A Literature Review on Frameworks and Methods for Measuring and Monitoring Sustainable Agriculture

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Contents

Acronyms

DSR	driving-force-state-response (method)
IDEA	*indicateurs de durabilité des exploitations agricoles* (farm sustainability indicators)
OECD	Organization for Economic Cooperation and Development
PG	public goods
RISE	response-inducing sustainability evaluation
SAFA	sustainability assessment of food and agriculture systems

1. Agriculture – elements and definition

The activity termed "agriculture" encompasses several different elements such as crops, livestock, fisheries, aquaculture and forestry. Spedding (2012) notes that the first issue to clarify is "What is agriculture?" Although there is general agreement as to the types of things, people, plants and animals that can be included in the concept, this is inadequate if the objective is the measurement of agricultural sustainability. Even so, few attempts have been made to formulate a precise definition that is measurable, nationally relevant and internationally comparable. There are many useful umbrella terms for sustainable agriculture that cover numerous different elements, but their usefulness may be limited if they are defined too rigidly.

Agriculture is a major human activity, and one that has a purpose. In an overall perspective, agriculture is defined as an activity carried out primarily to produce food, fibres, fuel and other commodities through the controlled use of mainly terrestrial plants and animals (Spedding, 2012).

The Spedding definition attempts to cover all systems of agriculture i.e. – crops, livestock, fisheries, aquaculture and so on – but each system has individual characteristics which creates some difficulties with regard to measurement. A number of production systems, for example, are based in buildings and use little or no land: they do handle biological organisms, usually in highly controlled environments, and yet nobody would classify them as "farming[1]". The major crop-production systems are designed to produce food for human consumption, feed for animals, fibres for fuel, construction or manufacturing, and miscellaneous products such as tobacco and ingredients for perfumes and drugs.

In terms of land area used, seven major crops – wheat, rice, maize, pulses, roots and tubers, sugar and cotton – occupy the largest proportion of the word's cultivated areas. Their importance is evident in that they contribute substantially to the energy intake of the world's population (Spedding, 2012). Ten Napel *et al*. (2011) show that the practice of agriculture started approximately 10,000 years ago when humans sought to produce food, feed and other useful biomass through the management of biological and ecological systems, with technical inputs. In this context, livestock production or farming systems constitute one of the most important agricultural sectors.

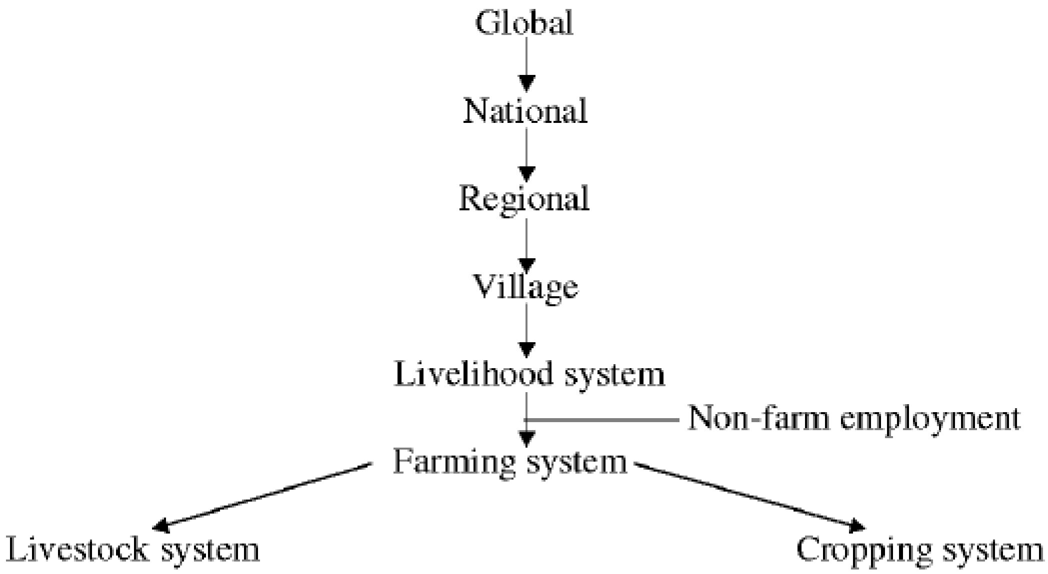
Smith and McDonald (1997) consider the scope of agriculture in terms of spatial scale, emphasizing that at the field scale agriculture is largely concerned with soil conditions, nutrient levels, water availability and plant growth. At the farm scale, agriculture is concerned with crop and livestock production and management, and the organization and viability of farm operations. At the regional scale, agriculture is a major factor in natural resource use and land use. And at the national and global scales, agriculture involves trade, equity (such as equitable distribution of income) and the supply of sufficient food.

Since the first agricultural revolution approximately 10,000 years ago, crop growing and livestock raising have been the primary causes of loss and degradation of natural ecosystems. Today, 37 percent of the Earth’s land surface other than Antarctica is dedicated to growing food: 12 percent is cropland and 25 percent is grazing land. Most current changes in land-use involve forests, wetlands and grasslands being converted into farms and pastures: for example, agriculture was responsible for about 80 percent of tropical deforestation between 2000 and 2010 (Reytar *et al*., 2014).

[1]. "Faming" and "Agriculture" are used interchangeably. But, it should be noted that they are different concepts. This study follows the measurement of agricultural sustainability as a whole and farming is considered as a distinct (common) form of agriculture.

Rao and Rogers (2006) state that an agro-ecosystem is an ecological and socio-economic system comprising domesticated plants and/or animals and the people who husband them with a view to producing food, fibre or other agricultural products. Agro-ecosystems defined in this way are hierarchical, starting from cropping systems and livestock systems to farming systems, village systems and global-level systems (see Figure 1). At each level there are distinct attributes for which sustainability indicators can be derived.

Figure 1. Hierarchy of agro-ecosystems



On the basis of the earlier discussion about "agriculture", it can be said that there are different interpretations of the term, but that the definition of agriculture in this literature review mainly refers to cropping, land-based or cultivation-based agriculture and livestock production and management.

2. The concepts and definitions of sustainable agriculture

The idea of "sustainable agriculture" has gained prominence since the publication of the Brundtland Report in 1987,[2] in line with the overarching concept of "sustainable development" (Velten *et al*., 2015). Sustainability in agricultural systems is widely discussed, and is viewed in international fora as essential for the transition to global sustainable development (Organization for Economic Cooperation and Development [OECD], 2001; Binder *et al*., 2010).

Despite wide consensus as to its relevance, there has been considerable variation in terms of how sustainability in agriculture is defined and how it is actually pursued in the policy-making process (Binder *et al*., 2010). This is partly because it is a derivative of a range of "alternative" agricultures such as organic, regenerative, low-input and ecological agriculture (Lockeretz, 1988; Dunlap *et al*., 1992).

It also reflects the fact that competing stakeholders tend to define sustainability in ways that serve their particular interests (Dunlap *et al*., 1992; Allen *et al*., 1991). The lack of agreement

[2] Published as *Our Common Future* by the United Nations World Commission on Environment and Development. Its targets were multilateralism and interdependence of nations in the search for a sustainable development path.

on the definition has led some researchers such as Hansen (1996) to question the usefulness of the concept of “agricultural sustainability” (Binder *et al*., 2010), and it has allowed vested interests to exploit the concept and use it for their own purposes (Constance, 2009; Velten *et al*., 2015).

It should be noted that the idea of agricultural sustainability was first published in the 1798 work by Thomas Malthus *An Essay on the Principle of Population*. Malthus drew attention to possible unlimited population growth that could outstrip humanity's ability to produce food, leading to starvation and wars. This had not happened by the beginning of the 21st century because our growing need for food was satisfied through technological development, but in this context constraints on economic growth and the consequent adverse effects on agricultural productivity have become more and more important (Feher and Beke, 2013).

The concept of sustainable agriculture became widespread in the 1980s, and at least 70 definitions can be identified in the literature. These differ in subtle ways, reflecting different values, priorities, and goals (Pretty 1995; Zhen and Routray, 2003).

Attempting to arrive at a precise, operational and absolute definition of sustainable agriculture is exceptionally challenging, partly because there are a wide variety of parties involved in the debate (Pretty and Hine, 2000; Rigby and Caceres, 2001). To put it briefly, three dimensions and various levels are used to assess sustainability in agriculture, as shown in Table 1.

Table 1. Basic dimensions and levels for assessing agriculture sustainability

Dimensions	Levels
Normative	Ecological aspects Economic aspects Social aspects
Spatial	Local Regional National
Temporal	Long-term Short-term

Source: Zhen and Routray (2003); Hayati *et al*., 2010.

There have been numerous attempts to define sustainable agriculture. All try to address the challenge of reducing the ambiguity around the concept and making it more concrete (Velten *et al*., 2015). Table 2 shows the various concepts and definitions of sustainable agriculture compiled by Hansen (1996); Table 3 gives 44 definitions published between 1984 and 2016.

Table 2. Concepts and definitions of sustainable agriculture

1. Sustainability as an ideology	**Source**
Sustainable agriculture is a philosophy and system of farming. It has its roots in a set of values that reflect a state of empowerment, of awareness of ecological and social realities, and of one's ability to take effective action.	MacRae *et al*., 1990
...an approach or a philosophy...that integrates land stewardship with agriculture. Land stewardship is the philosophy that land is managed with respect for use by future generations.	Neher, 1992
...a philosophy based on human goals and on understanding the long-term impact of our activities on the environment and on other species. Use of this philosophy guides our application of prior experience and the latest scientific advances to create integrated, resource-conserving, equitable farming systems.	Francis and Youngberg, 1990
...farming in the image of Nature and predicated on the spiritual and practical notions and ethical dimensions of responsible stewardship and sustainable production of wholesome food.	Bidwell, 1986
2. Sustainability as a set of strategies	
...a management strategy which helps the producers to choose hybrids and varieties, a soil fertility package, a pest management approach, a tillage system, and a crop rotation to reduce costs of purchased inputs, minimize the impact of the system on the immediate and the off-farm environment, and provide a sustained level of production and profit from farming.	Francis *et al.*, 1987
...a loosely defined term for a range of strategies to cope with several agriculturally related problems causing increased concern in the US and around the world.	Lockeretz, 1988
Farming systems are sustainable if "they minimize the use of external inputs and maximize the use of internal inputs already existing on the farm".	Carter, 1989
...(a) the development of technology and practices that maintain and/or enhance the quality of land and water resources; and (b) the improvements in plants and animals and the advances in production practices that will facilitate the substitution of biological technology for chemical technology.	Ruttan, 1988
3. Sustainability as the ability to fuel a set of goals	
A sustainable agriculture is one that, over the long term, enhances environmental quality and the resource base on which agriculture depends, provides for basic human food and fiber needs, is economically viable, and enhances the quality of life for farmers and society as a whole.	American Society of Agronomy, 1989
...agricultural systems that are environmentally sound, profitable, and productive and that maintain the social fabric of the rural community.	Keeney, 1989
...an agrifood sector that over the long term can simultaneously (1) maintain or enhance environmental quality, (2) provide adequate economic and social rewards to all individuals and firms in the production system, and (3) produce a sufficient and accessible food supply.	Brklacich *et al*., 1991
...an agriculture that can evolve indefinitely toward greater human utility, greater efficiency of resource use, and a balance with the environment that is favourable both to humans and to most other species.	Harwood, 1990
4. Sustainability as the ability to continue to survive	
A system is sustainable over a defined period if outputs do not decrease when inputs are not increased.	Monteith, 1990
Sustainability is the ability of a system to maintain productivity in spite of a major disturbance, such as is caused by intensive stress or a large perturbation.	Conway, 1985
...the maintenance of the net benefits agriculture provides to society for present and future generations.	Gray, 1991
Agriculture is sustainable when it remains the dominant land use over time and the resource base can continually support production at levels needed for profitability (cash economy) or survival (subsistence economy).	Hamblin, 1992

Table 3. Definitions of sustainable agriculture

Definition	Source
Sustainability as food sufficiency: Agriculture is sustainable when farmers produce enough food to meet reasonable projections of global market demand.	Douglass, 1984
Sustainability as stewardship: Global agriculture is sustainable if both the real economic costs of production and the real environmental costs of production are expected to remain constant or to fall as production expands to meet future demands for foodstuffs.	
Sustainability as community: Agriculture will be found to be sustainable when ways are discovered to meet future demands for foodstuffs without imposing on society real increases in the social costs of production and without causing the distribution of opportunities or incomes to worsen.	
Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs	Francis *et al.*, 1987
Sustainability is the ability of an agro-ecosystem to maintain production through time, in the face of long term ecological constraints and socioeconomic pressures.	Altieri, 1987; reported by Goldman, 1996
The concept of sustainable development encompasses: - help for the very poor...; - ... self-reliant development, within natural resource constraints; - ... development should not degrade environmental quality, nor should it reduce productivity in the long run; - ... health control, appropriate technologies, food self-reliance, clean water and shelter for all; - people-centred initiatives...; human beings, in other words, are the resources in the concept.	Tolba, 1987
In the narrowest sense, global sustainability means the indefinite survival of the human species across all the regions of the world .... The broadest sense of global sustainability includes the persistence of all components of the biosphere, even those with no apparent benefit to humanity.	Brown *et al*., 1987
Any definition of sustainability suitable as a guide to agricultural practice must recognize the need for enhancement of productivity to meet the increased demands created by growing populations and rising incomes.	Ruttan, 1988
Sustainable agriculture must be ecologically sound, economically viable, socially just, and culturally appropriate.	Goldman, 1995
Sustainability should involve the successful management of resources for agriculture to satisfy changing human needs while maintaining or enhancing the quality of the environment and conserving natural resources	Consultative Group on International Agricultural Research, 1989; reported by Goldman, 1995
Sustainable Agriculture comprises "...management procedures that work with natural processes to conserve all resources, minimize waste and environmental impact, prevent problems and promote agro-ecosystem resilience, self-regulation, evolution and sustained production for the nourishment and fulfilment of all".	MacRae *et al*., 1989
We define sustainability as the capacity of a system to maintain output at a level approximately equal to or greater than its historical average, with the approximation determined by its historical level of variability. Hence, a sustainable system is one with a non-negative trend in measured output; a technology adds to system sustainability if it increases the slope of the trend line.	Lynam and Herdt, 1989
...sustainable agriculture attempts to mimic the key characteristics of a natural ecosystem...	Hauptli *et al*., 1990
We define agricultural sustainability as the ability to maintain productivity, whether of a field or farm or nation, in the face of stress or shock. A stress may be increasing salinity, erosion, or debt; ... a frequent, sometimes continuous, relatively small, predictable force having a large cumulative effect .... [A shock is] a force that was relatively large and unpredictable.	Conway and Barbier, 1990
We take development to be a vector of desirable social objectives... [which] might include: increases in real income per capita; improvements in health and nutritional status; educational achievement; access to resources; a 'fairer' distribution of income; increases in basic freedoms .... Sustainable development is a situation in which the development vector does not decrease over time.... [There is also a] set of minimum	Barbier *et al*., 1990

