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Measurement of sustainability in agriculture: a review of indicators

In recent decades, the concept of sustainability has become increasingly prominent in agricultural policy debates. This has led more and more stakeholders to pay attention to the questions of monitoring and evaluation of agricultural practices, and raised the question of appropriate indicators to assess sustainability aspects of given practices. We provide here a review of indicators of sustainability for agriculture. We describe sustainability indicators used in the literature following the typology based on the three sustainability pillars: environmental, economic and social. The literature review shows that the environmental pillar has undergone an 'indicator explosion', due to the multitude of themes covered and the attention given by society to this dimension of sustainability. By contrast, economic indicators target a relatively small number of themes. Social indicators typically cover two main themes: sustainability relating to the farming community and sustainability relating to society as a whole. The measurement of these social indicators is challenging as they are often qualitative and may therefore be considered subjective. Careful attention should be given to the choice of indicators, since the data measured will influence the calculation of that indicator and therefore the outcome of the analysis. It should first be decided whether individual or composite indicators are preferable, and whether single indicators or a set of indicators should be used. Also, sustainability assessments should be validated, credible and reproducible. Several selection criteria are provided in the literature, such as representativeness, transferability, adaptability and measurability at an acceptable cost.

Keywords: indicator typology, indicator selection, composite indicators, stakeholders, data

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Introduction

The concept of 'sustainable development' was introduced by the 'Brundtland report' in the late 1980s (WCED, 1987). The report attempts to reach a consensus on the perception of the concept, defining sustainable development as an 'economically viable, environmentally sound and socially acceptable development that meets the needs of the present without compromising the ability of future generations to meet their own needs'. Since then, 'sustainability', 'sustainable development' and 'sustainable intensification' have often been used as catch-phrases with different interpretations to qualify actions undertaken to reduce the impacts of human activities on the environment. Nevertheless, the concept is increasingly prominent in current agricultural policy debates.

The principle of sustainability has been integrated into the objectives of the European Union's (EU) Common Agricultural Policy (CAP), however the application of this concept to agriculture has resulted in a multiplicity of definitions. Efforts have been made to produce an integrated definition of this term: the application of the concept of sustainable development in agriculture is of interest both for the sustainability of the agricultural system itself and its contribution to sustainable development (Alkan Olsson *et al*., 2009a). For farms, the contribution to sustainable agriculture often involves: (a) the production of goods and services (economic function); (b) the management of natural resources (ecological function); and (c) the contribution to rural dynamics (social function). The harmonious combination of these three interconnected functions constitutes the backbone of sustainable agriculture. To move towards sustainability, it is necessary to achieve acceptable results in all dimensions of sustainability. A key point in agriculture is the dependence of sustainability assessment on farm-scale indicators: the farm is the unit of decision-making and there is high variability across farms, even within given individual contexts and farming systems.

In practice, sustainability assessment generally involves dividing the individual dimensions into various issues of concern – called objectives, attributes or themes (see Figure 1 in Ode *et al*., 2016) – and assessing these objectives using indicators. Indicators are variables (qualitative/quantitative data observed, measured or calculated from other data) which supply information on other variables (criteria) which are more difficult to access and which can be used as a benchmark for decision making. Indicators are "statistical constructs which support decision-making by revealing trends in data" (Dillon *et al*., 2014, p.3). The last fifteen years have seen an international proliferation of methods based on sets of indicators to assess various issues under one or more dimensions of sustainability (over 200 identified, see Rosnoblet *et al*., 2006) or to evaluate a specific problem (Bockstaller *et al*., 2009a) (see Diazabakana *et al*., 2014 for a more detailed review).

We provide here an overview of how sustainability is measured in an agricultural context. We firstly describe the three main sustainability pillars that are generally used in the literature and discuss the main themes of indicators within each of the pillars. We then provide some guidance on how to choose indicators.

Typology of indicators based on the three sustainability pillars

Environmental pillar

Lebacq *et al*. (2013) grouped environmental indicators found in the literature into ten environmental themes/topics that focus either on discernible physical aspects of the

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environment or on human activities with substantial environmental impact. These themes relate to nutrients, pesticides, non-renewable resources (i.e. energy and water), land management, emissions of greenhouse gases (GHG) and acidifying substances, biodiversity, and physical, chemical and biological soil quality. More generally, three groups of environmental themes can be distinguished:

- themes related to local or global impacts, which have consequences on the functional units used to express the indicators (Halberg *et al*., 2005);
- themes according to the action chain, namely the ultimate goal (e.g. human health), the process to achieve the goal (e.g. balance of environmental function) and the means (e.g. protecting environmental compartment) (Alkan Olsson *et al*., 2009b);
- themes based on goal-oriented frameworks (where themes are goals to be achieved) and frameworks oriented towards system properties (where themes are system properties) (Bockstaller *et al*., 2007).

