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Research article

Sustainability assessment of farms using SALCAsustain methodology

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ABSTRACT

In recent decades, many sustainability indicators and methods have been developed at farm level, but a validated set of quantitative and scientifically-sound indicators covering all three dimensions of sustainability is still needed. For this reason, the sustainability method SALCAsustain was developed in order to estimate the environmental impact and economic and social situation of farms using a manageable number of indicators. The primary aim of this study was to assess the feasibility, explanatory power, and acceptability to farmers of the SALCAsustain methodical framework. To achieve this goal, SALCAsustain was applied for the first time to selected Swiss farms. In-depth personal feedback interviews were conducted to gain more insights into the feasibility and farmers' acceptance of the method. The results showed that SALCAsustain is a feasible, acceptable and robust method for assessing farm sustainability based on a set of indicators. Correlation analysis demonstrated that the number of environmental indicators can be reduced due to high correlation, but that the correlation between environmental impact and socioeconomic indicators was generally low. Evaluation of responses to questionnaires and semi-structured interviews with farmers revealed that the majority would adjust their medium and long-term planning to achieve higher sustainability scores. Additional efforts are needed to speed up data collection and to refine plausibility checks, through exploiting the increasing digitalisation in agriculture. Recommendations and instructions on actions for more sustainable farm management are also needed.

1. Introduction

Agricultural production significantly impacts the environment through the release of greenhouse gases, nitrate leaching, residues from application of pesticides and manure, and use of natural resources such as land, water, non-renewable energy (fossil fuels) and minerals (phosphorus, potassium) (Nemecek et al., 2011; IPCC, 2013). Intensive agriculture is also responsible for a crucial loss of biodiversity, leading to profound negative changes in the functioning of agroecosystems (Emmerson et al., 2016). The significant pressure of agriculture on the natural environment can be assessed using the concept of planetary boundaries, the boundaries of a safe operating space for Earth system processes (Rockström et al., 2009; Campbell et al., 2017).

In the past few decades, it has become generally accepted that economic and social sustainability must also be included when considering the long-term sustainability of farming systems (Riley, 2001; Sadok et al., 2009; Purvis et al., 2019). This implies that sustainable farms should be environmentally sound, economically feasible and socially acceptable (Rasul and Thapa, 2004). The explicitly equal status of the three sustainability dimensions (environmental, economic and social) was first suggested in the 'Triple Bottom Line' concept formulated by Elkington (1999), which postulates that sufficient sustainability can only be achieved in one dimension when a minimum level of sustainability is reached in the other two dimensions (McKenzie, 2004). Today, the three-pillar model of sustainability is widely applied in the agricultural sphere (Krishnaveni and Nandagopal, 2018). Nevertheless, the majority of tools and methods focus on the environmental impacts, largely ignoring economic and social sustainability, which results in an imbalance between the three dimensions of sustainability (Finkbeiner et al., 2010). Looking more closely at existing sustainability approaches reveals a lack of indicator sets that are as quantitative as possible and targeted to national conditions. In order to fill this gap, we developed an indicator-based sustainability method called SALCAsustain (Roesch et al., 2017). The method is especially adapted for holistic sustainability assessment of Swiss farms using indicators that are reproducible, scientifically-based and as quantitative as possible.

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In this study, we apply SALCAsustain for the first time to a small sample of Swiss farms belonging to the IP-SUISSE federation of farmers, the aim of which is to produce in an environmentally sound manner according to integrated production (IP) standards. The primary aim was to assess the entire SALCAsustain methodical framework for its feasibility, acceptability to farmers and informative value. The evaluation considered all steps necessary for holistic farm sustainability assessment, such as data acquisition, selection of calculation methods, statistical analyses and communication of the results to the farmer. Data acquisition using Excel data entry forms and calculation of all sustainability indicators were tested in this study. This allowed us to evaluate the entire process, including subjects such as the time needed for data collection on both the farmers' side and the analysts' side.

There were two main objectives of the study: i) to analyse the informative value of sustainability indicators, including synergies and trade-offs between indicators, and ii) to evaluate the feasibility and acceptability to farmers of the SALCAsustain method, based on a comprehensive questionnaire and personal interviews with farm managers. Selected Swiss farms were used to illustrate application of the method and the tool. The results were then used to formulate recommendations for improvement in order to simplify and accelerate the entire process from data-gathering to graphical representation of the results.

The remainder of this paper is structured as follows: Section 2 reviews the relevant literature, Section 3 describes the sustainability indicators and the procedure used for data acquisition, the semi-structured interviews with farm managers and the structure of the pilot farms. Section 4 summarises the main results, which are discussed in Section 5. Some conclusions are presented in Section 6.

2. Literature review

During the past two decades, many different approaches have been developed for assessing overall sustainability (Singh et al., 2009; Schader et al., 2014; De Olde et al., 2016). Most sustainability methods are structured across the three sustainability dimensions (environmental, economic, social). The challenge is to select an appropriate set of indicators based on existing assessment methods (Lebacq et al., 2013). Therefore, several authors have developed guidelines for this purpose (Marchand et al., 2014; Bockstaller et al., 2008; Sala et al., 2015). Essential steps for developing a suitable sustainability framework include identifying the end-users (scientists, advisors, farmers, decision makers, consumers) and determining the practical objectives. The latter can be, for example, acquiring knowledge about a system or selecting the 'best' system or communicating complex information in a simple and easily understandable way (Sadok et al., 2008; Bockstaller et al., 2015).

Several classification schemes for comparing existing sustainability methods are suggested in the literature. Gasparatos and Scolobig (2012) classify sustainability tools into monetary tools, biophysical tools and indicator-based tools. Monetary tools rely on the subjective preferences of individuals, often expressed by one's willingness to pay (Gasparatos and Scolobig, 2012). They suffer from the fact that they are preference-based and rely on models of human behaviour.

Use of indicators is a broadly accepted concept for assessing the sustainability of farms based on a conceptual framework (Bockstaller et al., 2015). An indicator is defined as "a variable which supplies information on other variables which are difficult to access and can be used as a benchmark to make a decision" (Lebacq et al., 2013). The use of indicators is required because environmental impacts cannot be directly measured or the system's complexity, such as biodiversity or soil quality, is too high (Bockstaller et al., 2015). Indicators simplify and quantify information so that it can be easily communicated and intuitively understood, allowing policy-makers and decision-makers to base their decisions on evidence (Layke, 2009). Numerous indicator-based sustainability approaches have been developed in the past few decades. However, only a limited number assess all three dimensions of sustainability at the single farm level (Schader et al., 2014; De Olde et al., 2016). Quite a few of the existing approaches can only be used for a specific branch, such as dairy (DairySAT) (England and White, 2009) or coffee and cocoa (COSA) (Giovannucci et al., 2008). Some of the methods that deal with overall sustainability at farm level use a system of rather simplistic indicators. The French IDEA method (Indicateurs de Durabilité des Exploitations Agricoles or Farm Sustainability Indicators) is based on 41 indicators of a multi-criterion character that have to be adapted to local farming before use (Zahm et al., 2008, 2018). Meul et al. (2008) developed the multilevel indicator-based Monitoring Tool for Integrated Farm Sustainability (MOTIFS), which provides a visual overview of farm sustainability, but also allows zoom-in to learn more about specific themes. Three methods, Response-Inducing Sustainabilty Evaluation (RISE) (Grenz et al., 2012), Sustainability Monitoring and Assessment RouTine (SMART) (Schader et al., 2014) and SALCAsustain, cover sustainability comprehensively, and concrete measures for improvement and decision-making can be derived for relevant interest groups from the results. The strength of RISE is its flexible applicability that allows its use in advisory work and teaching. SMART enables rapid screening of farm sustainability and provides results that also allow for inter-farm comparisons that can easily be communicated to third parties. SALCAsustain is more complex and is particularly suitable for answering research queries and for analysing different farm management strategies. In the present study, the SALCAsustain method was verified by applying it for the first time to some typical Swiss farms.