conditions for development to be sustainable .... based on the requirement that the natural capital stock should not decrease over time.	
For a farm to be sustainable, it must produce adequate amounts of high-quality food, protect its resources and be both environmentally safe and profitable. Instead of depending on purchased materials such as fertilizers, a sustainable farm relies as much as possible on beneficial natural processes and renewable resources drawn from the farm itself.	Reganold *et al*., 1990
The management and conservation of the natural resource base, and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such development (in agriculture, forestry and fishing etc.) conserves land, water, plant and animal genetic resources, is environmentally non-degrading, technically appropriate, economically viable and socially acceptable.	Food and Agriculture Organization of the United Nations (FAO), 1991
A sustainable process is one that can be maintained without interruption, weakening, or loss of valued qualities. Sustainability is a necessary and sufficient condition for a population to be at or below any carrying capacity	Daily and Ehrlich, 1992
An average definition would include such elements as soil fertility and productivity (rotations, integrated pest management and biological control, tillage methods, crop sequences), controlling pesticide and fertilizer pollution, management strategies (choice of hybrids and varieties, low cost inputs, etc.), human needs (demands for basic food and fibres), economic viability, social acceptability, ecological soundness, time span (long term as opposed to short term profitability), and philosophical ethics (implying satisfaction of spiritual and material goals of mankind)	Farshad and Zinck, 1993
(1) Sustainability refers to the qualitative and quantitative continuity in the use of a resource. As a general concept, it may be applied to development, of which agriculture may be only one of the components. (2) Sustainable agriculture is dynamic because it is coupled with both land use, which reflects the changing needs of population, and world economy. (3) Sustainability implies a state of equilibrium between human activities as influenced by social behaviour, acquired knowledge and applied technology, on the one hand and the food production resources on the other. Most renewable natural resources are sustainable before human intervention. (4) Sustainability does not only mean feeding the present and future population, but also requires an improved infrastructure and a stable economy. Equitability, being a measure of how welfared the human beneficiaries of a system are, is one of the major issues in sustainability. (5) Sustainable agriculture entails that the food production resources (soil, water, biota, etc.) be properly managed so that the applied practices do not cause degradation and/or pollution.	Farshad and Zinck, 1993
Sustainable agriculture in developing countries implies: 1) Intensive farming, thus increasing land use efficiency and productivity through diversified cropping patterns, such as intercropping, mixed cropping and multiple cropping; 2) Maximum use of internal resources and balanced use of external resources. Balanced use of external inputs means that the use of chemical fertilizers should be based on soil nutrient status, dosage of pesticides use should refer to recommended dosages of pesticides for specific pests or diseases, and the use of irrigation water should be based on the water demand of different crops and the availability of water resources; 3) Profitable and efficient production, with an emphasis on increased production, per capita products and net farm income; 4) The inherent capacity of soil and water resources that support agricultural production are maintained or improved over time; and 5) A greater productive use of local knowledge and practices, and enhanced innovation and application of resource conservation technologies.	Bowers, 1995
Sustainable agriculture has been described as an umbrella term encompassing several ideological approaches to agriculture (Gips, 1988) including organic farming, biological agriculture, alternative agriculture, ecological agriculture, low-input agriculture, biodynamic agriculture, regenerative agriculture, permaculture and agro-ecology	Hansen, 1996; reported by Goldman, 1995
Szakál classified the definitions into four main groups: a group emphasizing the maintenance of human well-being, in a way that the situation of future generations will not be worse than that of present generation, a group with concepts built on the survival of the human race, a group with concepts built on the flexibility of producing systems, and finally the group of non-economic concepts, whose major role is to	Szakal, 1998; reported by Feher and Beke, 2013

preserve cultural heritage and communities and maintain the diversity of the ecological system.	
Sustainable agriculture is multi-functional within landscapes and economies-it produces food and other goods for farm families and markets, but it also contributes to a range of public goods, such as clean water, wildlife, carbon sequestration in soils, flood protection, and landscape quality. It delivers many unique non-food functions that cannot be produced by other sectors (e.g. on-farm biodiversity, urban to rural migration, social cohesion).	Pretty and Hine, 2000
Sustainability is defined by seven general attributes of NRMS [natural resource management systems]: (a) productivity, (b) stability, (c) reliability (d) resilience, (e) adaptability; (f) equity; (g) self-reliance (self-empowerment).	López-Ridaura *et al*., 2002
Sustainable agriculture (a) conserves the resources on which it depends; (b) restricts itself to a minimum input of production means, which do not have their origin in the same farming system; (c) controls pests and diseases by internal regulation processes as far as possible; (d) provides natural resources with the ability to recover from disturbances through cultivation means and harvesting by processes of natural succession.	Buchs, 2003
Sustainable Agriculture adopts productive, competitive and efficient production practices, while protecting and improving the natural environment and the global ecosystem, as well as the socio-economic conditions of local communities.	Hani *et al*., 2003
...sustainable agriculture is viewed as low-input and regenerative, which makes better use of a farm's internal resources through incorporation of natural processes into agricultural production and greater use of improved knowledge and practices. It uses external and non-renewable inputs to the extent that these are deficient in the natural environment.	Rasul and Thapa, 2004
Sustainable agriculture is an integrated system of plant and animal production practices having a site specific application that will over the long term -Satisfy human food and fiber needs; -Enhance environmental quality; -Promote efficient use of renewable resources; -Sustain the economic vitality of farm operations; and -Enhance the quality of life for farmers and society as a whole.	Horne and McDermott, 2005
...it is generally agreed that sustainable agriculture must satisfy economic, social and environmental objectives. Sustainable agriculture must achieve productivity in perpetuity without accompanying ecologic and social harm.	Swaminathan, 2006
...agricultural sustainability should be viewed from three alternative perspectives: people, planet and profit.	Bos *et al*., 2007
...agricultural sustainability centre on the need to develop agricultural technologies and practices that: (i) do not have adverse effects on the environment, (ii) are accessible to and effective for farmers, and (iii) lead to both improvements in food productivity and have positive side effects on environmental goods and services.	Pretty, 2008
...the best approach to analysing agricultural sustainability is to assess it through the lens of economic growth, environmental protection and social progress.	Pretty *et al*., 2008
Sustainable agriculture and rural development seeks an appropriate balance between food self-sufficiency and food self-reliance; employment and income generation in rural areas, particularly to eradicate poverty; and natural resource conservation and environmental protection.	Guttenstein *et al*., 2010
...activity that permanently satisfies a given set of conditions for an indefinite period of time (Hansen, 1996). These conditions are related to the multidimensional character inherent in the concept of sustainable development, which requires this activity to be sustainable from the triple perspective of economics (profitable operation), social justice (fair and equitable distribution of the wealth it generates) and environmental friendliness (compatible with the maintenance of natural ecosystems).	Gómez-Limón and Sanchez-Fernandez, 2010
...about the definition of "sustainable agriculture" as an activity that permanently satisfies a given set of conditions for an indefinite period of time. These conditions are highly congruent to the multidimensional attributes inherent in the concept of sustainable development, highlighting ecological stability, economic viability and socially fair agricultural systems.	Roy and Chan, 2012
Sustainability is a "contextual concept". But in general, it means: 1. Maintain a high yield and productivity of rice that ensure economic viability;	Chan *et al*., 2013

2. Less ecologically degrading production systems with special emphasis on the preservation and improvement of the natural resources; 3. Signify the quality of producers' life in terms of adequate access to information, education, market and decision-making.	
An integrated system of plant and animal production practices having a site-specific application that will, over the long term, satisfy human food and fiber needs; enhance environmental quality and the natural resource base upon which the agricultural economy depends; make the most efficient use of non-renewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls; sustain the economic viability of farm operations; and enhance the quality of life for farmers and society as a whole.	Definition by United States Congress; reported by Feher and Beke, 2013
Need to safeguard agricultural products, while protecting and improving the natural environment and social/economic conditions of local communities.	Frater and Franks, 2013
...it is generally agreed that sustainable agriculture must satisfy economic, social and environmental objectives. Sustainable agriculture must achieve productivity in perpetuity without accompanying ecologic and social harm.	Van Pham and Smith, 2014
Sustainable agricultural systems are those that aim to make the best use of environmental goods and services while not damaging these assets.	Van Pham and Smith, 2014
Sustainable agriculture arises as alternatives approach to conventional agriculture, which including the use of on-farm or locally available resources, reduced use of synthetic fertilizers and pesticides, increased use of crop rotations and organic materials as soil ameliorates, diversification of crop and animal species and reduced stocking rates.	Waney *et al*., 2014
The core concept in defining agricultural sustainability is multidimensionality and so sustainability of agriculture is based on the economic, ecological and social dimensions.	Jane Dillon *et al*., 2015
The sustainability of agricultural system can be evaluated in terms of its ability to maintain certain well-defined level of performance over time, and enhance the same through link-ages with other systems without damaging the ecological integrity of the system.	Chand *et al*., 2015
Integrated system of plant and animal production practices having a site specific application that will, over the long term: (a) satisfy human food and fiber needs; (b) enhance environmental quality; (c) make efficient use of non-renewable resources and on-farm resources and integrate appropriate natural biological cycles and controls; (d) sustain the economic viability of farm operations; and (e) enhance the quality of life for farmers and society as a whole.	Velten *et al*., 2015
Sustainable agriculture is defined using the taxonomy of ''levels'' of practices from a spectrum supporting socio-ecologically sustainable food systems. The levels instrumental to this analysis are: improving system efficiency to reduce the use of inputs (L1), substituting more sustainable inputs and practices into farming systems (L2), redesigning systems based on ecological principles (L3: agro-ecology), and re-establishing connections between producers and consumers to support a socio-ecological transformation of the food system (L4: social dimensions of agro-ecology). A fifth level of sustainable agriculture describes the establishment of an equitable, participatory, and just food system that is built upon the farm-scale practices of L3 and the food relationships supported by L4.	De Longe *et al*., 2016

As previously discussed, sustainability in agricultural systems is viewed as a prerequisite for transition to sustainable development at the global level. Despite general consensus as to its relevance, there is no agreement with regard to the definition of sustainability in agriculture; as highlighted earlier, this is partly because it is a derivative of a range of "alternative" agricultures that includes organic, regenerative, low-input and ecological agriculture (Lockeretz, 1988). The concept of sustainable agriculture encompasses different aspects of agriculture in different regional and country contexts (Zhen and Routray, 2003). A review of the definitions of sustainable agriculture, however, reveals some agreement and commonalities on the concept. Most of the definitions, for example, take into account the three pillars of sustainability – environmental, social and economic. Table 3 shows the multi-dimensional approach developed in FAO (1991) with a view to encapsulating it adequately: "The management and conservation of the natural resource base, and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such development (in agriculture, forestry and fishing etc.) conserves land, water, plant and animal genetic resources, is environmentally non-degrading, technically appropriate, economically viable and socially acceptable".

The three-pillar approach is currently the most comprehensive in terms of defining sustainable agriculture, a fact emphasized in various studies. An evaluation of the definitions given in Table 3 shows that the FAO (1991) definition is the most appropriate, and hence suitable for identifying and designing agricultural sustainability indicators.

3.The main principles and characteristics of agricultural sustainability

According to Pretty (1996), sustainable agriculture is any system of food or fibre production that systematically seeks the following goals:

i. incorporation of natural processes such as nutrient cycling, nitrogen fixing and pest/predator relationships into the agricultural production process;
ii. minimum use of off-farm, external and non-renewable inputs;
iii. equitable access to productive resources and opportunities, and progress towards socially just forms of agriculture;
iv. maximum self-reliance among farmers and rural people;
v. long-term sustainability of production levels; and
vi. profitable and efficient production, with an emphasis on integrated farm management and the conservation of soil, water, energy and biological resources.

But in order to put the concept of sustainability into practice, it must be understood holistically. Rasure (2010), drawing on the recommendations of Swaminathan (1999), described 14 major dimensions of sustainable agriculture that cover the multi-dimensional aspects of sustainability: technological appropriateness, economic feasibility, economic viability, environmental soundness, temporal stability, efficiency of resource use, local adaptability, social acceptability, political acceptability, administrative manageability, cultural desirability, equity and productivity.

Lockeretz (1988) sets out the following physical and biological parameters for sustainable agriculture:

i. diversity of crop species;
ii. selection of crops and livestock that are adapted to a particular environment;
iii. preference for farm-generated resources rather than purchased inputs;
iv. tightening of nutrient cycles to minimize nutrient losses;
v. livestock housed and grazed at low densities;
vi. optimum storage of nutrients in the soil;
vii. maintenance of protective cover on the soil;
viii. rotations that include deep-rooted crops, and control of weeds;
ix. use of soluble inorganic fertilizer; and
x. use of pesticides for crop protection only as a last resort.

Pretty (1996) and Rasure (2010) recommend the following goals and parameters of sustainable agriculture:

- Environmental soundness. Producers create and sustain cultivated landscapes that are complex, diverse and balanced biological systems, and implement practices that conserve and restore resources.
- Animal management. While being raised, animals are allowed to engage in the natural behaviours important to their well-being, and are harvested in ways that minimize stress to the animals and the environment.
- Economic viability. Producers operate within a framework of sound business planning and pursue integrated and proactive approaches to marketing and sales.
- Social justice. Producers and their employees receive fair and reasonable compensation, and work in a safe and respectful environment.

The fundamental principles for agricultural sustainability in developing countries as summarized by Zhen and Routray (2003) and Pretty (2008) are:

i. optimum land-use efficiency and productivity;
ii. maximum use of internal resources, and minimal use of non-renewable resources;
iii. profitable and efficient production, with an emphasis on maximum net farm income;
iv. maintenance of natural resources that support agricultural production; and
v. maximum use of locally appropriate farming practices and natural resource-conservation strategies.

Appropriate principles and indicators of sustainable agriculture in a country or region can hence be found in the following dimensions (Saifi and Drake, 2008):

i. value system and ethics;
ii. traditional agriculture;
iii. demand for food;
iv. technological development;
v. energy and biomass;
vi. on-farm natural resources;
vii. off-farm natural resources;
viii. degradation of ecological systems and the environment;
ix. food safety and other health considerations;
x. food security and regional distribution; and
xi. farm economy.

Study of the sustainability issues in the above dimensions for a particular country or region and consideration of the relationships between them should enable us to identify a limited number of reasonable principles for sustainable agriculture. The eleven dimensions above are relevant to sustainability in most agricultural systems, but they will vary with respect to different societies, different periods of development in a given society and within communities in relation to nutrient circulation and local ecological systems. Certain principles may be valid for a number of communities and societies, and also relevant to different dimensions: the integration of crop and animal production is an example. Sustainable agricultural development, however, cannot be based on one or some of the principles because there will be conflict and reinforcement between them, even in a particular country or region.

4. Explaining the need for monitoring and measuring of agricultural sustainability

Academic, scientific and policy-making communities have focused their attention in recent years on the concepts of the “sustainable environment” and “sustainable development” (Zhen and Routray, 2003; and others). This has been accompanied by attempts to develop practical systems for measuring sustainability in the different systems of farming, cropping and livestock raising on which humanity depends for subsistence. Zhen and Routray (2003) urge agricultural researchers to: i) recognize the importance of sustainability in agricultural systems; ii) devise ways of measuring sustainability; and iii) examine empirically the sustainability of some well-defined cropping or farming systems and develop methods to measure it.

In any study of sustainable agriculture, in other words, the question arises as to how agricultural sustainability can be measured. David (1989), Webster (1999) and Hayati *et al*. (2010) argue that the concept of sustainability is a "social construct"; Webster (1997) observes that it had yet to be made operational. Precise measurement of sustainability is impossible because it is a dynamic concept and site-specific (Ikerd, 1993) and because what is defined as "sustainable" depends to some extent on the perspectives of the analysts (Webster, 1999). But even if precise measurement of sustainable agriculture is not possible, "... when specific parameters or criteria are selected, it is possible to say whether certain trends are steady, going up or going down... " (Hayati *et al*., 2010).

Agricultural practices that erode soil, destroy the habitats of insect predators and cut trees down without replacing them can be considered "unsustainable"; sustainable systems conserve these resources. According to Altieri (1995), farmers can improve the biological stability and resilience of their systems by choosing suitable crops, rotating them, growing a mixture of crops and irrigating, mulching and manuring the land. Lynam and Herdt (1989) observe that sustainability can be measured by examining changes in yields and total factor productivity. Beus and Dunlap (1994) consider that practices such as the use of pesticides and inorganic fertilizers and maintenance of diversity are features of sustainable agriculture; Hayati *et al*. (2010) note that for sustainable agriculture, a major requirement is sustainable management of land and water resources.