An ‘indicator explosion’ (Riley, 2001) is particularly evident for the environmental dimension. Over the last 20 years, a plethora of initiatives has been proposed with a very broad array of indicators (Rosnoblet *et al*., 2006), due to ‘the growing concern for environmental issues and sustainability’ (Bockstaller *et al*., 2008). Although literature reviews are available for sustainability assessment methods based on indicators for specific themes, such as pesticides (e.g. Reus *et al*., 2002), nitrogen (Buczko and Kuchenbuch, 2010) or biodiversity (Dennis *et al*., 2009; Bockstaller *et al*., 2011), there is relatively little integration of these topics into whole-farm assessments across indicator sub-themes, and then across the three dimensions.

A key feature of many environmental indicators is their reliance on a valid cause-and-effect relationship, and that indicator data can then be used to measure some combination of causes and effects. The well-known Driving force – Pressure – State – Impact – Response (DPSIR) (EEA, 2005) framework is inspired by this cause-effect chain. One major drawback is the impression of linearity between pressure, state and impact given by the framework, whereas the reality is more complex and closer to a causal network than to a chain. Bockstaller *et al*. (2008) further elucidated the concept of impact by dividing it successively into state/exposure/impact, so that impact means the final effects on human health or the economy. In Life Cycle Analysis (LCA), indicators of final impacts are qualified as ‘endpoint impact’ indicators, whereas indicators related to the cause-effect chain somewhere between emissions and end-point are ‘midpoint’ indicators (see Figure 1 in Payraudeau and van der Werf, 2005; Bare and Gloria, 2006; Teillard *et al*., 2016). Another typology based on four categories was proposed by Lebacq *et al*. (2013): practice-based, system-state, emission and effect-based indicators. However, the authors recognised that system-state indicators are intermediate and can be grouped with emission indicators as in Bockstaller *et al*. (2008).

Bockstaller *et al*. (2011 and 2015) considered the nature or structure of environmental indicators (Figure 1) and proposed three categories for environmental indicators that may address a single theme: (a) simple indicator based on a causal variable or a simple combination of variables; (b) predictive indicators based on outputs from models of varying complexity; and (c) measured indicators based on field measurement or observation. Both (a) and (b) correspond to pressure variables while (c) correspond to state variables.

Some authors differentiate between (a) practice-based indicators (van der Werf and Petit, 2002) or action-oriented indicators (Braband *et al*., 2003) using information on farmers’ practices or other causal variables (corresponding to most of pressure indicators); and (b) effect-based indicators or result-oriented indicators, based on an assessment of the effect at different stages of the cause-effect chain (from emission to impact indicators) (Figure 1). With regard to biodiversity, indicators are often categorised in indirect (practice-based, e.g. nitrogen use on grassland as a predictor of vegetation diversity) or direct (effect-based, e.g. number of species in grassland vegetation) indicators (Clergué *et al*., 2005). The more reliance on effect indicators, the more reliance on the validity of the cause-and-effect model e.g. the predictive indicators in Figure 1.

The importance of valid cause-and-effect relationships cannot be understated. In an assessment of agri-environmen-