The scope of current sustainability assessment methods differs widely. Schader et al. (2014) developed a typology for characterising sustainability methods by defining a set of criteria, including the level of assessment, geographical scope and the primary purpose. Those authors claim that the goal of the study largely determines the appropriate tool, but that the workload in data acquisition and the required precision of the indicator values also have to be carefully evaluated when choosing the most suitable tool. However, Gasparatos and Scolobig (2012) point out that tool selection is generally done by the analyst and usually depends on time, data and financial constraints, whereas the quality of the indicators and the context of the study are often not taken into account in decision-making. Sophisticated sustainability assessment tools often require a large amount of input data, leading to a potentially significant time commitment from farmers. It is therefore important to critically assess participating farmers' acceptance of the tool. Nevertheless, Whitehead et al. (2020) claim that most studies on sustainability tools focus on the development phase, while less attention is paid to how the tool might be successfully implemented. Triste et al. (2014) show that adoption of a sustainability tool by farmers and farm advisors can be challenging for various reasons, but suggest that tool adoption can be substantially improved through early involvement of stakeholders and end-users and a well-prepared introduction to appropriate tool use. Van Messel et al. (2011) found that participatory processes positively influence success in practical use of a tool. De Mey et al. (2011) concluded that individual discussions between farmers, advisors and model developers are crucial for successful tool implementation. The present study gives a first insight into acceptance of the indicator-based SALCAsustain method, based on comprehensive questionnaires complemented with individual face-to-face interviews.

Some existing methods provide an explicit aggregation of indicators, aiming at a reduction in the complexity and thus facilitating interpretation for interested stakeholders and decision-makers. Building composite indicators requires normalisation and weighting of individual indicators. Normalisation involves calculating the magnitude of the indicator results relative to some reference information (ISO, 2006b). Weightings are often based on value choices (Pizzol et al., 2017; Grubert, 2017). To reduce the subjective component in the weighting process, it is crucial to examine the dependency and structure of the individual indicators. Multivariate data analysis allows reducing the subjective value judgement that is necessary in most weighting schemes (Ahlroth et al., 2011). According to EC-JRC-IES (2008), multivariate data analysis is one of the key steps for reducing the number of indicators by determining appropriate weights. The weights of (possibly correlated) indicators can be determined using different methods. Due to the advantages of objectivity, principal component analysis (PCA) is often used to determine the weights of individual indicators and to integrate them into one sustainability score (Jiang et al., 2018). PCA transforms correlated original variables into a new set of uncorrelated variables using a covariance matrix, or its standardised form – a correlation matrix. Correlation analysis, which is methodologically closely related to the PCA method, is also a suitable method for estimating weights for individual indicators. It helps to provide insights into the synergies and trade-offs between sustainability indicators, with positive correlations pointing to synergies and negative correlations to trade-offs. This is important in identifying management solutions to improve sustainability (German et al., 2017). Reducing the number of sustainability indicators and avoiding redundancy is also crucial for the sake of parsimony. This helps to reduce double-counting or overweighting of some processes when constructing an aggregated sustainability indicator. According to (Dormann et al., 2013), regression models that include predictor variables with a correlation coefficient above a threshold of $|0.70|$ lead to degraded predictions, so special attention should be paid to variables with correlation coefficient $>|0.70|$. High correlation between indicators indicates that they are strongly coupled to a similar underlying mechanism. Several studies have analysed the correlation between sustainability indicators. For example, in a previous PCA of 14 selected environmental indicators, Yu et al. (1998) found great redundancy among the indicators. Based on more than 14,000 accountancies of Swiss dairy farms, Zorn et al. (2018) found great potential for reducing the number of economic indicators based on a correlation analyses of 17 indicators. Using a correlation analysis, Jan et al. (2012) found a positive relationship between farm economic performance and environmental performance. In the present study, we examined the correlation pattern between sustainability indicators estimated by the SALCAsustain method for a small sample of typical Swiss farms.

3. Methods

The study was based on the indicator-based sustainability method SALCAsustain, which is summarised in Table 1 and described in detail in Roesch et al. (2017).

In the following, information is provided on methodical aspects, tools applied and the dataflow in SALCAsustain. Due to fundamental differences in the methodology, tools applied and data acquisition, the information is given separately for the environmental dimension of sustainability and the socioeconomic indicators.

3.1. Environmental impacts

The environmental impacts were computed using life cycle assessment (LCA) according to ISO 14040 and 14044 (ISO 2006a, 2006b). This methodology allows computation of the environmental impacts associated with all stages of the life cycle (‘from cradle to grave’) of a process, service or product.

Direct emissions from field and farm were calculated based on the Swiss Agriculture Life Cycle Analysis (SALCA) method (Gaillard and Nemecek, 2009). Life Cycle Impact Assessment (LCIA) was conducted using SimaPro software (PRéConsultants, 2019), supplemented with data from the ecoinvent v3.5 database (ecoinvent Centre, 2018) and AGRYBALYSE (Koch and Salou, 2015).

Life Cycle Inventories (LCI) for the pilot farms were taken from an ongoing long-term project at Agroscope, that aims at climate change mitigation by implementing different measures to reduce greenhouse gas emissions (Alig et al., 2015). The LCI consists of: 1) a comprehensive dataset containing information on agricultural activities (e.g. fertiliser and manure application), the type and amount of production means (seeds, plant protection, fertiliser, feedstuffs, machines, buildings) and energy use (i.e. fuel, gas, electricity) and 2) the resources used (inputs) and 3) the emissions released in relation to one unit of infrastructure or product in order to include processes in the background system. The Excel template for data acquisition in German is provided as Supplementary Material S1.

In contrast to the other environmental impacts, the system boundary for soil quality and biodiversity was the farm, ignoring upstream processes. Soil quality was assessed using the standalone Excel-based tool SALCA-SQ, which shows the impact of on-farm agricultural activities on soil quality (Oberholzer et al., 2012). This tool requires detailed information on all field operations (machinery weight, wheel load, operating width), which was collected by the farmer using Excel data entry forms with drop-down menus and a well-developed help tool to minimise erroneous entries (the Excel template in German is provided as Supplementary Material S2).

For biodiversity, the IP-SUISSE credit point system was preferred over SALCA-BD (SALCA-biodiversity) due to time, cost and data constraints. This credit point system acts at the farm scale and covers a catalogue of 32 options with which farmers can positively influence biodiversity on their farms. Farmers can ‘score points’ by applying these measures on their farms (Jenny et al., 2013).

3.2. Economic indicators

In SALCAsustain, the financial situation of a farm is characterised by two indicators from each of three themes: profitability, liquidity and stability (Roesch et al., 2017). The economic indicators are depicted by financial ratios that facilitates comparison of differently structured farms (Zorn et al., 2018). Great value is placed on selecting indicators that have practical relevance for farm management, which also enables farm advice and self-assessment at farm level.

Profitability ratios relate the profit during a period to the factors of production, such as capital and labour. The two indicators proposed are income per family work unit and return on assets. The income per family work unit is derived from the farm net income, while the return on assets relates to the return on total farm investment.

For liquidity, that is, a farm’s liability to meet its financial obligations, the two indicators cash flow ratio and dynamic gearing ratio are recommended. The cash flow ratio divides the cash flow by the turnover. The dynamic gearing ratio is obtained by dividing farm liabilities, including short- and long-term debts, by the cash flow.