Nonetheless, sustainability assessments are a significant aid to this process, and a growing number of sustainability assessment tools and frameworks have been developed to support decision-making in agriculture (Gasparatos 2010; Marchand *et al*., 2014). But few of them consider the holistic indicators that must be applied at the global level to enable measurement and monitoring of agricultural sustainability in different countries. And because they are context-specific, these tools and frameworks do not provide a robust basis for comparing countries in terms of agricultural sustainability. Hence the recommendation is to introduce a set of indicators that enables countries to evaluate the sustainability of their own agricultural sector and subsequently compare their status with other countries. Such sets of indicators should be cost-effective, and the countries with different agricultural systems such as cropping and livestock raising should be able to implement them. To achieve this, policymakers will need accurate, transparent and up-to-date information on crop and livestock production, adoption of new technologies, land degradation, fertilizer and pesticide use, availability of credit and machinery, water use and efficiency, labour, agrochemicals, diversity of crop and animal breeds, trade, end-of-year stocks, non-food uses of crops, food prices, post-harvest food losses and waste (United Nations Sustainable Development Solutions Network, 2014).

The development of such indicators has value in several respects: i) in promoting and developing discussion of sustainable agriculture in practice by assessing actual farms in terms of input use; ii) in enhancing understanding of the nature of indicators and the need for them, and considering the practical issues relating to their design and validation; and iii) in showing how the indicators can advance discussion of organic and conventional agriculture in relation to policies for agricultural sustainability. The experience of constructing a holistic set of global indicators for monitoring and measuring agricultural sustainability will highlight the potential and limitations of the approach and show where further work is worthwhile (Rigby *et al*., 2001).

Sustainability indicators are increasingly seen as important tools in the assessment and implementation of sustainable farming systems, and numerous lists and matrixes of suggested indicators already exist (Hayati *et al*., 2010; Zhen and Routray, 2003).

5. Terminology used in assessing agricultural sustainability

Sustainable agriculture is a time-specific and location-specific concept, so any assessment of sustainability must be linked to the context in which a farming system operates. The current problem in the assessment of farming systems is obtaining and applying acceptable spatial and temporal indicators to find out whether a particular practice is sustainable or not. This challenging problem arises in part because sustainability normally involves at least three independent but interrelated dimensions – ecological, economic and social. Sustainability in these dimensions may be difficult to reconcile because each will have a different time-scale and perspective in each context (Zhen and Routray, 2003).

Components for measuring Agricultural sustainability

Various approaches to measuring agricultural sustainability have been proposed: these can, for simplicity, be classified into three groups – social, economic and ecological – as shown in Table 4 (Hayati *et al*., 2010, with some revision).

Table 4: Three components of agricultural sustainability

Component	Item	Sources
Social	Education levels of household members	Herzog and Gotsch, 1998; Von Cauwenbergh *et al*., 2007
	Housing facilities	Herzog and Gotsch, 1998
	Work/study	Herzog and Gotsch, 1998
	Nutritional and health status of family members	Herzog and Gotsch, 1998; Rasul and Thapa, 2003; von Cauwenbergh *et al*., 2007
	Improved decision-making	Ingels *et al*., 1997; Pannell and Glenn, 2000; Horrigan *et al*., 2002; Rasul and Thapa, 2003
	Improved quality of rural life	Karami, 1995; Ingels *et al*., 1997; Rezaei Moghaddam, 1997; Norman *et al*., 1998; Lyson, 1998; von Cauwenbergh *et al*., 2007
	Working and living conditions	Ingels *et al*., 1997; von Cauwenbergh *et al*., 2007
	Participation/social capital	Becker, 1997; Ingels *et al*., 1997; von Cauwenbergh *et al*., 2007
	Social equity	Becker, 1997; Rigby *et al*., 2001; Rasul and Thapa (2003); Rasul and Thapa, 2004
	Labour safety	Castellini *et al*., 2012

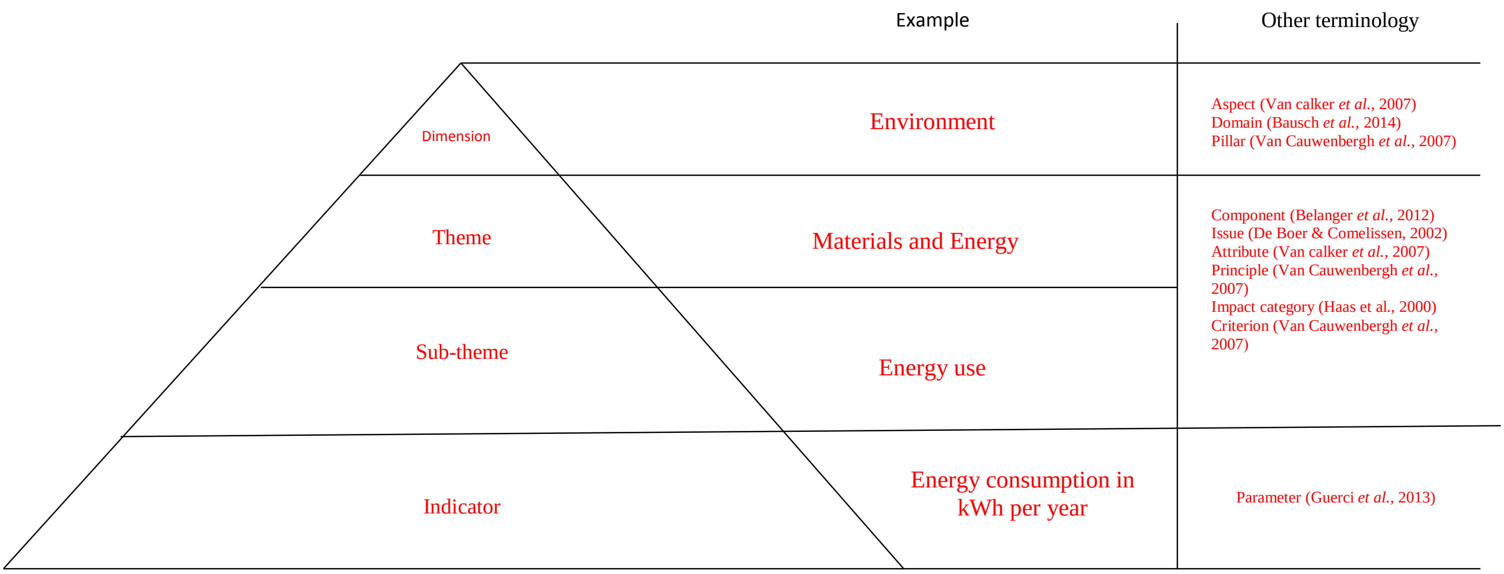
Component	Item	Sources
Economic	Labour per unit of poultry production	Castellini *et al*., 2012
	Average of crop production	Castellini *et al*., 2012
	Expenses for input	Nambiar *et al*., 2001; Rasul and Thapa, 2003
	Off-farm monetary income	Becker, 1997; Herzog and Gotsch, 1998
	Net income from poultry production systems	Herzog and Gotsch, 1998; von Cauwenbergh *et al*., 2007; Castellini *et al*., 2012
	Monetary income from farm	Herzog and Gotsch, 1998); Pannell and Glenn, 2000; Nijkamp and Vreeker, 2000; von Cauwenbergh *et al*., 2007
	Economic efficiency	Becker, 1997; Herzog and Gotsch, 1998; Nijkamp and Vreeker, 2000; von Cauwenbergh *et al*., 2007
	Profitability	Karami, 1995; Herzog and Gotsch, 1998; Lyson, 1998; Smith and McDonald, 1997; Comer *et al*., 1999; Pannell and Glenn, 2000; Rigby *et al*., 2001; Koeijer *et al*., 2002; Rasul and Thapa, 2003; Gafsi *et al*., 2006
	Salaries paid to farm workers	Herzog and Gotsch, 1998
	Net income	Castellini *et al*., 2012
	Employment opportunities	Herzog and Gotsch, 1998; Rasul and Thapa, 2003
	Market availability	Smith and McDonald, 1997; von Cauwenbergh *et al*., 2007
	Land ownership	Karami, 1995; Nijkamp and Vreeker, 2000; von Cauwenbergh *et al*., 2007
	Final weight at slaughter, feed conservation ratio, mortality rate, revenue and labour per production unit	Castellini *et al*., 2012

Component	Item	Sources
Ecological	Soil management	Hayati, 1995; Becker, 1997; Ingels *et al*., 1997; Bouma and Droogers, 1998; Pannell and Glenn, 2000; Sands and Podmore, 2000; Nambiar *et al*., 2001; Horrigan *et al*., 2002; Rasul and Thapa, 2003; von Cauwenbergh *et al*., 2007
	Improved management of water resources	Hayati, 1995; Ingels *et al*., 1997; Gafsi *et al*., 2006; von Cauwenbergh *et al*., 2007
	Usage of pesticides, herbicides and fungicides	Hayati, 1995; Rezaei Moghaddam, 1997; Ingels *et al*., 1997; Norman *et al*., 1998; Pannell and Glenn, 2000; Rasul and Thapa, 2004
	Usage of animal and plant-based manures	Saltiel *et al*., 1994; Hayati, 1995; Norman *et al*., 1998
	Usage of green manures	Senanayake, 1991; Saltiel *et al*., 1994; Hayati, 1995
	Physical inputs and efficient use of inputs	Ingels *et al*., 1997; Herzog and Gotsch, 1998
	Physical yield	Herzog and Gotsch, 1998; Rasul and Thapa, 2003
	Crop diversification	Senanayake, 1991; Saltiel *et al*., 1994; Ingels *et al*., 1997; Comer *et al*., 1999; Praneetvatakul *et al*., 2001; Nambiar *et al*., 2001; Horrigan *et al*., 2002; Rasul and Thapa, 2003
	Use of alternative crop	Saltiel *et al*., 1994; Rasul and Thapa, 200)
	Fat content, fatty acids, and total antioxidants	Castellini *et al*., 2012
	Usage of fallow system	Saltiel *et al*., 1994
	Crop rotation	Saltiel *et al*., 1994; Hayati, 1995; Comer *et al*., 1999; Horrigan *et al*., 2002; Rasul and Thapa, 2003
	Cropping pattern	Nijkamp and Vreeker, 2000; Rasul and Thapa, 2003; Rasul and Thapa, 2004
	Trend of change in climate	Smith and McDonald, 1997; von Cauwenbergh *et al*., 2007
	Usage of chemical fertilizer	Hayati, 1995; Rezaei Moghaddam, 1997; Ingels *et al*., 1997
	Conservation tillage: none or minimum	Hayati, 1995; Ingels *et al*., 1997; Comer *et al*., 1999; Horrigan *et al*., 2002
	Erosion control	Hayati, 1995; Ingels *et al*., 1997; Rasul and Thapa, 2003; Gafsi *et al*., 2006; von Cauwenbergh *et al*., 2007
	Microbial biomass in soil	Senanayake, 1991; Pannell and Glenn, 2000
	Energy	Senanayake, 1991; Ingels *et al*., 1997; Norman *et al*., 1998; Nambiar *et al*., 2001; von Cauwenbergh *et al*., 2007
	Cover crop/mulch	Ingels *et al*., 1997; Norman *et al*., 1998; Comer *et al*., 1999; Horrigan *et al*., 2002; Rasul and Thapa, 2003
	Depth of water table	Pannell and Glenn, 2000; Sands and Podmore, 2000; von Cauwenbergh *et al*., 2007
	Protein level of crops	Pannell and Glenn, 2000
	Integrated pest management	Comer *et al*., 1999; Praneetvatakul *et al*., 2001; Horrigan *et al*., 2002; Rasul and Thapa, 2003
	Climate change, land use, ecotoxicity, fossil fuels and ecological footprint	Castellini *et al*., 2012

Terminologies

Indicator-based tools for assessing sustainability are generally structured on the basis of three or four hierarchical levels (see Figure 2). A diversity of terminology, however, is used to define the various levels (Bausch *et al*., 2014; Bélanger *et al*., 2012; De Olde *et al*., 2016).

Figure 2. Hierarchical levels in sustainability assessment according to SAFA and terminology used in other sustainability assessment studies



Rigby *et al*. (2001) and Gallopin (1997) survey a range of literature in which environmental indicators were identified as a variable, a parameter, a statistical measure, a proxy, a value, a meter or measuring instrument, a fraction, an index, a piece of information, a single quantity, an empirical model and a sign. Moxey (1998) argues that there was no general agreement as to the design and use of what he called "agro-environmental indicators" because they had to "... address interactions of both socio-economic and environmental factors. Consequently, the debate is inevitably complicated".

In this context FAO (2013) provides a structure for developing indicators i.e. sustainability assessment of food and agriculture systems (SAFA). At the intermediate level, universal sustainability goals are translated into themes and in some cases more explicit sub-themes. Indicators are measurable variables for evaluating the sustainability in any theme or sub-theme.

6. Levels of agricultural sustainability

The sustainability of agriculture is measured and monitored at different levels. The literature shows, for example, actions carried out at the farm, regional and national levels, but there are fewer studies about measuring and monitoring sustainability in agriculture at the global level. Marchand *et al*. (2014) report that sustainability assessments were a significant aid in the process; Pope *et al*. (2004) stated that a growing number of sustainability assessment tools and frameworks had been developed to support decision-making in the agriculture sector. Based on Binder et al. (2010) this situation has led to the development of different tools that range from the farm level to applications at the international level.

These sources focused on different levels of analysis and consequently introduced various sustainability indicators based on their objectives and intellectual domain. Table 6 summarizes the level of analysis and the indices used in different studies.

Various factors can influence the choice of tool. This literature review shows that the variation among tools enables us to identify some of these factors. The current choice of assessment tool by researchers and governments, for example, usually depends on data, time, and budgetary constraints (Marchand *et al*., 2014).

The use of integrated, holistic and indicator-based global sustainability measurement tools is important at the farm level because it relates to the broader goal of integrating sustainability concepts such as ecological, economic and social issues into decision-making (Pope, 2006). The holistic and global characteristics of such tools means that the framework for measuring and monitoring the sustainability of agriculture will be applicable at the global level. The use of the indicators will be determined by operational choices such as whether they are treated individually, as part of a weighted set, or combined into a composite index (Farrell and Hart, 1998). The farm-level characteristic concerns the use of farm-level data, farmers as target groups and the farm as the system to be evaluated: in this case the individual farmer makes the strategic and operational management decisions that influence farm sustainability (Marchand *et al*., 2014).

Pretty (1995) argues: "At the farm level, it is possible for actors to weigh up, trade off and agree on these criteria for measuring trends in sustainability. But as we move to high levels of the hierarchy, to regional, national and international levels, it becomes increasingly difficult to do this in any meaningful way." He went on to say that when specific parameters or criteria were selected, it was possible to say whether certain trends were steady, going up, or going down. At the farm level, for example, practices that cause soil erosion can be considered more unsustainable than those that conserve soil. Practices that remove the habitats of insect predators or kill them directly are more unsustainable than those that do not. Forming a group as a forum for collective action is likely to be more sustainable than individuals trying to act alone.

Indicators of agricultural sustainability can generally be applied at several levels according to the scale at which evaluations are made (see Table 5). Apart from different scales of application, indicators may also differ in the directness of measurement and the timescale over which they are applied. Measurement, for example, may vary from a direct measure such as soil loss through a proxy measure such as soil cover to an indirect measure such as density of livestock. Similarly, the timescale of operation may vary from a leading indicator such as clearing of steep lands to a concurrent indicator such as inappropriate land management to a lagging indicator such as abandonment of land (Smith and McDonald, 1997).