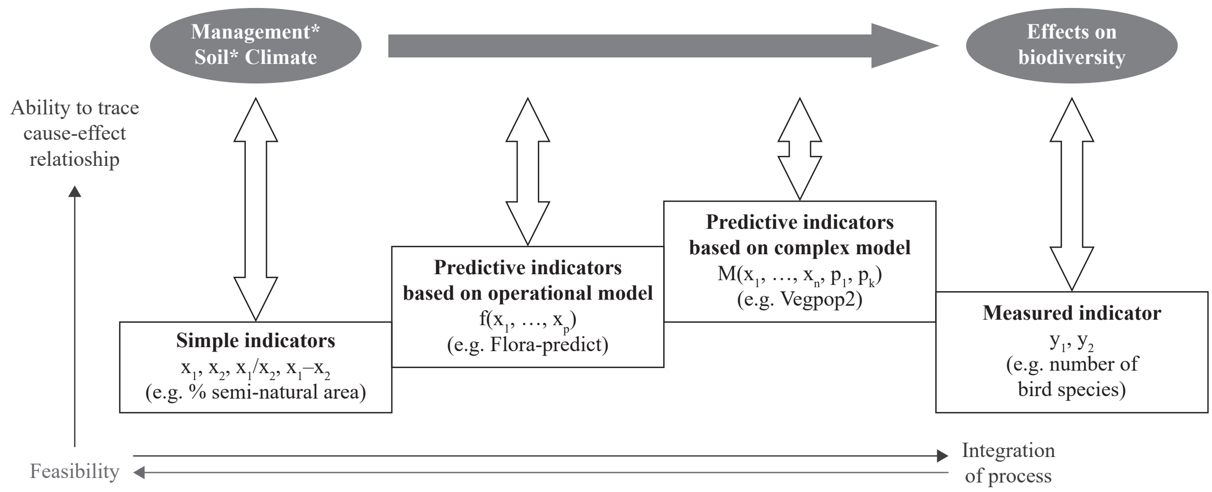

Figure 1: Typology of indicators according to their nature.
Source: Bockstaller *et al*. (2011)

tal policy measures in seven EU Member States, 51 per cent of management prescriptions were based on common-sense judgements about their possible impact rather than on documented evidence of the relationship between policy objectives, farming practices and environmental outcomes (Primdahl *et al*., 2010). Only a sixth of the measures studied were based on well-tested quantitative models. There are more general lessons from this example for policies that promote sustainability and for measurement of their effects. The absence of cause-and-effect models in policy design and assessment makes it difficult to assess the effects and to choose among alternative options. It also makes it difficult to identify the reasons for policy success; in the event of policy failure it hinders ability to identify and implement corrective actions.

Economic pillar

As suggested by van Cauwenbergh *et al*. (2007, p.238), agriculture should "provide prosperity to the farming community". In this context, economic sustainability is generally viewed as economic viability, namely whether a farming system can survive in the long term in a changing economic context. Changes in the economic context may be driven by variability in output and input prices, yields, output outlets, and public support and regulation. The concept of 'long term' can be understood as during the professional life of the farmer, or across generations. The latter is related to durability, i.e. the capacity of a farm to be transferred to a successor.

Economic viability is mainly measured through profitability, liquidity, stability and productivity. Profitability is calculated by comparing revenue and cost, either as a difference or as a ratio, or proxied by income variables such as farm income. Liquidity measures the availability of cash to meet immediate and short-term obligations, and stability is usually measured by the share and development of equity capital. Productivity is a measure of the ability of the factors of production to generate output. It is generally measured as a partial productivity indicator which is a ratio of output to one input, but also by measures that account for the possibility of input substitution or output substitution, such as total factor productivity (TFP) and technical efficiency (see Latruffe, 2010). Profitability and productivity indicators are mainly quantitative indicators and are expressed in monetary terms or as ratios; more rarely, reference scales are used.

Although measurement of economic sustainability does not typically extend beyond such economic indicators, a wider range of indicators has been proposed to capture other economic properties of farming systems that are associated with sustainability. Some studies refer to 'autonomy' (or dependence) as an indicator of economic sustainability. Autonomy is essentially a measure of one of the basic properties of every system: freedom (Bossel, 1999). For this reason, autonomy may also be seen as a social indicator. It can be viewed in terms of inputs, meaning that farms that rely less on external inputs (such as feed or fertilisers) are less sensitive to input availability and price fluctuations. Autonomy is also viewed in terms of financing, in other words with regard to the pressure of debts. Another aspect of autonomy is the diversification of income (whether farm income or household income). Farm income can be diversified by implementing non-agricultural activities on the farm such as direct sales, on-farm processing or agritourism, while household income can be diversified by off-farm employment held by farmers or their families (this is called income diversification). Subsidy dependence is another aspect of autonomy: if farms are highly dependent on public support, any policy reform that reduces subsidies could put farm sustainability at risk.

Social pillar

Social sustainability relates to people, and two main categories can be distinguished (Terrier *et al*., 2013). Firstly, there is social sustainability that matters at the level of the farm community. This is related to the well-being of the farmers and their families. Lebacq *et al*. (2013) grouped the indicators found in the literature into three main categories: education; working conditions (measured by working time, workload including pain, and workforce); and quality of life (measured by isolation and social involvement). Van Cauwenbergh *et al*. (2007) considered only quality of life as a social theme, but separated it into physical well-being (indicators related to labour conditions and health) and psychological well-being (indicators related to education, gender equality, family access to infrastructures and services, and the farmer's feeling of independence). Other aspects of well-being can also be considered, such as the physical health of workers (e.g. van Calker *et al*., 2007), although this can also be viewed as a consequence of working conditions.