The stability of a farm determines risk with respect to profitability and liquidity, thereby underscoring the long-term component of economic sustainability. The two economic ratios fixed assets to total assets and equity to fixed assets ratio represent plau-

Table 1
Sustainability dimensions and subjects evaluated in the SALCAsustain method and the indicators used. The practical implementation is provided for each indicator.

Dimension	Subject	Indicator	Implementation
Social	Well-being	Workload in terms of time	Ratio of need to available labour units (Roesch et al., 2017, Chapter 3)
	Landscape quality	Landscape diversity and aesthetics	Shannon Index, calculated from annual farm census data (Schüpbach et al., 2020)
Economic	Profitability	Income per family work unit	Calculation of financial ratios based on accounting data; equations are presented in Roesch et al. (2017, Chapter 7)
		Return on capital	
	Liquidity	Cash flow ratio	
		Dynamic gearing ratio	
	Stability	Fixed assets to total assets	
		Equity to fixed assets ratio	
Environment	Resource use	Non-renewable energy resources	Cumulative energy demand (ecoinvent Centre, 2010)
		Phosphorus and potassium	CML 2001 method (Guinée et al., 2001)
		Water requirement (fresh water)	Method of Pfister et al. (2009)
		Land occupation	CML 2001 method (Guinée et al., 2001).
	Climate change	Greenhouse gases (CO_2, CH_4 and N_2O)	Global warming potential according to IPCC (2013) (100-year time horizon)
	Nutrient-related environmental impacts	Eutrophication (aquatic and terrestrial)	Eutrophication potential (EDIP2003 method) (Hauschild and Potting, 2005)
		Acidification (aquatic and terrestrial)	Acidification potential: 'accumulated exceedance' method for terrestrial acidification, see Seppälä et al. (2006) and Posch et al. (2008)
	Ecotoxicity	Ecotoxicity (terrestrial)	CML2001 method (Guinée et al., 2001)
	Biodiversity	Genetic and species diversity	IP-SUISSE credit point system (Birrer et al., 2014)
		Habitat diversity and linkage	
		Diversity of agricultural crops	
		Potentially natural habitat	
		Plant-protection products	
		Fertiliser use	
		Irrigation	
		Use intensity, management technique	
		Functional aspects	
	Soil quality	Physical indicators: rooting depth, macropore volume, aggregate stability	SALCA-SQ (Oberholzer et al., 2012)
		Chemical indicators: organic carbon, heavy metal content, organic pollutants	
		Biological indicators: microbial activity, microbial biomass, earthworm biomass	

sible and practical indicators for assessing the stability of a farm. For the fixed assets to total assets ratio, fixed assets (without livestock) are related to total assets. The equity to fixed assets ratio represents the relationship between own capital or (farm) equity and the fixed assets (Zorn et al., 2018).

The data used for computation of economic indicators were accounting data collected on Excel data entry forms provided to the farmers (see Supplementary Material S2).

3.3. Social indicators

The landscape quality indicator was calculated as the equally weighted mean of two sub-indicators (Schüpbach et al., 2020). The first sub-indicator covered naturalness, or visual quality, and was computed as an area-weighted mean of the 'preference values' of the landscape elements of a farm. The preference values reflect the preference of the general public for various land-use types. The second sub-indicator covered the aspect of complexity and the 'ephemera' of the landscape, and was approximated by the Shannon diversity index.

The indicator for landscape quality (LCI) was computed with the statistical software R (R Core Team, 2017), using the farm structure census results that are compiled annually by the Swiss Federal Statistical Office (FSO). The census involves an exhaustive farm inventory in terms of crop and grassland areas, livestock data and the labour force.

The indicator for temporal workload is expressed as the ratio of need for available labour units. The number of labour units required was estimated by the ART Work Budget System (Schick et al., 2007), while the labour available on the farm was computed from information on labour information available from the farm structure census.

The input data required for computing social indicators were collected on Excel data entry forms, enhanced by additional information. Simple plausibility checks were performed on all input data, in order to confirm their validity. In the first stage, very simple automated quality control procedures were carried out, mostly checking whether the value is within the expected range (e.g. percentages between 0% and 100%). In the second stage, the data were verified by visual inspection, a time-consuming process where the quality and success are heavily dependent on the skill and expertise of the analyst.

3.4. Correlation analysis

Spearman's rank correlation analysis was performed on the calculated sustainability indicators. The generally skewed distribution of sustainability indicators was considered by using the non-parametric Spearman approach, which does not require a linear relationship between the variables (Hauke and Kossowski, 2011). Compared with Pearson's correlation coefficient, Spearman's correlation coefficient is less sensitive to outliers and more appropriate for a small sample size (Shevlyakov and Oja, 2016; Schober et al., 2018).

3.5. Questionnaires

To learn more about farmers' perceptions of the entire SALCAsustain process from data acquisition to presentation of the final results, both test phases for the two operating years 2016 and 2018

Table 2
Mean key structural parameters of the pilot farms evaluated in 2016: utilised agricultural area (UAA), ecological focus area (EFA) and livestock units (LU). Figures in parentheses refer to the percentage of UAA. Note that the sum of arable land, grassland and EFA is not equal to UAA, as extensive grasslands belong to the EFA.

	Number	UAA [ha]	Arable land [ha]	Grassland [ha]	EFA [ha]	Total livestock [LU]
Mountain farms (MOUNT)	5	34.2	5.2 (15.2%)	28.5 (83.3%)	7.9 (23.1%)	51.5
Arable farms (ARAB)	3	35.7	30.3 (84.9%)	5.0 (14.0%)	6.7 (18.8%)	5.4
Lowland fattening farms (FAT)	4	22.0	5.9 (26.8%)	16.0 (72.7%)	2.2 (10.0%)	83.3

were evaluated using a questionnaire. For the operating year 2016, the farmers' perceptions on acceptance, feasibility and informative value were collected using a 26-item questionnaire (Questionnaire S3 in Supplementary material). These items were grouped into the following five categories: (i) general questions on sustainability, (ii) information/feedback during the entire course of the project, (iii) data amount and data acquisition, (iv) the farmer's personal support during the project and (v) the expected impact of the project on behaviour and business management. The questionnaire for the second test phase (Questionnaire S4 in Supplementary material) was revised and its structure was adapted in order to group the answers in terms of the three thematic areas (acceptance, feasibility and informative value (benefits)). The wording was only slightly adapted, but more detailed information was requested about the time required for data collection and prior knowledge on the topic of sustainability. The questionnaire included various types of response options: yes/no, five-point answer scale ('strongly agree', 'agree', 'neutral', 'disagree', 'strongly disagree'), and plain text.

The questionnaire was sent to the farmers by e-mail beforehand and was completed in face-to-face meetings. These face-to-face meetings allowed us to clarify the farmers' responses and to obtain new insights into possible weaknesses of the indicators.

3.6. *Sample*

The study involved a small sample of pilot farms for the operating years 2016 and 2018. Due to changes in personal circumstances over time, the farm sample was not identical in the first and second test phases. The sample consisted of 12 farms in 2016 and 13 in 2018, 10 of which were identical. In the following, some key parameters of the 12 pilot farms that were analysed in 2016 are summarised.

The sample covered three farm types representing typical Swiss production systems: mountain dairy farms (MOUNT), arable farms (ARAB) and lowland fattening farms (FAT). The mean key structural parameters for the sample used in the first test phase (2016) are shown in Table 2.