Table 5. Levels of analysis in sustainability assessments

Level of assessment	Typical characteristics of sustainability	Typical determinants
Field	Productive crops and animals; conservation of soil and water; low level of crop pests and animal diseases	Soil and water management; biological control of pests; use of organic manures; fertilizers, pesticides, crop varieties and animal breeds
Farm	Awareness among farmers; economic and social needs satisfied; viable production systems	Access to knowledge, inputs and markets
Country	Public awareness; sound development of agro-ecological potential; conservation of resources	Policies for agricultural development; population pressure; agricultural education, research and extension
World	Quality of natural environment; human welfare and equity mechanisms; international agricultural research and development	Control of pollution; climate stability; terms of trade; distribution

Source: Smith and Mcdonald (1997).

Izac and Swift (1994) note that agricultural systems may be defined at different spatial scales ranging from the crop field, where human influence may be regarded as largely external to the biological system, to the regional landscape, where human activities are part of the system. They also stated: "... there is no ‘correct' definition of agro-ecosystems since the research and management objectives determine the correctness.” Each level is relevant to sustainability in some respect: our purpose is to identify the levels most relevant to the assessment of sustainability in agricultural systems. A significant criterion in this respect is to identify the levels at which there is significant integration of ecological, economic and social factors. In practice the scales and their spatial boundaries must be directly relevant to the activities and perceptions of farmers: in this context OECD (2001) reports that "scale" or "level of analysis" is a separate principle in the measurement and monitoring of agricultural sustainability; Von Wiren-Lehr (2001) and Ness *et al*. (2010) make similar observations. The need for more granular scales of assessment arises from differences in socio-economic and environmental conditions (Dantsis *et al*., 2010): national and international indicators, for example, are often inapplicable to the local and household scales (Van Cauwenbergh *et al*., 2007; Van Pham and Smith, 2014).

On the other hand, the farm is the basic economic unit in the hierarchy of agricultural systems: even though the use of a single field, for example, may be uneconomic or unsustainable, the farm may remain economically viable. Conversely, fields on a farm may do well agronomically, but poorly in economic terms as a result of low commodity prices or high production costs. To be socio-economically viable, the economic and social needs of the farmer must be met, and the farmer must have access to information related to management processes, production inputs and commodity markets. Sustainability indicators at the farm scale must therefore include profitability, economic uncertainty, availability of inputs and markets, skills and information available to the farmer, the farmer's planning capacity and incentives to manage land sustainably. The latter may include best management practice guidelines, off-farm income and access to credit, government assistance and land tenure (Smith and Mcdonald, 1997). At the regional, national and international scales, macroeconomic constraints – especially economic policy – determine the focus of national economies and eventually the ability of a nation’s agricultural system to feed its population (Lowrance *et al*., 1986; Smith and McDonald, 1997).

7. Agricultural sustainability measurement indices

To enable a transition to sustainable production, various tools have been developed to provide insights into the sustainability of agricultural systems (Binder *et al*., 2010; Schader *et al*., 2014;

De Olde *et al*., 2016). Measurement and monitoring tools for sustainability vary widely in geographical and sectoral coverage, target groups such as farmers or policy-makers, selection of indicators, aggregation and weighting method, and the time required for implementation (Marchand *et al*., 2014; Schader *et al*., 2014). Many observers stress the importance of integrating environmental, economic and social themes in sustainability measurement tools, but environmental themes and tools generally receive more attention (De Olde *et al*., 2016; Binder *et al*., 2010; Finkbeiner *et al*., 2010; Lebacq *et al*., 2013; Marta-Costa and Silva, 2013; Schader *et al*., 2014).

In this regard, De Olde *et al*. (2016) tries to compare four farm-level sustainability measurement indices: response-inducing sustainability evaluation (RISE) (Häni *et al*., 2003), SAFA (FAO, 2013), public goods (PG) (Gerrard *et al*., 2012) and *indicateurs de durabilité des exploitations agricoles* (IDEA; farm sustainability indicators) (Zahm *et al*., 2008). The PG tool focuses on public goods instead of sustainability, but some consider it a suitable tool for assessing sustainability because of its compliance with the selection criteria (in PG data are more accessible) (Leach *et al*., 2013). The RISE, PG and IDEA indexes are adapted specifically for measuring the sustainability of farms, whereas SAFA has broader scope in that it extends to supply chains in agriculture, forestry and fisheries (De Olde *et al*., 2016).

A number of articles – Halberg *et al*. (2005), de Ridder *et al*. (2007), Binder *et al*. (2010), Gasparatos (2010) and Singh *et al*. (2012) – review, analyse or categorize sustainability assessment tools. Drawing on Marchand *et al*. (2014), Gasparatos (2010) categorizes sustainability assessment tools into "families" of biophysical, monetary or indicator tools. Binder *et al*. (2010) focus on indicator-based sustainability assessment tools in agriculture and distinguish three types by spatial level – farm, region and degree of stakeholder participation: i) top-down farm assessment methods; ii) top-down regional assessment methods with some stakeholder participation; and iii) bottom-up transdisciplinary methods with full stakeholder participation (Marchand *et al*., 2014).

Sustainability measurement indices differ in terms of starting point, objectives and assumptions such as what is to be measured, how to measure it and which sustainability perspectives are relevant and legitimate. These differences in basic features mean that the choice of index affects the outcome of the evaluation (Marchand *et al*., 2014).

Some of these sustainability measurement indices are presented in Table 6 (De Olde *et al*., 2016).

Table 6. Overview of indices

Index	Name	Measurement level	Peer rev.	Reference	Economic/ environmental/ social	Sector	Suitable NW Europe/ other countries
1. AEMBAC	European Analytical Framework for the Development of Local Agri-Environmental Programmes	Landscape	Yes	Bastian *et al*. (2007); Simoncini (2009)	Environmental	Universal	Yes/Yes
2. AESIS	Agro-Environmental Sustainability Information System	Farm	Yes	Pacini *et al*. (2009); Pacini *et al*. (2011)	Environmental	Universal	Yes/No
3. Agro-Eco-Index		Farm	Yes	Viglizzo *et al*. (2006)	Environmental	Universal	No/No
4. ANCA	Annual Nutrient Cycle Assessment	Farm	Yes	Aarts *et al*. (2015)	Environmental	Dairy	Yes/No
5. APOIA-NOVORURAL	The System for Weighted Environmental Impact Assessment of Rural Activities	Farm	Yes	Rodrigues *et al*. (2010)	Economic, environmental, social	Universal	No/Yes
6. ARBRE	*Arbre de l'Exploitation Agricole Durable*	Farm	No	Pervanchon (2004)	Economic, environmental, social	Universal	Yes/No
7. AUI	*Agrarumweltindikatoren*	Farm	No	www.blw.admin.ch	Environmental	Universal	Yes/No
8. Avibio	*AVIculture BIOlogique*	Farm, chain	Yes	Pottiez *et al*. (2012)	Economic, environmental, social	Poultry	Yes/No
9. BROA	Biodiversity Risk and Opportunity Assessment	Lanscape	No	www.batbiodiversity.org/broa	Environmental	Universal	Yes/Yes
10. COSA	Committee On Sustainability Assessment	Farm	Yes	COSA (2013)	Economic,Environmental,Social	Coffee andcacao	No/Yes
11. Coteur et al. (2014)		Farm	Yes	Coteur et al. (2014)	Economic,Environmental,Social	Fruit, arable, greenhouse	Yes/No
12. DairySAT	Dairy Self-Assessment Tool	Farm	No	www.dairysat.com.au	Environmental	Dairy	Yes/No
13. Dantsis *et al*. (2010)	-	Farm, regional	Yes	Dantsis *et al*. (2010)	Economic, environmental, social	Plant, production	Yes/No
14. DIAGE	*DIAgnostic Global d'Exploitation*	Farm	No	www.cooperation-agricole.asso.fr/sites/saf/guide/fiches/methodes evaluationsysteme individuelles/diage.aspx	Environmental	Universal	Yes/No
15. DIALECTE	*DIAgnostic Liant Environnement et Contrat Territorial d'Exploitation*	Farm	No	http://dialecte.solagro.org/	Environmental	Universal	Yes/No
16. DIALOGUE	*Diagnosticagri environnemental global d'exploitation*	Farm	No	www.solagro.org/site/imuser/014plaquette dialogue.pdf	Environmental	Universal	Yes/No
17. DLG	*DLG Zertifikat Nachhaltige Landwirtschaft*	Farm	No	www.nachhaltige-landwirtschaft.info	Environmental	Universal	Yes/No
18. DSI	Dairyman Sustainability Index	Farm	Yes	Elsaesser *et al*. (2015)	Economic,Environmental,Social	Dairy	Yes/Yes

19. DSR	Driving Force State Response	Regional	No	OECD (2001)	Economic,Environmental,Social	Universal	Yes/Yes
20. EF	Ecological Footprint	Farm, product, local, regional	Yes	Wackernagel *et al*. (1999)	Environmental	Universal	Yes/Yes
21. EMA	Environmental management for agriculture	Farm	Yes	Lewis and Bardon (1998)	Environmental	Universal	Yes/No
22. EP	Ecopoints	Farm	No	www.oekopunkte.at	Environmental	Universal	Yes/No
23. FARMSMART	-	Farm	Yes	Tzilivakis and Lewis (2004)	Economic, environmental, social	Universal	Yes/No
24. Field Print Calculator	-	Farm	No	www.fieldtomarket.org	Economic, environmental, social	Arablefarming	Yes/No
25. GA	Green Accounts for Farms	Farm	No	www.landbrugsinfo.dk/miljoe/natur-og-arealforvaltning/tilskudsordninger/groenne-regnskaber	Environmental	Universal	Yes/Yes
26. IDEA	*Indicateur de Durabilité des Exploitations Agricoles*	Farm	Yes	Zahm *et al*. (2008)	Economic, environmental, social	Universal	Yes/Yes
27. IFSC	Illinois Farm	Farm	No	www.ideals.illinois.edu/handle/2142/13458	Environmental, economic	Universal	No/No
28. INDIGO	Sustainability Calculater	Farm	Yes	Thiollet-Scholtus and Bockstaller (2014)	Environmental	Crop production, viticulture	Yes/No
29. ISAP	Indicator of Sustainable Agricultural Practice	Farm	Yes	Rigby *et al*. (2001)	Economic, environmental, social	Horticulture	Yes/No
30. KSNL	*Kriteriensystem Nachhaltige Landwirtschaft*	Farm	No	Breitschuh (2009)	Economic, environmental, social	Universal	Yes/No
31. LCA	Life Cycle Assessment	Product	Yes	e.g. Haas *et al*. (2000)	Environmental	Universal	Yes/Yes
32. MESMIS	Framework forAssessing the Sustainability of Natural Resource Management Systems	Farm, local	Yes	López-Ridaura *et al*. (2002), Speelman *et al*. (2007)	Economic, environmental, social	Smallholder	No/No
33. MMF	Multiscale Methodological Framework	Farm, local, regional	Yes	Lopéz-Ridaura *et al*. (2005)	Economic, environmental, social	Smallholder	No/No
34. MOTIFS	Monitoring Tool for Integrated Farm Sustainability	Farm	Yes	Meul *et al*. (2008)	Economic, environmental, social	Dairy	Yes/No
35. PG	Public Goods Tool	Farm	Yes	Gerrard *et al*. (2012)	Economic, environmental, social	Universal	Yes/Yes

36. RAD	*Réseau del'Agriculture Durable*	Farm	Yes	Le Rohellec and Mouchet (2008)	Economic, environmental, social	Dairy	Yes/No
37. REPRO	Reproduction of Soil Fertility	Farm	No	www.nachhaltige-landbewirtschaftung.de/repro/	Environmental	Universal	Yes/No
38. RISE	Response-Inducing Sustainability Evaluation 2.0	Farm	Yes	Häni *et al*. (2003)	Economic, environmental, social	Universal	Yes/Yes
39. SAFA	Sustainability Assessment of Food and Agriculture Systems	Farm, chain	Yes	FAO (2013)	Economic, environmental, social	Universal	Yes/Yes
40. SAFE	Sustainability Assessment of Farming and the Environment	Farm, landscape, regional	Yes	Van Cauwenbergh *et al*. (2007)	Economic, environmental, social	Universal	Yes/No
41. SAI – SPA	Farmer Self-Assessment 2.0	Farm	No	www.standardsmap.org/fsa	Economic, environmental, social	Universal	Yes/Yes
42. SALCA	Swiss Agricultural Life Cycle Assessment	Farm, product, system	Yes	Nemecek *et al*. (2011)	Environmental	Universal	Yes/No
43. SeeBalance	-	Product	Yes	Saling *et al*. (2005)	Economic, environmental, social	Universal	Yes/Yes
44. SLCA	Social Life Cycle Assessment	Product	Yes	Benoît and Mazijn (2009)	Social	Universal	Yes/Yes
45. SMART	Sustainability Monitoring and Assessment RouTine	Farm	No	www.fibl.org/en/themes/smart-en.html	Economic, environmental, social	Dairy	Yes/Yes
46. SoilandMoreFlower	Sustainability Flower Quick Assessment	Farm	No	www.soilandmorefoundation.org/projects/sustainability-flower	Economic, environmental, social		Yes/Yes
47. SustainabilityDashboard	-	Farm	No	www.triplehelix.com.au/documents/FarmSustainabilityDashboard.pdf	Economic, environmental, social		Yes/No
48. van Calker *et al*. (2006)	-	Farm	Yes	van Calker *et al*. (2006)	Economic, environmental, social		Yes/No

Criteria for selecting indicators

Selection of effective indicators is the key to the success of any monitoring programme (Zhen and Routray, 2003). The choice must be indicators that are globally applicable, cost-effective, comprehensive, realistic and comparable that can hence identify, measure and describe the condition of sustainability. Zhen and Routray (2003) and Dale and Beyeler (2001) propose that the criteria for selecting sustainability indicators should be: i) easily measurable; ii) sensitive to stresses on the system; iii) responsive to stress in a predictable manner; iv) anticipatory, in that they signify any impending change in the system; v) able to predict changes that can be averted by management actions; vi) integrative, in that the full suite of indicators provides a measure of coverage of gradients in different agricultural systems such as cropping, livestock and pasture; vii) reliably responsive to natural disturbances, anthropogenic stresses and changes over time; and viii) only slightly variable in response. Other criteria are discussed in the literature on the selection of indicators (Braat, 1991).

To summarize: the aspects listed below should be taken into consideration in the selection of indicators for assessing agricultural sustainability at the national level (Zhen and Routray, 2003).

i. relative availability of data representing the indicators;
ii. sensitivity to stresses on the system;
iii. existence of threshold values and guidelines;
iv. productivity;
v. integratability, and
vi. known response to disturbances, anthropogenic stresses and changes over time.

De Mey *et al*. (2011) report other criteria for choosing indicators of agricultural sustainability:

i. Attitude of model users – advisers and farmers – toward sustainability: "Values and beliefs of the model users (advisers and farmers) regarding sustainability issues."
ii. Compatibility: "Extent to which the design and the proposed use of the tool is compatible with the data systems and institutional structure of accountancy and consultancy agencies."
iii. User-friendliness: "Extent to which the ISA-tool is flexible and easy to use. This is related to the graphical design, ease of assessment, and calculation (automation), etc."
iv. Data availability: "Availability of data necessary for indicator calculation".
v. Transparency: "Transparency of the used model and data (design, generalizations, etc.) and transparency on uncertainties of model-derived results."
vi. Correctness of data: "Correctness of the data that are used to calculate the indicators of the ISA tool."
vii. Value in communication: "Use of Integrated sustainability assessment-tool in discussion sessions and its ability to support discussion on sustainability. Both communication aid of the model itself as communication through using it in farmer groups are included."
viii. Complexity: "Degree of complexity of the integrated sustainability assessment tool."
ix. Organization of discussion sessions: "Practical organization of the discussion sessions with farmers. Which aspects need to be considered to make the discussion sessions more successful?"
x. Effectiveness: "Extent to which the integrated sustainability assessment tool is perceived as being relevant to use and implement."