Secondly, there is social sustainability that matters at the level of society. This is "related to society's demands, depending on its values and concerns" (Lebacq *et al*., 2013, p.315). Here Lebacq *et al*. (2013) grouped the indicators found in the literature into three main categories: multifunctionality (this includes quality of rural areas, contribution to employment and ecosystem services), acceptable agricultural practices (this includes environmental impacts and animal welfare), and quality of products (this includes food safety and quality processes). Van Calker *et al*. (2007) considered the contribution to the rural economy, which is less strict than the contribution to employment but could also be included in Lebacq *et al*.'s (2013) quality of rural areas. Van Cauwenbergh *et al*. (2007) added equity, as well as heritage, cultural, spiritual and aesthetic values. Also, the succession theme is sometimes included in the social sustainability dimension. For example, Gómez-Limón and Sanchez-Fernandez (2010) measured intergenerational continuity in agriculture, and Dillon *et al*. (2009) considered demographic viability.

Unlike most environmental and economic indicators, many social indicators are qualitative. They are difficult to quantify as they are often subjective. Indicators relating to the farm community are often based on farmers' self-evaluation through surveys or interviews.

Selection of indicators

As underlined by Lebacq *et al*. (2013), the choice of an indicator is crucial as it influences conclusions. It is crucial to use a procedure for selection of indicators that is well-defined, robust and transparent, so that the assessment is validated, credible and reproducible (Dale and Beyeler, 2001; Niemeijer and de Groot, 2008a). Therefore, careful choices have to be made before launching the process of sustainability assessment. For example, in the case of agri-environment schemes (AES), Mauchline *et al*. (2012, p.326) reported that "two evaluation methodologies applied to the same scheme produce two different overall conclusions when conducted by a multi-disciplinary team compared with an ecologist alone".

Selection processes

One of the primary challenges associated with indicator selection is highlighted by de Olde *et al*. (2016, p.2) who report a "startling lack of consensus" among a broad range of sustainability experts who were asked to rank the relative importance of criteria for selecting individual indicators and for balancing a collective set of indicators. The study suggests that while differences may arise as a result of different expert perspectives in relation to social and economic contexts, farming systems and end-users, the divergence in views also has a positive dimension, as a broad range of expertise and perspectives can improve our understanding of sustainability issues, lead to a more rigorous selection process and ultimately to the improved design of indicators.

The importance of a strong focus on the process of indicator selection is highlighted by de Olde *et al*. (2016) as being critical in the development of transparent, transformative and enduring indicators. Lebacq *et al*. (2013) described two main stages in the selection of indicators: (a) contextualisation of the assessment; and (b) comparison of indicators. In the first stage, also called the 'pre-modelling phase' (Alkan Olsson *et al*., 2009a) or the step of 'preliminary choices and assumptions' (Bockstaller *et al*., 2008), the purpose of the assessment needs to be clarified (in terms of precise objectives and end-users), and the system boundaries (in terms of issues/themes of concern, scope, time and spatial scales and the involvement and role of stakeholders in the assessment). In the second stage, comparisons should be based on various criteria which need to be precisely defined in advance. Lebacq *et al*. (2013) listed three main criteria: (a) relevance; this is related to the appropriateness of the indicator to the context and scale; (b) practicability, which consists of measurability, quantification and compatibility of the data with the aggregation method selected, and transferability to other farm types; and (c) end user value, relating to the appropriateness of the indicator to stakeholders' expectations in terms of clarity, comprehension and policy relevance.

Rice (2003) proposed additional criteria that can guide the selection of indicators: (a) representativeness, namely 'Can the dynamics of the indicator be taken to reflect more than the dynamics of the specific times and places where the data were collected?'; (b) availability of historic data, so that the performance of an indicator can be evaluated; (c) the theoretical basis, in particular 'the consistency of an indicator with ecological theory, but also the degree to which the diversity of professional views all accept the theoretical arguments'.

The criteria described above are 'ideal' criteria. However, one aspect that should not be forgotten is the operational capacity of an indicator in terms of cost. As explained by Pingault (2007), data should be available at an acceptable cost, and the cost related to the design and calculation of the indicator should also be tolerable. More generally, the author suggested considering the implementation cost, the cost of using the indicator, and the cost of adapting it to changes in the context.