The mountain farms (MOUNT) studied were comprised mainly of grassland with a relatively high percentage of ecological focus areas (EFA), such as low-input meadows and pastures and moist meadows (Table 2). The principal production animals were dairy cows and suckler cows. The three sampled arable farms (ARAB) were characterised by a high percentage of arable land and little livestock. They primarily grow winter wheat, grain maize, potatoes, sugar beet and rapeseed. The lowland fattening farms (FAT) typically had small utilised agricultural area (UAA) and ecological focus areas (EFA), and a high number of livestock (mainly fattening pigs) (Table 2).

4. Results

4.1. *Sustainability indicators: descriptive statistics*

4.1.1. *Environmental indicators*

A short summary of some key statistical measures for environmental impacts per hectare (ha) on the 12 pilot farms analysed in 2016 is provided in Table 3. The indicator values at farm level are given in Table S5 (Supplementary Material) for 2016 and in Table S6 (Supplementary Material) for 2018.

The mean energy demand amounted to 54.1 GJ-eq per ha and year. Detailed analysis at farm level revealed that the energy demand for FAT farms was markedly higher than that for the other farm types, primarily due to purchased concentrates (Table 3). The lowest energy demand per ha was found for the ARAB farms. Global warming potential (GWP) with a 100-year time horizon showed a similar pattern to energy demand. On average, slightly more than 11.3 tons of CO_2-eq were emitted per unit area in 2016. As found for energy demand, the two FAT farms analysed also had the highest GWP values (Table 3). The aquatic eutrophication potential (AEP) was equal to about 78 kg N per unit area, with a range of 24.4–179.3 kg N per ha UAA. The acidification potential (AP) was highest for the FAT farms, as acidification was largely related to ammonia (NH_3) emissions, caused primarily by animal husbandry and production of purchased animals. The median value of terrestrial ecotoxicity potential (TEP), i.e. the impact of toxic pollutants such as pesticides on soil ecosystems, was 7.02 kg 1,4-DB eq per unit area and year but with high variability, as indicated by coefficient of variation (COV) of 1.07. This is clearly above the values found for the other environmental impacts (Table 3). Closer verification at the farm level revealed that the high TEP values were primarily caused by purchased concentrate feed on FAT farms and pesticide use on ARAB farms.

The biodiversity score following Birrer et al. (2014) ranged between 19.5 and 30.3. The MOUNT farms provided the most beneficial landscape structure in terms of promoting biodiversity. This was primarily due to their high percentage of high-quality ecological compensation areas. The FAT farms generally ranked low in potential contribution to biodiversity, due to modest fractions of EFA and few enhancement measures on arable land. Evaluation of soil quality based on nine soil quality indicators computed by SALCA-SQ revealed high variation among the pilot farms analysed. Some farms suffered from negative soil compaction effects caused by heavy machinery, leading to reduced macropore volume and aggregate stability. Analyses of the model results suggested that insufficient supply of organic matter to soils also contributed to reduced soil quality, expressed by negative effects on the simulated biological soil quality indicators earthworm biomass and microbial biomass/activity.

The environmental impacts scaled by the sample mean differed strongly for the two commonly used functional units ha UAA and MJ digestible energy (DE) (Fig. 1). This was directly related to the fact that MJ DE produced per ha varied significantly among the farms analysed (by a factor of 28). There were markedly lower values for the MOUNT farms, with generally conserving land management, compared with the ARAB and FAT farms, characterised by high productive output (Baumgartner et al., 2011). The TEP results clearly showed the highest variability of all environmental impacts among the individual farms, due to highly variable heavy metal input via fertilisers and very different amounts of purchased feedstuffs. Thus the environmental impacts of the sampled farms varied significantly (Fig. 1), as they differed widely regarding type, activities and management practices.

Table 3
Selected statistical variables for environmental impacts of the pilot farms evaluated within this study (year 2016, sample size 12). COV: coefficient of variation, ED: energy demand, GWP: global warming potential (100-year time horizon), LO: land occupation, AEP: aquatic eutrophication potential, AP: acidification potential, TEP: terrestrial ecotoxicity potential. Functional unit: ha utilised agricultural area (UAA).

	ED [GJ-eq/ha]	GWP [t CO_2-eq/ha]	LO [ha/ha]	AEP (N) [kg N/ha]	AP [m^2/ha]	TEP [kg 1,4-DB eq/ha]
Mean	54.1	11.32	1.91	78.25	2022	17.79
Median	42.2	10.83	1.78	69.65	1768	7.02
Stdev	38.3	7.35	0.80	40.35	1470	19.0
COV	0.71	0.65	0.42	0.52	0.73	1.07
Minima	14.9	1.87	1.09	24.4	200	1.14
Maxima	134.6	27.05	3.56	179.5	5319	63.03

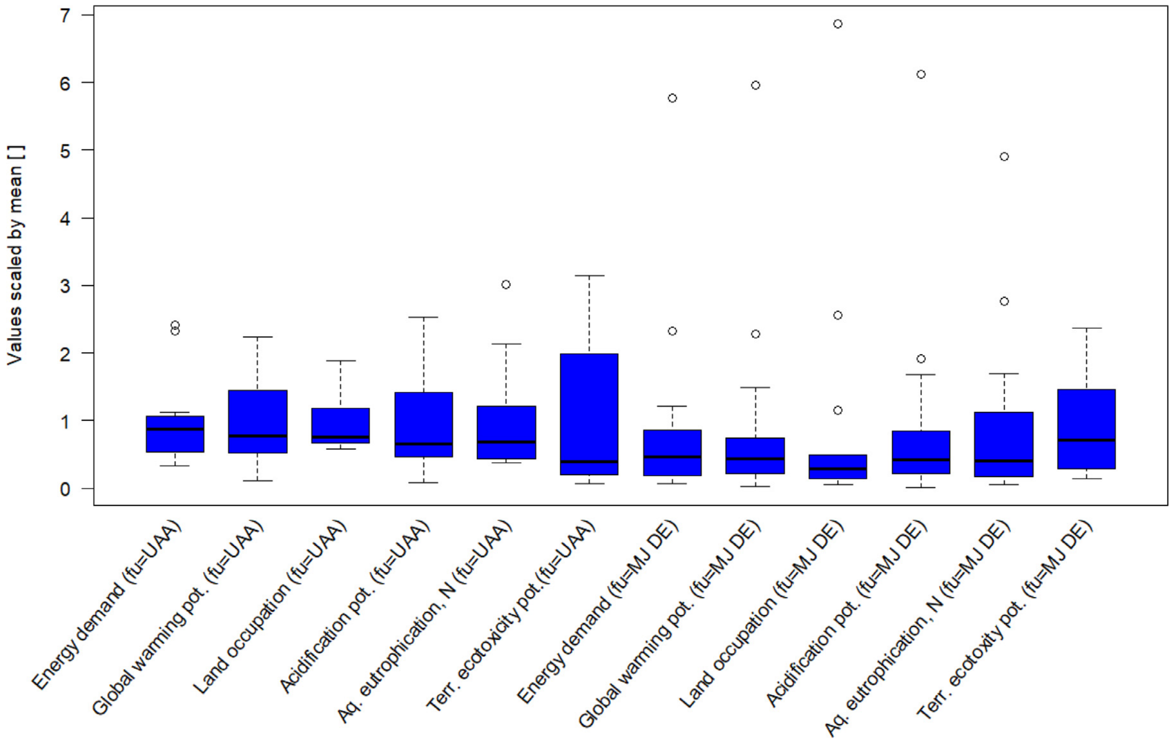

Fig. 1. Boxplots for selected environmental impacts, scaled by the mean of the 12 pilot farms analysed, 2016. fu: functional unit; UAA: utilised agricultural area; DE: digestible energy.

Table 4
Economic indicators for the 12 pilot farms analysed in 2016. IWU: income per family work unit, ROC: return on capital, CFR: cash flow ratio, DGR: dynamic gearing ratio, FATA: fixed assets to total assets, EFAR: equity to fixed assets ratio. COV: coefficient of variation.

