measure indicators without these issues would have led to other indicators being used, we identify a trade-off between data availability and the comprehensibility and analytical validity of indicators. As described in section 3.4 in the case of the climate impact theme, the presence of a trade-off between data availability and comprehensibility implies that a choice must be made between not to measure climate impact at all, or using an indicator with limited comprehensibility. Since the vast majority of the indicators analysed in this paper were derived from secondary data sources, some use of such flawed indicators, as well as the recurrent use of limited, one-dimensional or single indicator approaches to sustainability assessments, may very well be a consequence of the current data availability.

Furthermore, and of relevance for the broader discussion on sustainability measurement, the aggregation level or unit of analysis is an important determinant for data availability and measurability of indicators. For assessments at farm level, aggregated national and regional data on e.g. greenhouse gas emissions, soil quality inventories or biodiversity indices are too general for measurement of individual farm activities, for microeconomic impact assessment, and for supporting sustainable actions at the farm. Data for units of analysis other than the farm are hence only relevant if they can be connected to and analysed at farm level. Detailed and transparent information are therefore of importance when constructing indicators. For example, the units of measurement of indicators are often overlooked but are shown here to have meaningful implications for measurability. For dairy farm assessment, indicators are typically expressed in quantities, per hectare of land used, kg milk output or annual working units. If data are not available in suitable units, a conversion factor or additional data will be needed, which may be time- and resource-demanding and may compromise the accuracy of results. Units in a data source depend on the purpose of data collection; when reporting economic data (for firms in FEK and farms in FADN), many variables are in currency units and economic indicators are therefore more easily defined than indicators specified in other units, such as in per hectare terms in the environmental dimension. Finally, if a sustainability assessment aims to evaluate progress towards sustainable production over time, longitudinal data are needed to construct indicators. Data for a single point in time (e.g. SFA survey data on innovation, succession and cooperation in primary production) are unsuitable for this purpose.

Several issues identified in this paper highlights potential and scope for further research. First, the result of the data inventory highlights national availability of data with a broad scope that can be used for constructing many sustainability indicators, but that no single data source cover all relevant sustainability themes in our case study. Rather, 13 different sources contain the data to construct, without significant issues, indicators within 17 out of 20 essential sustainability themes for dairy farming. A holistic assessment of sustainability at farm level using secondary longitudinal data will therefore require that data from different sources can be merged at the farm level to analyse a larger set of indicators simultaneously. To enable such an exercise, careful attention need to be paid to the unit of analysis; population and sample of the different data sets (see Appendix for information on the data sources considered here). While this may be a very challenging task with data sources as diverse in scope as the ones in our example, it is technically possible with the use of a farm level identifier. A methodological example of how samples, censuses and register data can be combined can be found in Kish and Verma (1986). Practical examples using merged combinations of the data sources in our inventory include Nilsson et al. (2022) and Owusu-Sekyere et al. (2023). However, since we ourselves have not attempted a merging exercise in practice in this paper, we remain unaware of further challenges that may arise. This also provides important implications for data collection agencies, which should consider the need for merging datasets in the data collection design.

Second, the above consideration as well as the argument that the current availability of secondary data limits the construction of sustainability indicators, requires a discussion on the definition of data availability, when a data source can be considered available, and to which extent detailed data can be made available without compromising the integrity of individuals. While this paper considers open source data, data available upon request as well as data with some legally restricted access, the access to data can be restricted or limited in many other ways than legally, such as lack of knowledge, experience, contacts, or time to clean and compile raw data. Such a discussion is crucial for improving the conditions for data-driven sustainability assessment at the farm-level in the future.

Finally, no data source in our inventory was originally designed to assess farm-level sustainability. Data-driven assessments, in Sweden and internationally, currently rely on data collected for administrative or other purposes and the technical and practical capacity to combine different data that, almost by chance, will be able to say something meaningful about the sustainability performance of farms. With the increasing importance of sustainability monitoring in society and in agriculture, this situation should be forced to change. Previous projects such as the FLINT project from Wagenigen University and Research (2017) have highlighted specific needs for an extended data collection on sustainability aspects at farm level. The need to improve sustainability assessments at farm level is recognised at both national and EU level and initiatives to develop such data will create new and improved possibilities in terms of indicator based sustainability assessments (e.g. Farm Sustainability Data Network (FSDN) and the Swedish national infrastructure for data sharing in agriculture (Agronod)). These initiatives will also raise new questions regarding financing, openness, personal integrity and independence.

In conclusion, our results highlight that while many different sources of secondary data may be available, gaps and measurement issues still can limit construction of sustainability indicators from these data, in our case this is particularly evident within the environmental dimension. Additionally, we identify trade-offs between data availability and the comprehensibility and analytical validity of indicators. Furthermore, currently no single data source can be used to measure all relevant sustainability themes needed for farm-level sustainability analysis. This leads to problems in assessing some indicators and current availability of secondary data hence risk the use of flawed indicators. Another potential consequence is that the scope of assessments is limited to single indicators, which fail to appropriately grasp the complexity of the sustainability concept. For holistic sustainability assessments to track progress in the food system and inform policy, directing efforts towards sustainable actions, indicators are crucial and longitudinal secondary data are needed to measure indicators over time. Available secondary longitudinal data may however not be able to cover the broad data needs of sustainability assessment, as illustrated by the example of Swedish dairy farms in this paper, and other data sources such as field experiments or interviews may be needed for completion. Future programmes collecting sustainability data at farm level should consider these data needs as well as the capacity to merge several different data sets to create a comprehensive basis for holistic sustainability assessments.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

Acknowledgements

We would like to express our gratitude to the group of dairy sustainability experts who contributed with their valuable time and comments for this paper; Pernilla Tidåker from the department of energy and technology, Karin Alvåsen from the department of clinical science, Sigrid Agenäs from the department of animal nutrition and management, Peter Lundkvist from the department of work science, Helena Nordström-Källström at the department of urban and rural development, Åsa Berggren at the department of ecology and Pia Nilsson at the department of economics, all at the Swedish University of Agricultural Sciences, as well as Serina Ahlgren from RISE- Research Institutes of Sweden. The work is part of Mistra Food Futures (DIA 2018/24 #8); a research program funded by Mistra (The Swedish foundation for strategic environmental research). Funding is gratefully acknowledged. The funding source had no involvement in the study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2023.100258.

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