Several authors highlighted the need to consider indicators as a set instead of single indicators for specific themes (e.g. Lyytimäki and Rosenström, 2008). Niemeijer and de Groot (2008a and 2008b), referring to environmental sustainability, stressed that indicators have to be selected on the basis of how they jointly provide an answer to our environmental questions. They recommended considering causal networks and the various causal chains that are inter-related within the networks. Lebacq *et al*. (2013) indicated three criteria for selecting a set of indicators: (a) parsimony, i.e. indicators should be as few as possible and not redundant; (b) consistency, i.e. all necessary indicators are in the set; and (c) sufficiency, that is to say that the set is exhaustive in the sense that it embraces all sustainability objectives.

Development of composite indicators

Individual indicators are built from raw/input data, and they may be aggregated to form aggregated indicators. Composite indicators are then the combination of individual and/or aggregated indicators representing different dimensions of sustainability (Figure 2).

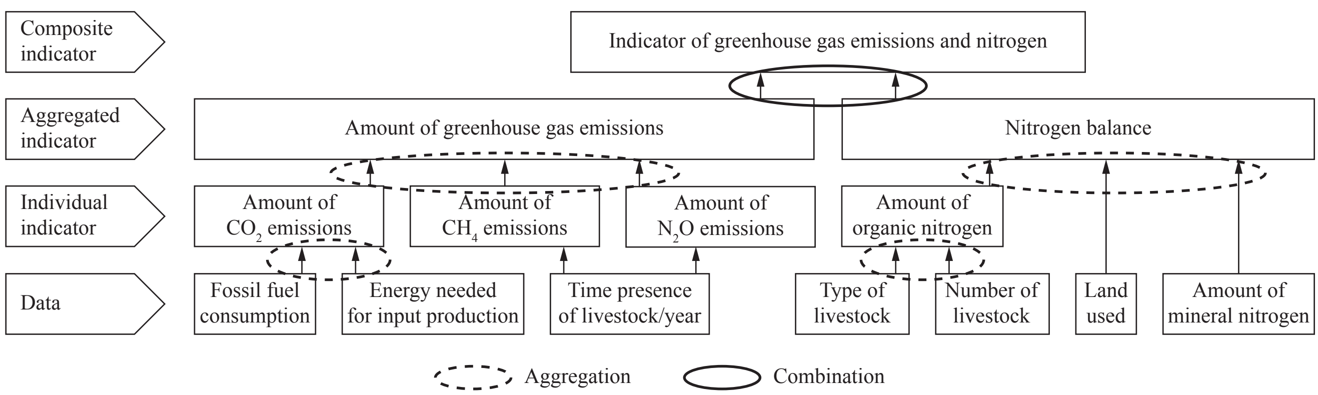

Figure 2: From raw data to composite indicators: an illustration.
Source: own composition

Many approaches are based on lists of indicators which are organised in more or less well-structured frameworks (see van der Werf and Petit, 2002; Géniaux *et al*., 2009; Singh *et al*., 2009). However, the question of aggregation arises when the objective is to comment on the sustainability outcome of a policy, or to compare two or more policy options via a set of indicators. There is a need for a methodology to combine diverse information in an explicit, consistent and transparent way, whilst presenting it in an easily intelligible form to facilitate policy evaluation. There are two general schools within the indicators community.

'Aggregators' prefer to combine different sources of information into a single value, with a sum or a weighted mean or using normalisation technique: linear scaling techniques, Gaussian normalisation distance to target, ranking by experts, categorical scales etc. (Géniaux *et al*., 2009). A crucial issue here is to choose the weights carefully. This may be done with the help of experts' and stakeholders' opinions (Finn *et al.*, 2009). Another aggregation approach is to convert all values into the same unit, monetary or physical (e.g. ecological footprint). Aggregation methods based on a common monetary unit as in cost-benefit analyses raise the complex issue of how to value non-market goods and services such as environmental assets, water quality, biodiversity etc.

By contrast, 'non-aggregators' caution about the subjectivity involved in aggregating and about the potential pitfalls in adding 'apples' and 'oranges' and the potential for loss of information in the aggregation process. A possible solution to these problems is multi-criteria analysis, which is a methodology for selecting between, or prioritising, different options described by a set of criteria (Sadok *et al*., 2008). Qualitative approaches can also be considered as a way to aggregate. These types of approaches lead to a conclusion in the form of a score for multiple classes of a given criterion (e.g. sustainability). There may be multiple scores, one for each of the major sub-themes (e.g. biodiversity, profitability). Such approaches are based on decision rules expressed as 'if then' rules, i.e. presented either as decision trees based on qualitative multi-attribute decision modelling or in the form of a dashboard (Bockstaller *et al*., 2009b). Reconciling both schools, Bockstaller *et al*. (2008) suggest to use both aggregated and individual indicators, where the former are used to compare systems and the latter are used to analyse each system. More generally, it may be necessary to use several methods in combination, as they may not produce the same results.