	Profitability		Liquidity		Stability	
	IWU[CHF]	ROC[%]	CFR[%]	DGR[ ]	FATA[ ]	EFAR[ ]
Mean	47940	-11.9	48.2	10.85	0.76	1.00
Median	46910	-4.9	36.0	11.59	0.85	0.93
Stdev	22350	17.0	35.8	10.38	0.19	0.83
COV	0.466	-1.4	0.7	0.96	0.25	0.82
Minima	16770	-54.3	-7.0	0.44	0.30	0.16
Maxima	88850	1.0	119.0	29.06	0.91	3.12

4.1.2. Economic indicators

Economic sustainability was assessed by six commonly used economic ratios, two each for profitability, liquidity and stability (Table 4).

The economic performance of the farms analysed differed significantly regarding profitability, liquidity and stability (Table 4). Annual income (IWU) varied between 16,770 and 88,850 CHF, with a mean of 47,940 CHF, which was close to the value of 47,200 CHF for the entire Swiss agricultural sector in 2016 (Hoop et al., 2017). The variability measure COV was clearly lowest for FATA, defined as the ratio of fixed assets (machinery and buildings) to total assets. A number of the pilot farms suffered from low income and/or critical liquidity and stability. The mean return on capital (ROC) of -11.9% means that farm profit after remuneration of family members was negative. Only two farms showed a profit, with a slightly positive ROC. Generally, the sampled farms seemed to have sufficient financial resources, as mean cash flow ratio (CFR) amounted to 48.2%, indicating that cash flow was approximately half of turnover (Table 4). Inspecting the liquidity measure dynamic gearing ratio (DGR) revealed that the pilot farms needed an average of almost 11 years to pay all their debts with the cash flow generated in 2016, with a massive difference between the least and most liquid farms (Table 4). The average equity to fixed assets ratio (EFAR) of 1.0 provides evidence that the farms were generally economically stable because they could largely cover their fixed assets (machinery and buildings) with their own capital. A critical situation in terms of insufficient capital was found for some MOUNT farms. Arable farming seemed to have a favourable effect on EVAR.

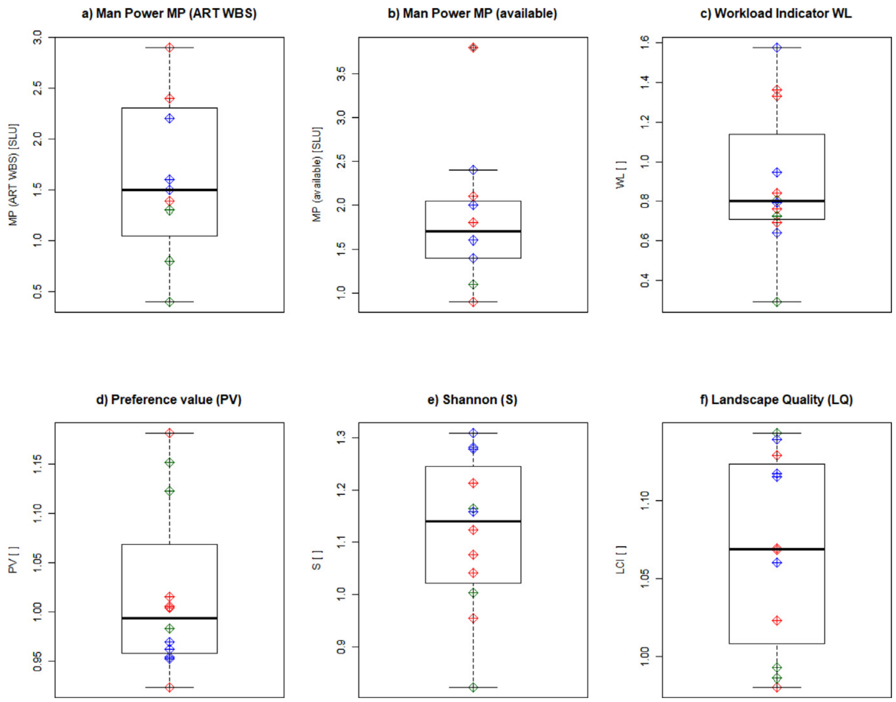

Fig. 2. Social indicators for the 12 pilot farms analysed, 2016. Temporal workload (WL): panels (a)–(c), and panels (d)–(f): landscape quality (LQ). Panels (c) and (f) show the composite indicators for WL und LQ. ART WBS: ARTWork Budget System. Colour codes: red: mountain (MOUNT) farms, green: arable (ARAB) farms, blue: animal fattening (FAT) farms. Manpower (MP) in panels (a) and (b) is given in standard labour units (SLU), with 1 SLU = 2800 h. LQ indicators are normalised with the mean in the respective reference group ('homogenous agricultural zones'). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.1.3. Social indicators

The results for the two social indicators, temporal workload (TW) and landscape quality (LQ), for the 12 sampled pilot farms in 2016 are illustrated in Fig. 2.

Fig. 2a and b show the distribution of the theoretically derived work time requirements and the manpower available on the farm. The workload (WL) differed greatly among the sampled farms, with the mean value of 0.86 pointing to slight underemployment on the pilot farms (Fig. 2c). Three farms with WL>1.2 showed a clear tendency toward a potential overload, while one farm with WL = 0.29 seemed to suffer from distinct underemployment. Further evaluation clarified that no farming type was particularly prone to strong under- or overemployment. Detailed analyses and the face-to-face interviews with farmers showed that the manpower values calculated by the ART Work Budget System has two potential deficiencies: a mean degree of mechanisation for all farms analysed was assumed, and some niche production (such as own production of marmalade for a farm shop or keeping rare farm animals) and some land types were not captured.

Fig. 2d and e show the two normalised sub-indicators (PV and S), normalised with the mean value in the respective reference group. Most of the farms analysed had above-average LQ, depicted by values above 1 (Fig. 2f). The graphic representation shows that both the aesthetic value of the landscape elements as represented in the area-averaged preference value (Fig. 2d) and the diversity (shown by the Shannon index in Fig. 2e) contribute to this result. Regarding WL, no pattern for the different farm types was seen.

4.2. Sustainability indicators: correlation analysis

This section provides some insights into the relationship between the sustainability indicators (cf. Table 1), as identified from correlation analysis.

As can be seen from Fig. 3, several environmental indicators, such as energy demand, GWP, land occupation and acidification, were highly correlated, with correlation coefficients above 0.9. The relationship with the two environmental impacts, aquatic eutrophication N (AEN) and terrestrial ecotoxicity potential (TEP), was clearly weaker. The correlation coefficients between TEP and the other environmental impacts were generally low and not significantly different from zero. TEP and biodiversity can be expected to be highly negatively correlated (R = -0.78), as pesticide use is one of the major factors affecting biological diversity. The correlation of biodiversity and soil quality scores with the other environmental impacts was generally low and not statistically significant.

The strong and consistent relationship observed between many of the environmental impact indicators reflected the fact that they are driven by similar physical processes. Fertiliser management on-farm has strong impacts on both the energy demand and GWP, through purchased mineral fertilisers. The fertilisers applied to the fields strongly affect ammonia emissions and thus nitrous oxide emissions, leading to increased GWP. The statistically significant correlation between AP and AEN (R=0.67) is due to the fact that these two environmental impacts are both largely determined by the ammonia emissions. The high correlation between land occupation and energy demand is primarily related to the fact that purchased feed and livestock are associated with high emissions and land use. Land is used for grazing livestock and cultivation of crops, production of concentrated feed is energy-intensive and cattle produce methane through their digestive processes.