Binder *et al*. (2010) state that the selection of indicators is linked to the normative and systemic aspects mentioned above. It should be based on the characteristics of the field, farm or region and problems existing in the selected system. In general, the main criteria for the selection of indicators should be: i) orientation to particular goals; ii) system representation; and iii) data availability (Scholz and Tietje, 2002; Wiek and Binder, 2005; Zhen and Routray, 2003; Binder *et al*., 2010).

Sala *et al*. (2015) consider the criteria for the selection of indicators from the perspectives of ontology, epistemology and methodology. In terms of ontology, the criteria for selecting indicators were: i) the subject of assessment; ii) the scope of measurement; iii) comprehensiveness in terms of taking the three pillars (namely economy, environment and society) into account and the level of integration among the pillars; iv) use of resources; v) environmental effects and/or economic effects; vi) ability to address indirect inputs and effects; vii) scenario development; and viii) system boundaries. The epistemology criteria were: i) accounting versus change-orientation; and ii) ability to communicate with individual stakeholders and groups of stakeholders. The methodology criteria were: i) analytical versus procedural tools; ii) methods in terms of aggregation, system boundaries, data inclusion, normalization and weighting and establishing whether mono-dimensional or multi-dimensional; iii) rigour of the methods, strategies and techniques used to construct any index: whether quantitative or qualitative, subjective or objective and with cardinal or ordinal metrics; iv) availability, flexibility and transparency of data; and v) spatial and temporal issues (Sala *et al.,* 2015).

The SAFA (2013) recommendations for selecting sustainability monitoring indicators involve consideration of:

i. default indicators, or their replacement;
ii. availability of information on the performance of the entity;
iii. budgetary constraints of the assessment; and
iv. the use of results, and the associated compliance review.

Neher (1992) observes that indicators were often selected on the basis of the availability of techniques for obtaining measurements, the suitability of indicators for use in a single sampling period and the interpretability of data.

8. Introducing indicators for measuring agricultural sustainability

Sustainable agriculture must be regarded as more than the sum of related principles and theoretical issues. To facilitate decision-making, it is essential to study the actual state of the complex and dynamic environment and to define the processes of change. Sustainable agriculture can be described and measured by cost-benefit analysis, risk analysis, charts of ecosystems and indicator systems (Feher and Beke, 2013). López-Ridaura *et al*. (2002) report that sustainability is defined by seven general attributes of natural resource management systems: productivity, stability, reliability, resilience, adaptability, equity and self-reliance or self-empowerment. They also introduced indicators for these attributes of sustainability: **[Lopez-Ridaura *et al.* (2002) have combined three attributes (stability, reliability and resilience) and used them as one attribute (stability)]**

i. Productivity: yields, quality of products, cost/benefit ratio, economic return to labour.
ii. Stability: resilience and reliability, nutrient balance, erosion levels, biophysical characteristics of soils such as compaction and percentage of organic matter, yield trends, number of species grown, income per species, incidence of pests, diseases and

weeds, and variation of input and output prices such as coefficients of variation of input/output.

iii. Adaptability: adoption of new alternatives and/or farmers' permanence in a system, capacity-building activities, proportion of area with an adopted technology.

iv. Equity: initial investment costs and share of benefits by different farmers' groups.

v. Self-reliance: participation in the design, implementation and evaluation of alternatives, degree of participation in decision-making, cost of external inputs, use of external resources.

Rigby *et al*. (2001) also construct a farm-level sustainability index using data collected in a survey of farmers and agricultural producers. Their indicators of farm-level sustainability were:

i. seed sourcing;

ii. soil fertility;

iii. pest and disease control;

iv. weed control; and

v. crop management

Their work supplemented the farm-level sustainability indicators of Tylor *et al*. (1993):

i. insect control;

ii. disease control;

iii. weed control;

iv. maintenance of soil fertility; and

v. control of soil erosion.

Rigby *et al*. (2001) and Gomez *et al*. (1996) construct farm-level indices of sustainability covering six aspects: yield, profit, frequency of crop failure, soil depth, organic certification and permanent ground cover.

Van Asseldonk *et al.* (2016) mentioned that adoption risk management strategies are important in sustainability of European agriculture. In their study the risk management data (and other additional indicators collected in the EU Framework 7 FLINT, Farm-Level Indicators for New Topics in Policy Evaluation) were merged with the FADN (Farm Accountancy Data Network) database. Indicators of risk management in this study were: crop insurance, livestock insurance, building insurance, price contract, off-farm employment, off-farm investment and so on. In line with this study that investigated the adoption of risk management strategies, Van der Meulen *et al.* (2016) concentrated on the role of innovation to promote agricultural sustainability. These scholars cited that innovation and adoption of innovation are considered key indicators of competitiveness and sustainability. Furthermore, in this study the EU Framework 7 project FLINT collected farm-level indicators on innovation and related aspects in nine EU Member States. Consequently, in combination with data collected by the Farm Accountancy Data Network (FADN), the FLINT data are used to obtain insight into different adoption rates and determinants of adoption of five types of innovation in agriculture across Europe.

The five types of innovation indicators and one aggregated indicator distinguished in the dataset are:

1. Product innovation that is new for the company within the last three years, but not new to the market (product not new);

2. Product that is new to the market (product new);

3. Process innovation that is new for the company within the last three years, but not new for the market (process not new);

4. Process innovation that is new for the company and new for the market (process new);

5. Market and organizational innovation (organizational);

6. Having one or more of the above-mentioned types of innovation (farms with innovations).

Bockstaller *et al*. (1997) consider the seven indicators of integrated arable farming systems from a one-dimensional approach to agricultural sustainability: crop diversity, crop succession, pesticides, nitrogen, phosphorus, organic matter and irrigation.

OECD (1997) uses a “driving force state response” framework to identify 13 “priority issues”, for each of which several potential indicators were suggested for policy relevance, analytical soundness and measurability. The aim was to provide information to improve the targeting, monitoring and assessment of agri-environmental schemes. This initiative was followed by the publication of a consultative document by the Government of the United Kingdom (Webster, 1999). Proposals were set out for 34 individual indicators based on 11 issues, as listed below:

Issue		Theme(s)	Proposed indicators
1	Nutrient use	Nutrient losses to fresh water; soil P levels; nutrient management practices; ammonia emissions	N losses in selected catchments, P losses in selected catchments, percentage of land sampled for P, slurry storage and timing of application, nutrient application techniques and quantity emitted
2	Greenhouse gases	Greenhouse gas emissions	CH_4 emissions and NO emissions
3	Pesticide use	Pesticide use	Pesticides in rivers, pesticides in groundwater, quantity of active ingredient, area sprayed, number of wildlife incidents, residues in food
4	Water use	Water use	Storage capacity as percentage of irrigated area
5	Water quality	Water quality	Economic value of irrigated crops
6	Soil quality	i) soil protection; ii) agricultural land resources	i) Topsoil organic matter content, topsoil heavy metal content and soil management practices; ii) Area lost to non-agricultural development, area restored following mineral extraction or landfill
7	Land use and conservation	Conservation value of agricultural land	Area under environmental conservation, area under organic production, length of hedgerows and walls, population of farmland birds, area of semi-natural grassland and area of field margin under environmental management
8	Wildlife habitats	Wildlife habitats	Upland management
9	Farm management	Environmental management systems	Farmers' adoption of environmental management systems
10	Socio-cultural issues	Rural economy	European Union producer subsidy equivalent, and environmental payments as percentage of Common Agricultural Policy expenditure
11	Farm financial resources	Energy	Agricultural productivity, rural unemployment and area planted with crops for conversion to energy

Gafsi *et al*. (2006) investigate the sustainability of farming systems and considered two sections for agricultural sustainability: socio-economic, and environmental and territorial. The classification of indicators is shown in Table 7.

Table 7. Sustainability assessment framework, Gafsi *et al*. (2006)

Section (dimension of sustainability)	Aspect or indicator

Table 7. Sustainability assessment framework, Gafsi *et al*. (2006)

Socio-economic	Employment	- Maintain and create employment - Facilitate establishment of young farmers
	Human resources and work	- Adapt expertise and qualifications - Improve work conditions and organization
	Product quality	- Improve product quality - Increase food safety
	Animal well-being	- Improve animal well-being
	Economics and autonomy	- Consolidate farmers' economic organization - Diversify farm and non-farm activities - Improve marketing channels for farm products - Increase added value whilst reducing production costs and optimizing natural resources
Environmental and territorial	Water	- Preserve and improve water quality - Improve water resource management
	Soils	- Control erosion - Preserve physical/chemical/biological fertility
	Air	- Preserve and improve air quality
	Biodiversity	- Preserve natural species and biotopes
	Landscape and cultural heritage	- Preserve and enhance heritage buildings - Preserve, enhance and improve landscape quality
	Natural risks	- Control erosion, flooding, fires, avalanches
	Energy	- Reduce energy consumption - Develop the use of renewable energy resources

Van Passel *et al*. (2007) consider agricultural sustainability its indicators from the perspective of sustainable efficiency, introducing labour productivity, land productivity, capital productivity, eco-efficiency in terms of energy and eco-efficiency in terms of nitrogen output as the indicators of farm sustainability.

Bosshard (2000) provides an effective assessment of sustainability in terms of agricultural land use, and recommended five principal criteria for consideration: i) abiotic environment; ii) biotic environment, including animal welfare; iii) cultural values, defined as human and social emotional and mental wellbeing; iv) sociology; and v) economics.

Velten *et al*. (2015) work from a different perspective to conceptualize the indicators of agricultural sustainability. They observe that sustainable agriculture is often described as a set of ideal objectives – goals – that must be achieved, and study different approaches and principles – strategies – that should or should not be applied in different areas, which they define as fields of action. They identify 17 themes and specify clear goals, strategies and fields of action for sustainable agriculture in a context of social science and governance to form a framework of sustainable agriculture (see Figure 3). The 17 themes include the 66 categories of sustainable agriculture identified through qualitative analysis (see Tables 8–10).

Figure 3: Groups and themes of the sustainable agriculture framework

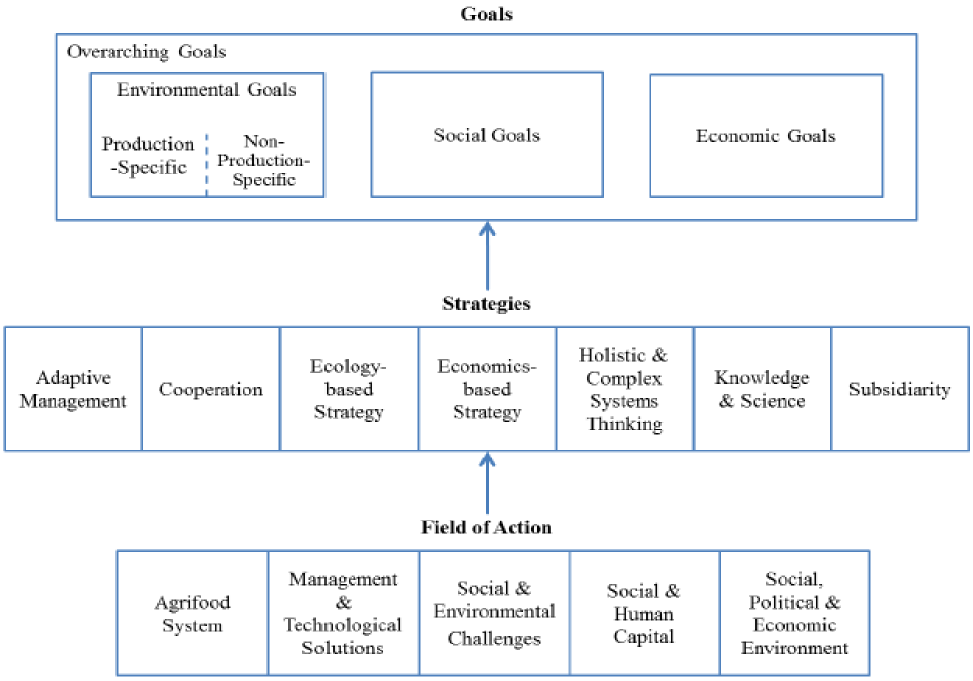


Table 8. Themes and categories of sustainable agriculture: goals

Goal themes	**Goal categories**	
	General	Specific
Overarching goals		Ethics Multifunctionality Safety Stability and resilience
Environmental goals: production-specific	Ecological soundness	Ecosystem function conservation Natural resource conservation Productive capacity
Environmental goals: non production-specific		Animal wellbeing Environment conservation and improvement Harmony with nature
Social goals	Social responsibility	Acceptability Cultural preservation Equity, justice, fairness Fulfilment of human needs Good working conditions Human health Nourishment Quality of life Strong communities
Economic goals	Economic viability	Development Livelihood Provision of products Thriving economy

Table 9. Themes and categories of sustainable agriculture: strategies

Strategy themes	Strategy Categories
Adaptive management	Adaptation Learning and experimentation Management, integration and redesign Prevention Substitution
Cooperation	Collaboration and communication Participation
Ecology-based strategy	Diversification Ecological principles
Economics-based strategy	Capital asset maintenance

	Demand orientation Efficiency Quality orientation
Holistic and complex systems thinking	Long-term perspective Sensitivity to scale Systemic thinking
Knowledge and science	Innovation Modern Traditional
Subsidiarity	Decentralization Independence Local/regional

Table 10. Themes and categories of sustainable agriculture: fields of action

Field of action themes	Field of action categories
Agrifood system	Consumption Production Supply chain
Management and technological solutions	Crops and livestock Management tools Resource use Technology and practices
Social and environmental challenges	Emission reduction Global trends
Social and human capital	Organization Knowledge, education, skills Research and development
Social, Political and Economic environment	Accessibility Economic system Infrastructure Investment Policy and institutions Society

Roy *et al*. (2013) develop indicators for sustainable rice farming in Bangladesh using a Delphi technique encompassing three dimensions: economic, social and environmental, as set out below:

Dimension	Theme(s)	Indicators
1. Economic	Land productivity	Farm profitability, land holding, farmers income, input subsidies, extent of farm mechanization, market diversification
2. Social	Availability of labour, cropping patterns, health hazards, rural infrastructure	Social capital, human capital, input availability, food self-sufficiency, resource-conservation practices and technologies, information availability, equity, extension services, availability of new rice varieties, e.g. flood-resistant
3. Environmental	Agro-biodiversity, water pollution, disaster management, soil erosion	Soil quality, crop diversification, soil fertility management, integrated pest and disease management, nutrient management, irrigation efficiency, extent of greenhouse gas emissions

Smith and McDonald (1997) argue that profitability indicators such as total production and net farm income are the primary indicators of agricultural sustainability. They adopted an environmental point of view, focusing on trends in land and water use. Chen (2000) proposes a set of indicators for assessing agricultural sustainability, and identified challenges with regard to balanced development of the environmental, resource, population, economic and social components. Zhen and Routray (2003) propose operational indicators based on defined selection criteria, and suggested that the selection of indicators should be prioritized according to the spatial and temporal characteristics under consideration.

Saifia and Drake (2008) present a model for agricultural sustainability based on the relations between principles, dimensions and indicators. Guttenstein *et al*. (2010) stress that per capita income and equity and human rights should be considered in selecting economic and social indicators, and accorded equal importance to greenhouse gas emissions, biodiversity and desertification as core indicators in the ecological dimension.

Ion (2011) attempts to monitor the development of sustainable agriculture in Romania with the following indicators:

- consumption of certain foods per inhabitant;
- ecolabel licenses;
- area under agri-environmental management;
- area under organic farming; and
- lLivestock density index.

There have been numerous attempts to assess agricultural sustainability with a view to constructing a complete set of indicators (Roy and Chan, 2012). Table 11 summarizes the agricultural sustainability indicators proposed by researchers.