New indicators

Society's values and expectations of farming systems are changing and new principles have been added to the definition of sustainability such as governance, solidarity, transmission capital, local knowledge (e.g. Mancebo, 2006) and, more recently, innovation (e.g. Hennessy *et al*., 2013).

Many approaches to accomplishing the dual challenge of increasing agricultural production, while reducing its environmental impact, are based on increasing the efficiency of agricultural production relative to resource use and relative to unintended outcomes such as water pollution, biodiversity loss and greenhouse gas emissions (Bennett *et al*., 2014). This calls for a new category of indicators which measures the efficiency of production in relation to both inputs and environmental impact. In recent years there has been a concerted effort to monitor progress towards sustainable intensification (see, for example, Frater and Franks, 2013; Barnes and Thomson, 2014).

Innovation is a broad concept but it is fundamentally about embracing novelty. Thus, indicators of innovation can be used to gauge what farmers may be doing today that will impact on their future sustainability (OECD and Eurostat, 2005). The use of innovation or practice adoption as a measure of the long-term sustainability and resilience is relatively novel (van Galen and Poppe, 2013) and there is scope to broaden significantly the development of indicators of this aspect of sustainability (Ryan *et al*., 2016).

As the climate change debate intensifies, the concept of 'climate-smart agriculture' which builds on sustainable intensification to additionally take climate change into account, is gaining in prominence. However, according to Campbell *et al*. (2014), sustainable intensification is a 'cornerstone' of climate smart agriculture as increasing resource use efficiency contributes to both mitigation and adaptation by impacting positively on farm incomes and reducing emissions per unit product.

As our understanding of the interactions between the intensity of farming, its impact on the environment and climate change, and the role of innovation in these interactions become more important, new and more sophisticated indicators will have to be developed to quantify these interactions.

Conclusion

This overview underlines crucial decisions that need to be considered prior to an assessment of sustainability in agriculture. Choices should be made regarding the number of indicators, whether the selected indicators should apply to all case studies or whether they need to be adapted (in terms of indicator selection or setting threshold levels) to each case study (country, context, type of farming). Also, when simple indicators related to farm management practices (e.g. semi-natural area, or risk protection instruments respectively) are used instead of measured indicators measuring the sustainability outcome (e.g. biodiversity, or resilience respectively), then the causal direction between the simple indicator and the sustainability outcome should be fully clear. It should also be kept in mind that the effect of policies depends also on exogenous factors, that is to say on factors beyond the control of farmers such as climatic and topographic characteristics of their location, or position of the farm in its life cycle. In the words of Russillo and Pintér (2009, p.45): "The producer does not want to be held accountable for outcomes he or she cannot control". The participation of stakeholders within the process is crucial, as society's demands are constantly changing and therefore the range of indicators and frameworks need to be adapted (Lyytimäki and Rosenström, 2008; Lebacq *et al*., 2013). In addition, farmers who are surveyed within a sustainability assessment need to be convinced to provide their information: "Those collecting the data need to compensate the farmer through information that has value or other incentives" (Russillo and Pintér, 2009, p.45).

We highlight several themes for which few indicators are available. These typically concern social themes which to date are poorly investigated in the literature. Agriculture contributes to the quality of life in rural areas in terms of economic contribution (e.g. the level of farm output is crucial for the viability of upward and downward industries; the presence of farms helps keep a minimal level of public services in rural areas) and environmental contribution (e.g. creation of landscape; reduction of pollution). Hence, the social sustainability of farms (and, more broadly, of agriculture) is the dimension that would need the most development of indicators in the future. Indicators of innovative practices that promote more efficient use of natural resources and the resilience of farmers are also likely to become more important in the context of climate smart agriculture.

While this paper describes the concepts around indicator importance and selection, the range of farm-level data available limits the indicators that can be currently developed. Although this limitation can be addressed by collecting additional data and by using existing datasets or expert opinion, the most valuable use of sustainability indicators lies not in the interpretation of the (absolute or relative) values in any time period, but in the evaluation of trends in indicators over time that are of concern to stakeholders generally and policy makers in particular.

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