The evaluation based on the data from the second test phase in 2018 (not shown) generally confirmed the findings obtained for the farms analysed in 2016, although the strength of the relationship between the impacts analysed differed slightly. This is not surprising, given the small sample size and the high complexity and diversity of the processes involved in describing the various environmental impacts discussed above.

The relationship between socioeconomic indicators was generally weak and not significant at the 95% confidence level (Fig. 4).

Fig. 3. Correlation matrix of environmental indicators. Results are based on the analysis of 12 pilot farms for 2016. EDha: energy demand per ha; GWPha: global warming potential per ha; LOha: land occupation per ha; APha: acidification potential per ha; AENha: aquatic eutrophication N per ha; TEPha: terrestrial ecotoxicity potential per ha; BD: biodiversity score; BQ: soil quality indicator. All environmental impacts except BD and BQ are per ha utilised agricultural area (UAA). Positive correlations are displayed in blue and negative correlations in red. Colour intensity and circle size are proportional to the correlation coefficients (see colour key on the right). Crosses indicate non-significant correlation coefficient at 95% confidence level. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Analysis revealed that the environmental impacts (represented here by GWP) were generally weakly correlated with the socioeconomic indicators analysed. Interestingly, a higher workload in terms of time did not necessarily lead to better economic performance, with the possible exception of the two indicators IWU and ROC characterising farm profitability (Fig. 4). The pronounced negative correlation (R = -0.96) between EFAR and DGR is reasonable from an economic point of view, as high farm liabilities, including short- and long-term debts, are generally associated with low capital. This indicates that the sustainability assessment can be simplified by using a reduced number of financial ratios, as confirmed in a recent study on constructing a simplified composite indicator for economic sustainability based on more than 14,000 accounts for Swiss dairy farms (Zorn et al., 2018).

4.3. Evaluation of questionnaires

The main information gathered from the questionnaires sent to the farmers for the first test phase in 2016 and the second test phase in 2018 is described below. As the knowledge and experience of the participating farmers differed between the first and second test phases, the main findings from the evaluation are treated separately.

4.3.1. Questionnaire: first test phase (2016)

The 12 farmers analysed in 2016 were all familiar (7 strongly agreed, 5 agreed) with the concept of sustainability; all farmers believed that sustainability assessment is (very) important for the agricultural sector in general. To the question of whether aspects of sustainability are missing in the SALCAsustain method (indicators listed in Table 1), two participants mentioned animal welfare and two mentioned agroforestry. Some farmers stressed that local conditions are not sufficiently considered in the collected data; for example, the computation of manpower requirements on the farm ignores various working procedures related to handwork or niche products, such as production of marmalade or keeping rare animals.

Regarding the information/feedback during the entire course of the project, the participants were mostly satisfied; the information provided as part of an information event and the possibility for telephone enquiries were highly appreciated. Further, the farmers appreciated the personal feedback, although it was time-consuming for both parties.

Only four of the 12 participants were satisfied with the data acquisition process. The main shortcomings reported were in the application of different tools and the graphical user interface, which did not allow a reasonable grouping of input variables. Three out

Fig. 4. Correlation matrix of socioeconomic indicators. Results are based on the analysis of 12 pilot farms for the year 2016. All codes as in Table 4, global warming potential (GWP) per ha is included for illustration. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of 12 farmers demanded more on-site support, e.g. for feeding details of own machinery into the system, the provision of accounting data or the entry of plant protection products. The evaluation showed that the average time expenditure for the farmer was almost nine hours, with a range between four and 16 hours; young farmers tended to be faster than elderly farmers. Note that this time expenditure did not include the time used for compiling the inventory data used in LCA. The farmers did not agree regarding the question of whether the system design and data acquisition were appropriate for a large group of farms. Their answers indicated that the main stumbling blocks were the large amount of input data required and the user-unfriendly software.

The participants reported that they would profit from more interactions with other farmers involved (Fig. 5). Further, they agreed that more courses on topics related to sustainability should be provided by agricultural consultants, which they believed would trigger general acceptance of indicator-based assessments of sustainability at the farm level.

The great majority of the participants agreed that participating in the study had influenced their medium and long-term planning of operational management. Eight of the 12 farmers agreed the project will affect the kind of feedstuffs they purchase.

4.3.2. *Questionnaire: second test phase (2018)*

The median time required for the participating farmers to gather all the data (excluding data necessary for compiling the LCI) was three hours, clearly shorter than in the first test phase. This was due to learning effects and use of certain data (e.g. on machinery, size and name of the plots) taken from the first test phase. Most of the time was needed for providing the accountancy data and the single machine passages across plots for estimating soil compaction. Data plausibility checks and further data processing required 10-15 hours per farm; this work was done by scientific technical staff at Agroscope and an external office. The time required for the actual computation of the sustainability indicators for all pilot farms is given in Table 5. The very time-consuming computation of soil quality was remarkable, but can be explained by a very tedious procedure due to lack of automation and the requirement of several input files to feed the Excel data entry form.

Most of the participants mentioned that a single tool would considerably ease the data acquisition process. The farmers' responses led to the conclusion that they would accept different technical implementations, such as a simple Excel tool (9/13 agreed or strongly agreed), a web interface (10/13) or data entry via an app on a smartphone or tablet (9/13). It is interesting to note that the farmers thought that reducing the input data catalogue would lower the accuracy and expressive power of the sustainability assessment. A structured pulldown menu for selection of machinery and animal houses would ease data acquisition.

The second part of the questionnaire dealt with the expected benefits from the sustainability assessment. Eleven of 13 farmers agreed or strongly agreed that comparing the farm's own indicators against those of a similar reference group might help identify strengths and weaknesses in their farm management. The farmers confirmed that they would benefit from an in-depth understanding of the indicators. However, they believed that the evaluation would

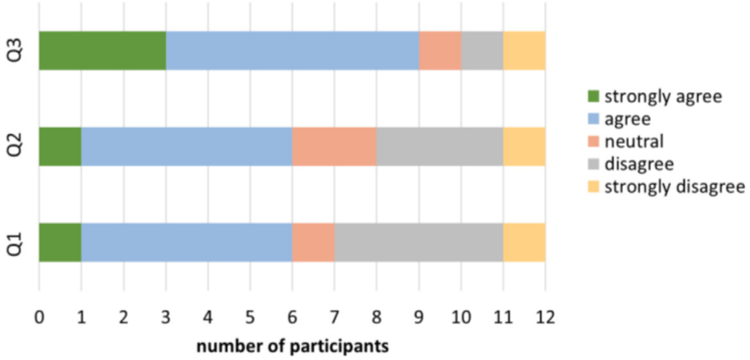

Fig. 5. Evaluation of the questionnaire used in the first test phase (2016). Q1: Are you interested in participating in a working group? Q2: Would you like to exchange information on sustainability topics with other farmers? Q3: Should courses on sustainability for farmers be offered by trained agricultural advisers?

Table 5
Time required for computation of sustainability indicators for all 13 farms analysed in the second test phase (2018). Biodiversity is not listed, as the biodiversity scores were provided by IP-SUISSE.

Indicator(s)	Model/ Tools	Time used [h]
Environmental impacts and resources (listed in Table 1), except for soil quality and biodiversity	SALCA model, SimaPro, ecoinvent database	4
Soil quality	SALCA-SQ (stand-alone Excel tool), see Oberholzer et al. (2012) and Table 1	8
Economic indicators (six financial ratios, see Table 1)	Stand-alone Excel tool	4
Workload in terms of time	ART Work Budget System (Schick et al., 2007)	4
Landscape quality	R-Programme (developed at Agroscope, Zurich)	1

primarily affect their long-term planning, while in the short-term (and partly mid-term) they would take no actions to improve the farm's overall sustainability (Fig. 6).