Table 11. Sustainability indicators proposed by researchers, in chronological order

Source	Indicator		
	Economical	Social	Ecological
Smith and McDonald, 1997	Production cost, product prices, net farm income	Access to resources, skills, knowledge and planning capacity of farmers, awareness	Land capability, nutrient balance, biological activity, soil erosion, use of F/Pe, WUE
Gowda and Jayaramaiah, 1998	Land Pd, crop yield security, input Pd	Input S, self-reliance for info., food sufficiency	Integrated nutrient Mgt, W, and Pe Mgt
Chen, 2000	Total Ag products, per capita food production, net farm income	Per-capita food supply, land tax, participation in decision-making	Use of external input, G/W quality, soil erosion, per-capita disaster loss, cropping index
Nambiar *et al*., 2001	Yield, income per labourer, real net output per unit land	Cultural level, number of varieties of livestock and organisms	Nutrient balance, efficiencies of F and I/W uses, soil erosion, saline content and soil quality
Zhen and Routray, 2003	Crop Pd, net farm income, cost/benefit ratio of production, per-capita food grain production	Food self-sufficiency, equality, access to resources and support services, farmers' knowledge and awareness	Amounts of F, Pe and W used, soil nutrient content, G/W table, WUE, quality of G/W and NO_3 in G/W and crops
Lopez-Ridaura *et al*., 2002	Sorghum, meat and milk yield, cost/benefit ratio, economic return from labour, investment cost	Availability of milk, labour demand, org. inputs dependency, stability in production,	OM, soil loss, run-off coefficient,
Rasul and Thapa, 2004	Land Pd, yield stability and profitability from staple crops	S input, equity, food security and risks, uncertainties in cultivation	Land-use pattern, cropping pattern, soil fertility Mgt, pest and disease Mgt, and soil fertility
Zhen *et al*., 2005	Crop Pd, per-capita food production, net farm return and benefit–cost ratio	Food S and adequacy and effectiveness of the extension services	Depth to GW table, WUE, soil quality – pH, OM, N, P and K – NO_3 in G/W and chive plants
Van Calker *et al*., 2006	Profitability	Working conditions, food safety, animal welfare and health, landscape quality	Eutrophication, G/W pollution, dehydration of soil, global warming, acidification, ecotoxicity
Häni *et al*,. 2006	Economic stability, economic efficiency, local economy	Working conditions, social security	W, soil, B, N, and P emission potential, plant protection, waste and energy
Zhen *et al*., 2006	Land holding; crop area, labor; I freq., quantity of G/W, N, P, K, F used; Pd, farm income	Age and education level of respondent	Soil fertility status including soil pH, N, P, K and OM content
Qiu *et al*., 2007	Ratio of fossil energy in total energy wage, ratio of product for process, ratio of actual yield in potential yield	Farmer development index – health, education, gross domestic product per capita	Ratio of water for irrigation in water resource recharge, Concentration of NO in groundwater, pollution level of surface water, soil organic matter
Saifia and Drake, 2008	Farm economy, technological development, traditional Ag	Value system and ethics, food demand, food safety and health aspects, food security and distribution	Ecological system and environmental degradation, on-farm and off-farm natural resources, energy and biomass
Sydorovych and Wossink, 2008	Profit, income stability, reliance on purchased inputs and subsidies, sufficiency of cash flow, govt. regulation	Stress, risks, safety, nutrition, quality, taste, impact, animal care, attractiveness, odours, noise, info.	Soil and water quality, agro and natural biodiversity, efficiency of natural resource use, solid waste disposal, air quality, GHG emissions
Pretty *et al*., 2008	Value chain, energy, water, local economy	Social and human capital, animal welfare	Soil fertility and health, soil loss, nutrients, pest Mgt, B
Binder *et al*., 2008	Return on investment, labor Pd, hourly wage, market power, subsidies, production	Level of education, social capital, social acceptance, human capital	GHG emissions, B eutrophication, electricity conservation, processing and cooling, energy conservation, transport
Gomez-Limon and Riesgo, 2008	Total gross margin, profit, public subsidies, gross domestic product contribution	Total labour, seasonal labour employment	Agro-diversity, soil cover, W use, nitrogen and energy balance, P risk
Jane Dillon *et al*., 2009	Market return, viability, direct payments	Demographic viability, isolation	W quality, air quality

Guttenstein *et al*., 2010	Ratio of income/capita of farm, social integration and connectedness, diversity of farm, volume of goods and services	Nutritional status, extent of aboriginal participation, gender ratio, enrolment ratio in education, access and control to land, W and B	G and surface W consumption, B, % of land affected by desertification, carbon dioxide emissions
Gafsi and Favreau, 2010	Viability, autonomy, transmissibility, efficiency	Working conditions, quality of life, local economy, social involvement	Agro-ecological: pollution control and soil fertility, crop rotation, Ag and natural B, resources Mgt
Dantsis *et al*., 2010	Gross Ag value and Ag margin, crop diversity, holding size, plot no/. farm, machinery	Age, level of education, pluri-activity, family size, E in ag	Use of F and Pe, I/W consumption, farm Mgt, agro-ecological Mgt, farm machinery, type of farming
Vecchione, 2010	Labour and land Pd, fragmentation, value addition, diversification, mechanization	E in ag, old-age index, education, gender composition, population	Arable surfaces, permanent crops, poplar wood, woods, other surfaces, biodiversity
Gomez-Limón and Riesgo, 2010	Profitability, changes in farmer's profitability, adaptation index, production value, changes in sales, Ag value addition, income, F	Total labour, labour productivity, soil cover, risk of ag abandonment, family and permanent labour, membership, olive oil classification	Olive grove varieties, biological diversity, Pe risk, % of land planted with crops, % of non-arable land, eroded soil, OM, N, and energy balance, herbicide and I W use,
Hřebíček *et al*., 2013	Farm income, net margin, indebtedness, gross margin, liquidity, profitability,	Salary, working hours, holidays, education and training, safety and health protection at work, workers participation, social engagement	Balances of NO, P and K, organic matter balance, specific energy consumption, intensity of plant protection, soil erosion, system diversity potential
Van Pham and Smith, 2014	Crop productivity, net farm income	Food self-sufficiency, access to services and resources	Soil fertility, pest and disease occurrence, W use efficiency, use of chemical F, use of chemical Pe
Waney *et al*., 2014	Pd, cost of production, farm income, product quality, product price stability, marketing network, producer/buyer relationship	Local community engagement, resources availability/accessibility, support system accessibility, knowledge about resource conservation, stakeholder support	Land preparation, erosion control, nutrient and soil fertility management, use of F, intensity of land occupation, cropping system, weed control, pest and disease control
Chand *et al*., 2015	Cost of milk production, labour productivity, capital productivity, feed productivity, family labour income per capita relative to consumption expenditure per capita	Women's empowerment measure, carrying of weight, sharing of work burden, days off	Proportion of dung production used for fuel, enteric methane emissions, adoption of scientific animal breeding practices
Roboredo *et al*., 2016	Family work, total net income, transport, commercialization,	Cooperatives of farmers, associations of farmers, unions	Physical quality index of soils, texture quality index, stoniness index, quality index of soil fertility, water quality index, plant diversity index,
King, 2016	Employment status, primary jobs/green jobs, income, waste generation, energy consumption, access to public transport, vehicle miles travelled, travel choice	Population growth, education attainment, voter participation, income inequality, poverty rate, health service coverage, affordability, accessibility of public spaces, "food deserts"	Ambient pollutants, GHG, W pollution, W use, W availability, floodplain expansion, land cover change, jobs/housing balance
Jane Dillon *et al*., 2016	Pd of labour, Pd of land, profitability, viability of investment, market orientation,	Household vulnerability, level of agricultural education, isolation risk, high age profile, work–life balance,	GHG emissions per farm, GHG emissions per kg of output, emissions from fuel and electricity, N balance per ha, N use efficiency per farm,
Latruffe *et al.* (2016)	Economic viability is mainly measured through profitability, liquidity, stability, productivity and autonomy.	Well-being, physical health, quality of life, social diversification, image of farmers/ agriculture in local communities	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

Ag – agriculture; G – ground; W – water; I – irrigation; Pe – pesticide; F – fertilizer; Pd – productivity; Mgt – management; OM: – organic matter content; B – biodiversity; WUE – water-use efficiency; Env – environment; E – employment; S – self-sufficiency; GHG – greenhouse gases; K – potassium; P – phosphorus; NO – nitrogen oxide

Indicators for measuring agricultural non-sustainability

A fundamental step in formulating policies for sustainable agricultural is to find quantitative indicators. Without them it is impossible to judge the exact nature of change and whether development is progressing or regressing (Zhen and Routray, 2003). The development of a quantitative measure of sustainability is an important prerequisite for the development of legislative measures for agriculture. Sustainability indicators have been defined as indicators that provide direct or indirect information about the future viability of particular social objectives such as material welfare, environmental quality and natural amenities (Zhen and Routray, 2003; Braat, 1991).

But it has been suggested in the literature that indicators of non-sustainability may be used in place of indicators of sustainability when evaluating agricultural systems. The logic is that it is easier and quicker to identify constraints to progress rather than all the factors that contribute to progress. As noted by Smith and McDonald (1997), indicators of non-sustainability are desirable because:

i. they remove the need to define what is sustainable;
ii. they are normally already available and measurable;
iii. their causes and effects are usually known; and
iv. they are easily linked to resource management practices.

Directly visible indicators of non-sustainability include land degradation, changed botanical composition of forests and pastures, prolonged negative trends in yields, lower per-capita availability of agricultural products, increasing use of sub-marginal lands, high intensity of input use and reduced biodiversity. Other indicators of change are the substitution of deep-rooted crops by shallow-rooted crops and excessive dependence on external resources such as fertilizers and pesticides (Feher and Beke, 2013). Bernard *et al*. (2014) identify some potential sources of non-sustainability in farms, as shown in Table 12.

Table 12. Aspects of farms and associated potential sources of unsustainability

Aspects of dynamic farms	Potential cause of unsustainability
Solar energy converters, linking carbon, nitrogen, phosphorus and water cycles and lateral flows	Loss of primary productivity, interrupted nutrient cycles and water flows, depleted soil carbon stocks, loss of soil structure and biota
Enterprises that use land, labour, knowledge, germplasm and capital in production	Loss of any of main production factors, for which more profitable uses may arise from new economic opportunities
Starting points of value-chains that feed the world and satisfy part of its fibre and fuel requirements	Loss of demand for products, for example due to concerns over product quality and/or quality of the production process
Part of social networks	Conflict and loss of collective action
A component of large household livelihood systems	Loss of complementarity with other parts of livelihood systems and evolving ambitions
Links in inter-generational knowledge chains that combine informal and formal science	Loss of relevance of existing knowledge under new circumstances, dominance of external, formal knowledge, loss of effective intergenerational transmission and learning
Part of landscapes	Conflicts over lateral flows such as water, nutrients, soil, organisms or fire and integral landscape functions such as perceived beauty
Agro-biodiversity management units, involved in selective reproduction of crops, livestock and trees making them drivers of inter- and intraspecific genetic diversity trends	Lack of adaptive capacity of farm-level germplasm in the face of new challenges (pests and diseases, climate change, shifting market demands), lack of access to external germplasm

The analysis by Bernard *et al*. (2014) suggests a number of indicators that characterize agricultural non-sustainability as a result of major actors' decisions, choices and interactions with farms. Examples of indicators that can be used in different countries and contexts are shown in Table 13. They can facilitate reviews of the current inter-relationship between agriculture and farming from the perspective of a social actor (such as farmers) and hence identify major threats. In this context, there may be thresholds for some indicators such as acceptable/unacceptable or "in"/"out"; for other indicators, quantitative and/or qualitative interpretation will guide learning and responses.

Table 13. Indicators for characterizing non-sustainability of agriculture resulting from major actors' decisions, choices and interactions with farms

Actors with potential to cause unsustainability	Indicators	Possible metrics
Loss-making investors and credit providers	Economic bottom line Opportunity costs of options foregone Risk quantifiers	Rate of return on investment Input/output accounting Known risks "Guesstimated" level of uncertainty
Angry neighbours	Conflicts over water use	Number of conflicts that are reported in media, and/or reach local or national parliaments
	Conflicts over pollution – water, atmosphere, noise, haze and similar lateral flows Conflicts over landscape beauty Conflicts caused by agricultural practices such as free grazing, fire setting, poor soil conservation practices	Number and type of monitoring systems set up to clarify and quantify issues Number of negotiated agreements
Dissatisfied customers	Emergence of new issues of consumer concern Shifts to alternative providers	Shifts in market shares Number of conversations between producers and consumers
	Responsiveness of producers to consumer concerns	Market share of certified products and price differential in relation to transaction costs
	Development of certification schemes that address consumer concerns	
Over-zealous regulators	Complexity and costs of procedures needed for permits for resource access and use Absence, inadequacy or outdatedness of development and land use plans Biased/top-down economic and development instruments such as subsidies and taxes	Transaction costs and time required for clearance Land use plan, its scope, origin and enforcement Number of negotiated agreements in multi-stakeholder fora
Farmers without options to respond to new conditions and challenges	Number of farms that are not sustained inter-generationally Rural–urban migration of young people	Inter-generational reduction in number of active farms Land conversion to non-agricultural functions

Source: Bernard *et al*., 2014

The indicators for agricultural non-sustainability proposed by Smith and McDonald (1997) were soil nutrient exhaustion, surface soil acidity, nutrients in streams, waterlogging and salinity, decline of soil structure and organic matter, chemical contamination, subsurface soil acidity, reduced diversity of species, increased "greenhouse" effects, organochlorine contamination, silting in bodies of stored water, salinity, loss of soil mass, loss of biodiversity, loss of habitats and contamination by heavy metals. Jodha (1990) examines indicators of agricultural non-sustainability as shown in Table 14.

Table 14. Indicators of non-sustainability

Visibility of change	Resource base	Production flows	Resource management practices
Directly visible	Increased landslides and other forms of land degradation; fragmentation of land; changed botanical composition of forests and pastures; reduced water flows for irrigation	Prolonged negative trends in yield; increasing production inputs per production unit; lower per-capita availability of agricultural products	Less fallow, crop rotation, intercropping and diversified management practices; increasing use of sub-marginal lands; increased use of legal measures to control land use; high intensity of input use
Changes concealed by responses to management	Substitution of deep-rooted crops by shallow-rooted crops; shift to non-local inputs	Introduction of externally supported public food and input distribution systems; intensive cropping on limited areas	Shifts in cropping patterns and composition of livestock; less diversity and increasing monocultures
Development initiatives	New systems without linkages to other diversified activities, generating excessive dependence on outside resources such as fertilizers and pesticides	Agricultural measures directed to short-term results, primarily product-centred rather than resource-centred approaches to agricultural development	

Some indicators for non-sustainability in livestock systems proposed by Ronchi and Nardone (2003) are shown in Table 15.

Table 15. Emerging indicators of non-sustainability in farming of small ruminants in the Mediterranean area

Landscape degradation
Degradation of communal pastures, also resulting from mixed grazing with other herbivores
Abandonment of marginal lands
Low level of integration between agriculture and livestock
Land fragmentation
High dependence of farmers on purchased feed
Reduced diversity and increased specialization in monocropping
Numerical reduction of local breeds and populations
High incidence of parasite disease and hence preventive and curative chemical treatments
High incidence of clinical and subclinical mastitis
High incidence of other diseases
High variability of milk quality

9. Proposing a common set of indicators for measuring agricultural sustainability at the farm level

The indicators discussed here draw on Taylor *et al*. (1993), who constructs and index of indicators for a sample of 85 agricultural producers in Malaysia that covered: i) insect control; ii) disease control; iii) weed control; iv) maintenance of soil fertility; and v) control of soil erosion.

The following indicators were constructed by Rigby and Caceres (2001) for a sample of ten farms in the Guba region of the Philippines:

Improved farm-level social and economic sustainability

- enhances farmers’ quality of life (United States Farm Bill, 1990);
- increases farmers’ self-reliance (Pretty, 1995); and
- sustains the viability/profitability of the farm (Pretty, 1995; United States Farm Bill, 1990; Ikerd, 1993).

Improved social and economic sustainability

- improves equity (Pretty, 1995) and is "socially supportive" (Ikerd, 1993); and
- meets society’s need for food and fibre (United States Farm Bill, 1990).

Increased yields and fewer losses while

- minimizing off-farm inputs (Hodge, 1993; Pretty, 1995; United States Farm Bill, 1990);
- minimizing inputs from non-renewable sources (Hodge, 1993; Ikerd, 1993; Pretty, 1995; United States Farm Bill, 1990);
- maximizing use of natural biological processes (Pretty, 1995; United States Farm Bill, 1990); and
- promoting local biodiversity and "environmental quality" (Hodge, 1993; Pretty, 1995; United States Farm Bill, 1990).

Jane Dillon *et al*. (2016) create farm-level agricultural sustainability indicators using the FADN (Farm Accountancy Data Network) Teagasc National Farm Survey data for Ireland, and suggested the following:

Economic facet	**Social facet**	**Ecological facet**
Productivity of labour	Household vulnerability	GHG emissions per farm
Productivity of land	Level of agricultural education	GHG emissions per kg output
Profitability	Isolation risk	Emissions from fuel
Viability of investment	High age profile	Electricity
Market orientation	Work–life balance	Nitrogen balance/ha
		Nitrogen use efficiency per farm

Meul *et al*. (2008) apply MOTIFS (Monitoring Tool for Integrated Farm Sustainability) as a tool for monitoring integrated farm sustainability by taking into account economic, ecological and social aspects. Four steps were considered: i) translating the principles of a vision of sustainable Flemish agriculture into themes; ii) designing indicators to monitor progress in sustainability for each theme; iii) aggregating the indicators into a farm sustainability monitoring tool; and iv) applying the tool on an actual farm as an initial attempt at end-use validation. Particular was paid to aspects such as communication and user-friendliness. Table 16 shows the indicators designed for the ten sustainability themes.

Table 16. Level 1, level 2 and level 3 themes and indicators of the Meul *et al.* (2008) monitoring system: definitions and choices of method

Level 1	Level 2	Level 3	Level 4
Ecological themes			
Use of inputs	Pesticides	Pesticide use	Amount used and environmental effects
		Pesticide management	Risk of environmental effects based on eight factors concerning pesticide management
	Energy	Energy use efficiency	Amount of product produced with one unit of energy
		Renewable energy use	Share of renewable energy sources used on the farm
		Water use efficiency	Amount of product produced with one unit of water
		Use of alternative water resources	Share of alternative water resources used on-farm – rainwater, surface water and shallow ground water
	Nutrients	N surplus	Risk of environmental effects
		N use efficiency	Amount of product produced per unit of N surplus
		P surplus	Risk of environmental effects
		P use efficiency	Amount of product produced per unit of P surplus
Quality of natural resources	Soil quality	Organic matter content	Organic matter content of the soil
		pH	Soil acidity as an indicator of chemical soil quality
		P content	P content of the soil as an indicator of chemical soil quality
		K content	K content of the soil as an indicator of chemical soil quality
		Biological soil quality	Biological quality of the soil
		Physical soil quality	Physical quality of the soil
	Water quality		Risk of surface water contamination from waste water based on three aspects of waste water management
	Air quality		Risk of air pollution from farming activities
Biodiversity	Genetic diversity		Diversity of crops and animals used in agriculture
	Species diversity		Diversity of wildlife species dependent or affected by agriculture
	Habitat diversity		Diversity of habitats related to agricultural production
Economic themes			
Productivity and efficiency	Labour productivity		Value added per unit of farm labour
	Capital productivity		Value added per unit of farm capital
	Land productivity		Value per unit of land use
	Efficiency		Ratio of actual total productivity to maximum attainable productivity
Profitability	Labour profitability		Farm labour income per unit of farm labour
	Return on equity		Farm profit per unit of own capital
	Return on assets		Farm profit per unit of total capital – farm capital and land capital
Risk			Probability that the production of value added is affected by external events

Social themes			
Level 1	**Level 2**	**Level 3**	**Level 4**
Internal social sustainability	Professional pride		How a farmer’s identity and expectations fit with the daily reality of farming in a changing social, cultural, environmental, economic and political environment Assessment based on eight factors in a list of 24 that the farmer considers essential for maintaining his pride
	Decision latitude		Room for manoeuvre to take own decisions according to own insights, capacities and desires
	Care		Existence of formal and informal structures and institutions that allow people to take care of each other according to their own values
External social sustainability	Animal health and welfare	Body condition score	Percentage of thin cows
		Level of dirt	Share of dirty cows – udders, flanks and legs
		Skin lesions	Share of cows with lesions on hock, neck and spine
		Locomotion score	Share of cows with a low mean locomotion score
		teat-end condition	Share of cows with thick and rough teat-end callosity rings
		Udder condition	Share of cows with subclinical and clinical mastitis
	Landscape management	Stewardship agreements	Presence of stewardship agreements
		Small landscape elements	Time spent maintaining small landscape elements
		Nature conservation	Work on nature conservation
		Visual nuisance	Work minimize visual nuisance
		Architectural quality	Work on architectural quality
		Surrounding landscape	Awareness of effects on surrounding landscape
	Social services		Provision of social services
Disposable income			Total income earned on-farm or off-farm that farmer and family have at their disposal
Entrepreneurship			Extent of farmer’s entrepreneurship based on three aspects – vision, strategy and management

Senanayake (1991) proposes that agricultural systems have varying degrees of sustainability according to the level of external inputs required to maintain the system. The resulting index is shown below:

$$S = f(E_i, E_r, P_e, S_e, R_s, R_b)$$

S = index of ecological sustainability

E_i = external input

E_r = energy ratio

P_e = power equivalent

S_e = efficiency of solar flux use

R_s = residence time of soil

R_b = residence time of biotic

Each parameter has its own two or three possible states: the three possible states of E_i, for example, are listed as 0.1, 0.5 and 1.0. E_i is seen to be more sustainable at lower values.

The terms R_s and R_b depict two possible states – 0 and 1. In the zero state the farming category is unsustainable no matter what the other measures are. In the value state, the farming type is sustainable but the degree of sustainability depends on the values of other parameters. In terms of agricultural sustainability:

$$S = R_s \times R_b / [\, f(v_e) - f(v_d) \,]$$

Where

$v_e = f(S_e, P_r)$

$V_d = f(E_i, E_r, P_e)$

Hence any farming system type that contributes to physical erosion or a high rate of soil biomass loss will yield a value of 0, and can be termed non-sustainable. A farming type that conserves these basic resources will yield a positive value, and can therefore be termed potentially sustainable.

Hayati and Karami (1995) suggest an operational index to measure agricultural sustainability trends at the farm level: the factors measured include those that appear in the crop-production process and that could have a positive effect in the process. The equation is:

$$S = f\left[\, \sum_{i=1}^{8} Xi \,,\ \sum_{j=1}^{3} Yj \,\right]$$

S = Trend of sustainability

X_1= Average of crop production per hectare

X_2= Rotation of crops

X_3= Use of organic manures

X_4= Use of green manures

X_5= Use of crop stubble

X_6= Use of conservational plough

X_7= Trend of change in on-farm water resources

X_8= Trend of change in on-farm soil resources

Y_1= Pesticide, herbicide and fungicide consumption on-farm in a single cultivation season

Y_2= Nitrate fertilizer consumption per tonne of crop production

Y3= Phosphate fertilizer consumption per tonne of crop production

In fact the parameters of X_1 to X_8 could lead to greater sustainability if they increase; parameters of Y_1 to Y_3 could lead to non-sustainability if they increase:

$$S = \sum_{i=1}^{8} Xi - \sum_{j=1}^{3} Yj$$

In order to measure agricultural sustainability at the farm level, Saltiel *et al*. (1994) presented an index consisting of seven components: cultivation of sustainable crops, conservational cultivation, crop rotation, reduced use of pesticides and herbicides, soil mulching and use of organic fertilizers.

Gómez-Limón and Riesgo (2010) introduce indicators for farm-level sustainability assessments and applied a definition of agricultural sustainability with three "pillars" for conceptualizing the indicators. The indicators in this research were:

- Economic – profitability, changes in farm profitability, adaptation index, production value, changes in sales, agriculture value addition, income;
- Social – total labour, labour productivity, soil cover, risk of abandonment, family and permanent labour, memberships, olive oil classification; and
- Ecological – olive varieties, biological diversity, pesticide risk, % of land planted with crops, % of non-arable land, eroded soil, organic matter content, energy balance, herbicide and use of irrigation water.

Indicators of sustainability at the regional level

Table 17 shows the indicators for 252 European regions selected with a view to assessing the sustainability of various European agricultural systems (Gerdessen and Pascucci, 2013).

Table 17. Indicators of agricultural sustainability in European regions

Economic dimension (feasibility)		**Description**
Productivity of labour	Value added per annual work unit	The gross value added is defined as the value of output less the value of intermediate consumption. Output is valued at basic prices and intermediate consumption is valued at purchasers' prices. As indicated by the European Commission the gross value added per annual work unit provides comparable data on labour productivity and allows for comparison among sub-sectors and regions. An annual work unit corresponds to 2,200 working hours per year, which is the number of hours an employee is willing to provide when fully employed in the agricultural business.
Investment level	Gross fixed capital formation in agriculture (Euro/farm)	The gross fixed capital formation in agriculture per farm refers to the investments in assets that are used repeatedly or continuously over a number of years to produce goods.
Social dimension (acceptability)		
Inter-generational equity	Ratio of farmers <35 years/farmers >55 years	Social indicator 3 refers to the ratio of young and old farmers in a given region. It provides the measurement of take-over in agriculture. A ratio close to zero indicates very low take-over and hence an unattractive agricultural sector, whereas a value close to one indicates high take-over and hence an attractive agricultural sector.
Education level	Training and education in agriculture (% land managers with high education)	Social indicator 4 refers to the percentage of farmers who have been fully trained in agriculture. This indicator is calculated as any training course continuing for the equivalent of at least two years full-time after the end of compulsory education, and completed at an agricultural college, university or other institute with courses in agriculture, horticulture, viticulture, forestry, aquaculture, veterinary science, agricultural technology or an associated subject.

Environmental dimension (carrying capacity)		
Land management	Risk of soil erosion (t/(year ha))	Environmental indicator 5 refers to the risk of soil erosion, which is estimated on the base of the Pan-European Soil Erosion Risk Assessment project. This indicator expresses the potentiality of soil loss in terms of tonnes per hectare and per year.
	Intensity of land use for plant production (% of utilized agricultural area)	Indicator 6 is the area under arable crops – not forage crops – when the regional yield for cereals other than rice is more than 60% of the EU-27 average. Cereal yield is a 3-year average.
	Intensity of land use for animal production (% of utilized agricultural area)	Indicator 7 is the area for grazing cattle, sheep and goats when stock density exceeds 1 livestock unit per hectare of forage crops, permanent pastures and meadows.
Water management	Relevance of irrigated areas (% of utilized agricultural area)	Environmental indicator 8 refers to the percentage of hectares in which irrigation is used. An irrigated area is defined as an area of irrigated crops – that is, the area of crops that have actually been irrigated at least once during the 12 months prior to the survey date. Crops under glass and kitchen gardens, which are almost always irrigated, are not included.

Nambiar *et al*. (2001) offer a regional index of agricultural sustainability that considered biophysical, chemical and socio-economic indicators of sustainability. The categories and indicators in the index were:

1. Agricultural nutrient balance: the parameters of agriculture nutrient balance are gross nutrient balance and input/output ratio.
2. Crop yield: long-term crop yield trends provide information on the biological productive capacity of agricultural land and the ability of agriculture to sustain resource production capacity and manage production risks.
3. Agricultural management: the parameters are fertilizer use efficiency (%) and irrigated water use efficiency (%).
4. Agri-environmental quality: the parameters are soil erosion (soil/km^2) and soil saline content (mg/kg).
5. Agricultural biodiversity: the parameters are the number of varieties of livestock and the number of organisms.
6. Economic and social viability: the parameters are income per labourer (US$), real net output per unit of land (US$/ha) and cultural level.
7. Net energy balance: the parameter is the input/output ratio of energy.
8. Soil quality: the parameters are clay content (%), soil depth (cm), bulk density, available water capacity (cm^3), organic matter (%), pH, permeability (cm/h), EC (mS/cm), and CEC (cmol/100 g).

Herrera *et al.* (2016) pointed to stakeholders' (farmers, farm advisors, farm data collectors, policy makers and/or policy evaluators and so on) perceptions of sustainability measurement at farm level. This research was part of the European Union (EU) Framework 7 project FLINT (Farm Level Indicators for New Topics in Policy Evaluation), the objective of which is to test the feasibility of establishing a common standard set of farm-level indicators for policy evaluation in nine EU Member States, ideally linked with the Farm Accountancy Data Network (FADN). The dimensions and indicators of farm level agricultural sustainability in this study were demonstrated in table 18.

The EU Framework 7 project FLINT (Farm-Level Indicators on New Topics in policy evaluation) was created to address the gap between the data needs for policy evaluation and research and the currently-available agricultural statistics. The monitoring and evaluation of the CAP requires data (preferably at farm level) which are not available at the moment in the EU information systems. FLINT provides an opportunity to test the feasibility and to show the added value of having a wider set of sustainability indicators to monitor and evaluate the agricultural policies and design more targeted policy measures (Pope *et al.*, 2016).

A comparison of the policy needs and the identified indicators has resulted in the identification of 33 sustainability themes to be included in the FLINT project. The themes cover the three sustainability dimensions of people, planet and profit for a description of the indicators. The list of environmental indicators themes is the longest, indicating the serious lack of data at farm level on these issues. The environmental indicators cover important topics such as use of pesticides, nitrogen balances, water consumption, greenhouse gas emissions, farm practices with respect to soil erosion, nitrate leaching and soil organic matter. There are fewer economic indicators but these refer exclusively to those not yet included in FADN. They cover topics such as risk management, innovation, sales channels, farm succession and the use of contracts. The social indicators are the most qualitative by nature and involve issues such as education and training (use of advisory services), engagement in the farming sector and rural society, quality of life and working conditions (Pope *et al.*, 2016).

Table 18. Indicators of sustainability at farm level by dimension of sustainability.

Environmental	Economic and innovation	Social
1. Permanent grassland 2. Ecological Focus Areas 3. Semi-natural farmland areas 4. Pesticide usage 5. Nutrient balance (N, P) 6. Soil organic matter in arable land 7. Indirect energy usage 8. Direct energy usage 9. On-farm renewable energy production 10. Farm management to reduce nitrate leaching 11. Farm management to reduce soil erosion 12. Use of legumes 13. GHG emissions per ha 14. GHG emissions per product 15. Carbon sequestering land uses 16. Water usage and storage 17. Irrigation practices	1. Innovation 2. Producing under a label or brand 3. Types of market outlet 4. Past/future duration in farming 5. Efficiency field parcel 6. Modernisation of the farm investment 7. Insurance: production, personal and farm (building structure) 8. Share of output under contract with fixed price delivery contracts 9. Non-agricultural activities	1. Advisory services 2. Education and training 3. Ownership-management 4. Social engagement and participation 5. Employment and working conditions 5. Quality of life/decision making 6. Social diversification: image of farmers/ agriculture in local communities

Indicators of sustainability at the national level

It should be noted that the first set of 134 sustainability indicators was published in 1996 by the United Nations Department of Economic and Social Affairs with a view to developing a central list of indicators to enable country-to-country comparisons. The indicators were organized into a framework with a view to capturing inter-relationships among the indictors; the framework used was the driving-force-state-response method (DSR). Utilization of a framework was the basis for the selection of indicators because characterization was the fundamental criterion (UN, 1996). After consultation and testing between 1996 and 1999, another system – the theme/sub-theme framework – was recommended because it could capture policy issues and major issues related to sustainable development more completely. This set of 58 indicators was organized into themes and sub-themes with four pillars: social development, economic development, environmental development and institutional development (UN, 2001). The most recent national-level framework contains 96 indicators, of which 50 are considered core indicators.