The participants' responses provided strong evidence that acceptance of the sustainability assessment can be increased by on-site feedback providing deeper insights into the results. Furthermore, all but one participant agreed or strongly agreed that they would profit from a comparison of their own farm's results with those of a reference group. The farmers indicated after the second test phase that they were equally interested in the three sustainability dimensions, with no clear preference for the environmental, economic or social dimension. The acceptable expenditure of time for collecting all data (including the data for compiling the LCI) varied significantly and was between 3 and 30 hours. As most participants were interested in the sustainability assessment, it is not surprising that 12 of the 13 farmers were ready to provide their data every second year.

5. Discussion

The focus in this section is on the correlations between the sustainability indicators and farmers' perception of the process used for the sustainability assessment. The main findings from the questionnaires, reflecting the views of the farmers, were used to analyse the feasibility and the expected benefits gained during the project. The difference between the average sustainability indica-

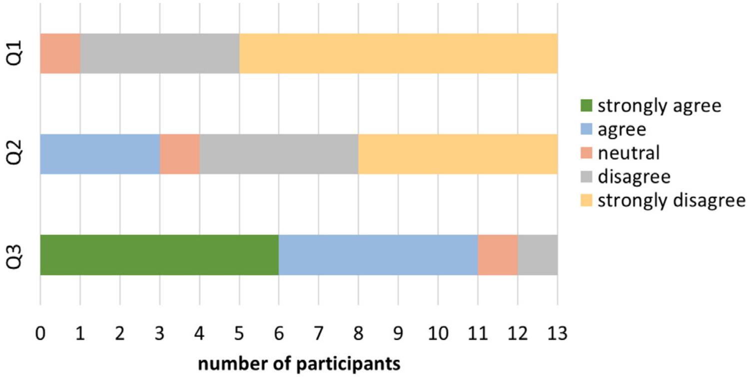

Fig. 6. Evaluation of the questionnaire used in the second test phase (2018). Q1: Will the results of the sustainability assessment influence your short-term planning? Q2: Will the results of the sustainability assessment influence your mid-term planning (following year)? Q3: Will the results of the sustainability assessment influence your long-term planning?

tors in 2016 and 2018 is not discussed, as the sample size was too small to verify steps towards changed (or improved) management practices at the individual farm level or even to derive reliable and robust trends in the Swiss agricultural sector.

5.1. Regression analysis

Regression analysis revealed that the environmental impacts GWP, AP, EP and the use of energy and land resources were generally highly positively correlated, in line with previous findings (Berger and Finkbeiner, 2011; Laurent et al., 2012; Röös et al., 2013; Mu et al., 2017). Correlation coefficient values were clearly above 0.7 for GWP, AP and land use, suggesting that a reduced set of indicators may be sufficient for adequate description of a farm's impact on the environment (Dormann et al., 2013). This is in line with Mu et al. (2017), who defined a reduced set of environmental indicators to benchmark dairy systems in an efficient way. The high correlation coefficient values can be attributed to similar physical processes driving these impacts and resource uses. For example, land is used for grazing cattle, production of concentrate feed and production of roughage. Ruminants (and monogastrics to a much lesser extent) produce the highly effective greenhouse gas methane from digestion and nitrous oxide from manure storage and management (Broucek, 2017). Further, the production of concentrate feed is a very energy-intensive process, but also requires much land. Manure from cattle is responsible for significant ammonia emissions, leading to acid deposition and eutrophication, with adverse effects on the aquatic ecosystems of rivers and lakes. Therefore, it is evident that most of the environmental impacts and resource use on farms will show a positive linear relationship. The high negative correlation between terrestrial ecotoxicity and biodiversity was also expected, as pesticide use has a strong negative impact on biodiversity (Relyea, 2005).

In contrast to the environmental dimension, the correlation matrix for socioeconomic indicators showed they were generally only slightly correlated. Analysis revealed e.g. that above-average work input did not necessarily lead to better economic performance. However, the analysis also showed that some of the six suggested financial ratios (see Table 1) can probably be excluded when computing an aggregated composite indicator for economic sustainability. The results of the present correlation analysis and those of Zorn et al. (2018) suggest that one of the two selected profitability indicators, IWU and ROC, could possibly be ignored when assessing economic sustainability.

There was no evidence of statistically significant correlations between environmental and socioeconomic indicators. Previous studies have reported conflicting findings on the relationship between environmental and socioeconomic indicators. For example, Jan et al. (2012) found no mutual conflicts between a farm's environmental and economic objectives. whereas Salvati and Carlucci (2011) showed that e.g. soil-improving crops with positive environmental effects contribute very little to farm profitability. These conflicting results are probably mainly related to very different conceptual frameworks, methods and objectives applied in previous studies. The results obtained in the present study must be viewed with caution due to the small sample size. In addition, the overall validity of the method suffers from incomplete coverage of the social dimension, since e.g. human well-being and animal welfare were not included in the evaluation due to limited financial resources and lack of methodological adjustment to Swiss conditions. Further, correlating the environmental and socioeconomic indicators used in the SALCAsustain method may be critical, due to the use of different system boundaries for LCA and the socioeconomic indicators. While LCA, by definition, includes upstream processes, the economic indicators are based on the farm's accounts and do not follow the rules for life cycle costing (LCC). The same applies to the two social indicators analysed, which consider the on-farm temporal workload and the on-farm landscape quality, ignoring background processes such as the working conditions for feed or fertiliser producers or the land use for production of concentrated feed or fertilisers.

Despite the limited size of the farm sample, the results obtained from analysing the farms participating in the second test phase (2018) were similar to the findings retrieved from the first test phase (2016). Thus the results can still be considered reasonably robust.

5.2. Evaluation of questionnaires

The questionnaire responses provided interesting insights into the farmers' perceptions of the entire study from launch to completion. Evaluation of the two test phases based on comprehensive questionnaires and individual semi-structured interviews with the farmers revealed that the study design allows the sustainability indicators listed in Table 1 to be computed with sufficient accuracy. As evaluation of the feasibility, acceptance and expected benefits of the SALCAsustain method was a primary goal of this study, these aspects are discussed in detail below.

5.2.1. Feasibility

The required input data can be collected by the farmer but the time required is considerable, reducing the feasibility of the sustainability assessment on a larger sample. Data collection and processing, including plausibility checks, format conversion and additional computations for deriving further input parameters, require considerable time on the part of the data collection agency. A number of components contribute to this time-intensive process chain: (i) the data are collected using various tools, such as differently structured Excel forms and mobile apps for smartphones, (ii) different sources of original data (LCI, fertiliser balance) (SuisseBilanz, see Agridea, 2015) or accounting data, (iii) rather user-unfriendly Excel data entry forms with no option for structuring data according to one's own wishes, (iv) insufficient written assistance for data entry and (v) use of unusual units that are not employed in practice. As the significant time requirements for data acquisition hamper sustainability assessment for a large farm sample at reasonable cost and personal resources, the major information technology (IT) project SALCAFuture has been launched at our institute (Lansche et al., 2017). This project includes an optimised data processing tool, user-friendly data entry via a web interface and a flexible and efficient calculation procedure using modular programming. Furthermore, access to external users via a central website will be provided.

The responses of participants in the present study showed that availability by phone and email was considered good by most farmers. Personal feedback was appreciated, although this might not be offered when extending the sample size due to financial considerations and limited resources.

5.2.2. Acceptance

The farmers' feedback suggested that they were generally interested in the topic of sustainability. Acceptance can be increased by periodic feedback, good reachability and a personal feedback interview about their own farm's results. We provided each individual farmer with a visual summary of the indicators, including a comparison with the other participating farms, but no advice was offered on translation into practice aimed at improving the farm's overall sustainability. In the literature, this discrepancy between knowledge and practice, also known as the knowledge-to-action gap (Siebrecht, 2020), is widely recognised (Pretty et al., 2010; Vellema, 2011). Some farmers stressed that acceptance would increase if they were provided with advice on how to improve sus-

Table 6
Four different strategies (A-D) for practical implementation of the SALCAsustain method and their advantages (+) and disadvantages (-). For details of the strategies, see the text.

	Use of specific farm data	Use of default values
Complete indicator set	A + Comprehensive, all aspects of sustainability are covered + Farm-specific – High computational effort – Extensive set of input data	B + Comprehensive, all aspects of sustainability are covered + Less farm-specific data – High computational effort – Less farm-specific statement
Reduced set of indicators	C + Reduced set of input data + Reduced computational effort + Allows farm-specific evaluations – limited informative value – Enhancement may be costly	D + Reduced set of input data + Reduced computational effort – Very limited informative value – Enhancement may be costly

tainability at little additional cost and reasonable time expenditure. From the farmers' responses, it is evident that exchanges with a group of farmers engaged in similar activities would further increase acceptance of the assessment method. The participants pointed out that the time required for data collection should be decreased considerably, to make the SALCAsustain method acceptable to a wide range of farmers. In addition, they indicated a need for financial compensation (for the time used and for the data).

Existing findings on how well farmers adopt sustainability assessment tools are contradictory and depend on both the underlying set of criteria and the tool(s) examined. Triste et al. (2014) found for the indicator-based sustainability assessment tool MOTIFS (MOnitoring Tool for Integrated Farm Sustainability) that, despite the participatory tool development process, adoption of the tool by farmers was disappointing. In-depth interviews revealed that the main reason for this unsatisfactory result was differences in expectations on the tool's objectives between the tool developers and stakeholders. In contrast, De Olde et al. (2016) found that farmers regarded RISE (Response Inducing Sustainability Evaluation; Häni et al., 2013) as an appropriate tool for gaining insights into the sustainability performance of their farm. However, based on an evaluation of four sustainability assessment tools, De Olde et al. (2016) also found that farmers generally hesitate to apply the results gained from sustainability tools in their decision making.

One reason for the farmers' generally positive perceptions about the SALCAsustain method could be that it was tested on a small group of highly motivated farmers in the IP-Suisse association, particularly since all farmers voluntarily agreed to participate. Farmers' acceptance might have been lower if the study had been based on a randomly selected sample of Swiss farms. The feedback interviews also revealed that it might be critical to generalise statements, but they should still be adapted to site-specific contexts, including the social environment (Slätmo et al., 2017).

5.2.3. *Benefits*

A large majority of the farmers agreed that participation in the study would lead to more sustainable use of resources in the long-term, and they planned to adapt their agricultural activities and management towards increased sustainability. Working groups consisting of farmers with similar agricultural activities and challenges with regard to more sustainable food production could communicate the benefits of participating in the sustainability assessment.

5.2.4. *Recommendations*

Comprehensive sustainability assessment based on the SALCAsustain method could be improved by reducing the temporal workload for data acquisition to increase acceptance and benefits for farmers and other stakeholders. Other recommendations are to:

(i) Provide a discussion platform for farmers engaged in similar agricultural activities and with similar interests.
(ii) Provide recommendations for actions and practical advice to achieve more sustainable production. Presenting only the value of the indicators is not sufficient.
(iii) Provide user-friendly data entry forms and easily available help. Data should always be in units with which the farmer is familiar.
(iv) Implement comprehensive plausibility checks to avoid time-consuming data work later in the project.
(v) Provide sufficient support during the entire process.

Based on the above, we formulated four strategies (A-D) for reducing the complexity of the SALCAsustain model when putting it into practice. Table 6 summarises these strategies, including the main advantages and disadvantages. In order to reduce the complexity and the time required for the calculations, either the number of indicators or the amount of data can be reduced. The latter option can be achieved by using appropriate default values for some input variables. Strategy A is the implementation described in this study; B keeps the complete set of indicators, but reduces the time for data acquisition by using default values; C reduces the number of sustainability indicators but requires farm-specific input data; and D is the most simple variant by simultaneously reducing the number of indicators and using default values. There is no clear dividing line between the four strategies, but there are some main differences (Table 6). The informative power decreases when omitting certain indicators (strategies C and D) or allowing the use of default values (strategies B and D). When acquisition of an input variable is very challenging or error-prone, specification of a default value may even increase the accuracy. However, use of too many default values carries the risk of missing site-specific properties (e.g. equipment used, information about animal housing or the size of the biogas plant) or farm management practices (e.g. fertiliser applied, pesticides used or cultivation of arable crops).

5.2.5. *Adaption of SALCAsustain to other countries*

The SALCAsustain method is especially designed for use in Switzerland. However, the conceptual framework allows the tool to be adapted for use in other countries, particularly Central European countries with pedoclimatic conditions similar to those in Switzerland. Additional work is needed to adapt the SALCA model e.g. for soil types that are not known in Switzerland. Additional efforts in data harmonisation are also required, as data availability generally differs between countries. Regarding the economic dimension, it should be noted that accounting and commonly used indicators may differ between countries. In summary, the general framework of SALCAsustain is suitable for other countries, but certain adjustments may have to be made to some of the calculations, for example because of differences in available data.

6. Conclusions

This study analysed the entire process necessary for comprehensive sustainability assessment at farm level using the SALCAsustain method, from data acquisition to the final graphic visualisation and statistical evaluation of the results, using a pilot farm network representing some farm types typically found in Switzerland. The results showed that overall farm sustainability assessment based on SALCAsustain is feasible. Analysis of the factors contributing to the indicators analysed for individual farms and comparison of indicator values obtained for two years (2016 and 2018) demonstrated that the method responds reasonably to changes in farm management and farming activities. The conclusions drawn from regression analysis were in line with expectations and the available literature. The limited size of the sample may impair the robustness of the results, but findings in the first (2016) and second test phase (2018) showed fairly good agreement.

The second test phase proved to be a crucial step for improving the entire data flow. It also provided more information on farmers' perceptions of the method. Analysis of farmers' responses in the first and second test phase suggested that sustainable agriculture is a guiding principle, with most farmers intending to optimise their activities in the long-term towards increased sustainability. However, for wider acceptance of the SALCAsustain method, the data flow must be improved considerably, e.g. data acquisition requires user-friendly entry formats, double surveys must be avoided and comprehensive plausibility checks must be carried out during data entry. Lack of in-depth consistency checks led to additional time-consuming data work later. Acceptance of the method critically depended on providing farms with sufficient, accurate and well-prepared information on the aims. Face-to-face interviews were highly appreciated, but are probably financially unfeasible for larger samples or monitoring purposes. Farmers appreciated the visual presentation of the sustainability assessment, but wanted practical advice on how farming activities and management have to be adapted towards more sustainable farming. The feedback interviews revealed that it might be critical to generalise statements, but that they should be adapted to site-specific contexts, including the social environment. Therefore, we must strive for a broader application of the SALCAsustain method, with subsequent analyses of farm managers' perceptions and acceptance.

The present study demonstrated for the first time that the SALCAsustain method can be successfully applied using data from typical Swiss farms. However, there is still room for improvement in some aspects of method itself and in the quality of the IT solutions. If time resources are a limiting factor, we recommend using default values for selected variables or reducing the number of sustainability indicators without losing too much information.

Declaration of Competing Interest

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

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.spc.2021.02.022.

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