The framework is still recommended, but separation of indicators in accordance with the social, economic, environmental and institutional pillars is no longer included (UN, 2007). Other systems include capital frameworks, accounting frameworks, aggregated indicators and goal-indicator frameworks (King, 2016).

Many researchers have investigated national-level sustainability indicators for agricultural sectors. Van Calker *et al*. (2006), for example, investigate multi-attribute sustainability functions for Dutch dairy farming systems: the approach utilized four steps: i) determination of attribute utility functions; ii) allocation of attribute weights to determine utility functions per aspect; iii) assessment of aspect weights to determine the overall sustainability function per stakeholder group; and iv) determination of the overall sustainability function for society by aggregating the preferences of stakeholders and experts. The indicators in this study were constructed in three dimensions of sustainability – economic, social and ecological. Indicators of agricultural sustainability for each dimension are:

> Economic: profitability;
>
> Social: working conditions, food safety, animal welfare and health, landscape quality; and
>
> Ecological: eutrophication, groundwater pollution, dehydration of soil, global warming, acidification, ecotoxicity.

Nambiar *et al*. (2001) reported the biophysical, chemical and socio-economic indicators of assessing agricultural sustainability in the coastal zone of China. The indicators of sustainable agriculture can also be categorized in the three dimensions:

> Economic: yield, income per labourer, real net output per unit land;
>
> Social: cultural level, number of varieties of livestock, number of organisms; and
>
> Ecological: nutrient balance, efficiency of fertilizer and irrigation water use, soil erosion, saline content and soil quality.

A set of indicators for sustainability applied in different national agricultural policy scenarios is presented by Lehtonen *et al*. (2005), who aim to provide material for policy dialogue rather than a comprehensive assessment of the sustainability of various agricultural policy alternatives (see Table 19). They also presented the kind of agricultural development reflected in each indicator and the overall goal of each indicator. It is important to understand that the numerical values of the calculated indicators and also relative changes over time are important when evaluating the sustainability of alternative agricultural policies.

Table 19. Indicators applied in agricultural policy scenario analysis: Lehtonen et al., 2005; Hayati et al., 2009

Applied indicator	Measured quality	Indicator reflecting	Overall goal of indicator
Total number of animal units up to 2020	Animal units	The scale and long-term economic viability of aggregate animal production	To determine the relative economic viability of animal production in different policy scenarios
Number of bovine animal units	Animal units	The scale and long-term economic viability of dairy and beef production	To determine the relative economic viability of dairy and beef production in different policy scenarios
Number of pig animal units	Animal units	The scale and long-term economic viability of pig production	To determine the relative economic viability of pig production in different policy scenarios
Number of poultry animal units	Animal units	The scale and long-term economic viability of poultry production	To determine the relative economic viability of poultry production in different policy scenarios
Total cultivated area (excluding set-aside) up to 2020	Hectares	Incentives for active crop production	Changes in incentives for active crop production
Set-aside area	Hectares	Incentives for fulfilling cross-compliance criteria and minimizing costs	Changes in incentives in fulfilling cross-compliance criteria and minimizing costs in different policy scenarios
Unused area	Hectares	Share of agricultural land abandoned because of unprofitable production	Changes in the share of land abandoned because of unprofitable production in different policy scenarios
Grass area	Hectares	The scale of gross feed production; incentive for gross feed use and bovine animal production	Changes in scale and incentive for gross feed production in different policy scenarios
Grain area	Hectares	The scales and incentive for grain production	Changes in scales and incentive for grain production in different policy scenarios
Nitrogen balance on cultivated area[1]	Kg/ha	Nitrogen leaching potential from cultivated land	Changes in nitrogen leaching potential in different policy scenarios
Phosphorous balance on cultivated area[1]	Kg/ha	Phosphorous leaching potential from cultivated land	Changes in phosphorous leaching potential in different policy scenarios
Agricultural income	Money unit	The level of economic activities in agriculture	Changes in the level of economic activities in different policy scenarios
Profitability coefficient[2]		Profitability of agricultural production	Changes in profitability of agricultural production in different policy scenarios
Labour hours in agriculture	Million hours	Social sustainability of farmers, the working conditions of agricultural labour	Changes in the number of people employed in agriculture in different policy scenarios
Agricultural income per hour of labour	Money/hour	Economic and social welfare of farmers	Changes in the economic and social viability of agriculture in different policy scenarios

[1] The balances of soil surface nitrogen and phosphorus are calculated as the difference between the total quantity of nitrogen or phosphorus inputs entering the soil and the quantity of nitrogen or phosphorus outputs leaving the soil annually, based on the nitrogen or phosphorus cycle.

[2] The profitability coefficient is a ratio obtained by dividing agricultural surplus by the sum of the entrepreneur family's salary requirement and the interest requirement on capital invested.

Indicators of sustainability at the international level

As shown above, most sustainability indicators target the farm, regional and national levels. International-level indicators have not been investigated often, and there are no comprehensive indices for assessment. There are sound reasons for this.

First, farm-level, regional-level and national-level indicators can be considered by governments, decision-makers and policy-makers. Dahl (2012) notes, however that although governments have a critical role in setting economic and social policy, and policies on land use and infrastructure planning, their influence on investment decisions, research support and nature conservation are not sufficient.

Second, at the farm level it is possible for actors to weigh up, trade off and agree on the criteria for measuring trends in agricultural sustainability. But at higher levels of the hierarchy such as the international level it becomes increasingly difficult to do this in any meaningful way.

Sustainability indicators for livestock systems

Livestock systems have inter-relationships with other agricultural systems and have an important role in the sustainability of agricultural systems at the global level. Ripoll-Bosch *et al*. (2012) assessed the sustainability of Mediterranean sheep farms with different degrees of intensification, and used case studies to investigate four sheep meat and dairy farms with different intensities of reproduction management. Critical points of sustainability, including weaknesses and opportunities, were obtained through a participatory process with farmers and technical advisers that resulted in the selection of 37 sustainability indicators; these were classified according to systemic attributes – productivity, stability, self-reliance, adaptability and equity – and based on the social, economic and environmental sustainability pillars (see Table 20).

Table 20. List of indicators and definitions

Attribute	Indicator	Pillar	Unit/definition
Productivity (n = 8)	Labour profitability	Economic	Net margin[d]/WU (€)
	Animal profitability	Economic	Net margin[d]/LUe (€)
	Economic efficiency	Economic	Agricultural outputs[e]/total costs (ratio)
	Land productivity	Economic	Agricultural outputs[e]/ha (€)
	Feed efficiency	Economic	MJ in product/MJ in feeds (ratio)
	Animal productivity	Economic	Animal outputs/LUe (€)
	Lambing rate	Economic	No. of lambings/LUe (%)
	Animals per WU	Economic	LUe/WU
Stability, reliance, resilience (n = 5)	Farm continuity	Social	Continuity in the next 15 years (scale)
	Off-farm income	Economic	Off-farm income/total income (%)
	Advisory services	Social	Scale
	Facilities	Social	Scale (qualitative evaluation)
	Wildlife conflicts	Environmental	Scale (qualitative evaluation)
Adaptability (n = 7)	Number of incomes	Economic	Number of different income sources
	Main agricultural income	Economic	Major ag. income/total ag. income (%)
	Land access problems	Social	Scale (qualitative evaluation)
	Farmer education	Social	Scale
	Distance to markets	Social	Travel time to nearest city > 10,000 inhabitants
	Communal grazing areas	Environmental	Dichotomic
	Distance to slaughterhouse	Social	Travel time to nearest slaughterhouse
Equity (n = 10)	Salary level	Social	Net margin per WU/reference salary (%)
	Satisfaction level	Social	Scale (farmer self assessment)
	Grazing	Environmental	MJ from grazing/total flock requirements (%)
	Energy efficiency	Environmental	MJ E inputs[i]/total ag. income (ratio)
	Grazing protected areas	Environmental	Dichotomic
	Distance to services	Social	Travel time to closest services[j] (min)
	Hired labour	Social	Contracted WU/total WU (%)
	Leisure time	Social	Holiday days per WU per year (d)
	Stocking rate	Environmental	LUe/ha of forage areas (ratio)
	Local breeds	Environmental	Number of local breeds/varieties
Self-reliance (n = 7)	Feed self-sufficiency	Economic	On-farm feed MJ/total feed MJ (%)
	Forage self-sufficiency	Economic	On-farm forage/total forage MJ (%)
	Indebtedness	Economic	Financial costs[k]/net margin (%)
	Family labour	Social	Family WU/total WU (%)
	Own area	Economic	Owned land area/total land area (%)
	Subsidies	Economic	Total subsidies/net margin (%)
	Added-value	Economic	Price per unit of product/reference price (%)

WU working unit; LUe livestock unit (adult ewes); MJ megajoule;
[d] Net Margin = agricultural outputs + subsidies – variable costs: feeding, cropping, veterinary and sanitary, machinery and building maintenance, fuel and electricity, insurance, temporary labour – fixed costs: permanent labour, financial costs and amortization.
[e] All incomes from agricultural activities excluding subsidies.
[i] Fuel and electricity.
[j] Health and education.
[k] Debts and depreciation.

In assessing the sustainability of agro-pastoral systems, Ayantunde *et al*. (2011) try to provide some indicators for the analysis of their sustainability, as shown in Table 21.

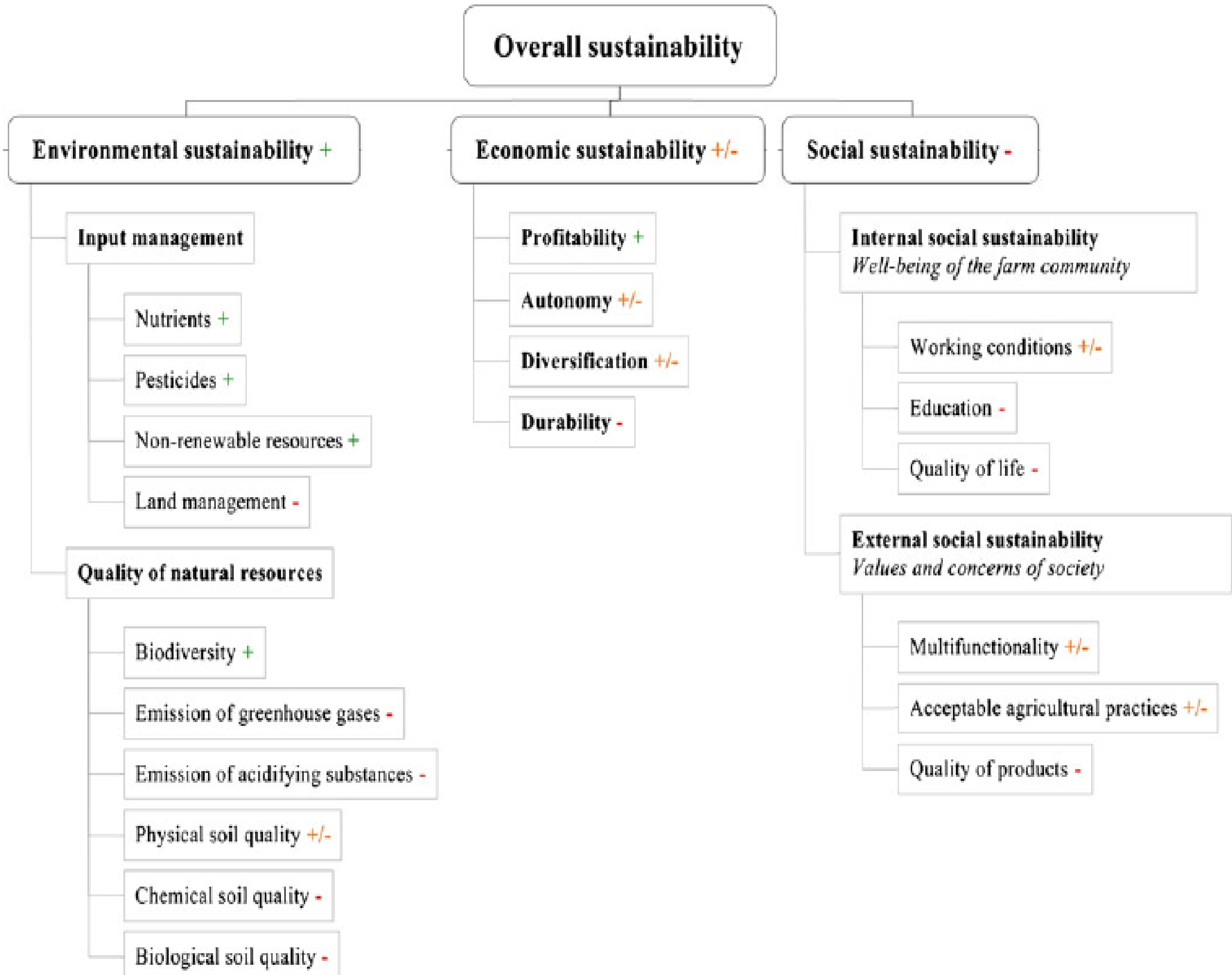
Table 21. Criteria and indicators for assessing sustainability of pastoral systems in East and West Africa at household and community level

Criterion	Sustainability component[a]	Indicator
Provision of food for the household: food security	Resilience	Energy intake
		% children under 5 malnourished: infant mortality
		Household dependency ratio
		Household income
Pasture productivity	Production, efficiency, stability, resilience	Carrying capacity
		Biomass
		Pasture quality
		Species richness and diversity
		Soil nutrients – organic matter, nitrogen, phosphorus
Livestock productivity	Production, efficiency, stability, resilience	Herd size
		Species composition
		Milk offtake
		Mortality rate
		Reproductive performance
Livestock mobility	Production, resilience	Distance livestock can move freely to pasture and water
		Animal performance and productivity
Livelihood diversification options	Production, stability, resilience	Revenue from non-livestock based livelihoods such as commerce, remittances from migration
		Number of rural credit institutions
Household economy and community development	Production, resilience	Household income
		Remittances from migrants
		Community infrastructures such as schools, primary health centres
		Employment rate in the community
Pastoral tradition and indigenous knowledge	Production, resilience	Emigration rate to urban areas
		Proportion of the community with higher education
		Proportion of the community growing crop

[a] These refer to conceptual components of sustainability: production = output from the system over time; efficiency = ratios of conversion of inputs into outputs; stability = degree of fluctuation around output trend; and resilience = speed of restoration of output trend after major disturbance.

Lebacq *et al*. (2013) argue that sustainable livestock systems must be environmentally friendly, economically viable for farmers and socially acceptable, particularly with regard to animal welfare, for which numerous farm-level sustainability indicators have been developed. The main challenge is that the selection of indicators must be fully objective to ensure that assessment subjectivity is avoided. The researchers reviewed types of sustainability indicator, and provided guidelines for selecting indicators in a data-driven context by examining selection criteria and methods. The selected set of indicators included: i) environmental indicators focusing on farm practice; ii) quantitative economic indicators; and iii) quantitative social indicators with a low degree of aggregation. Figure 4 shows the division of sustainability into dimensions and themes, with indicators for each:

Figure 4. Identifying farm-level indicators of sustainability by considering environmental, economic and social dimensions (Lebaq *et al*., 2013)



This set of themes and indicators provides appropriate, applicable, cost-effective and universal indicators of sustainable livestock production at the farm level. The three-pillar approach mentioned earlier – one of the most important trends in indicator-based analysis of agricultural sustainability – was used to design the indicators.

The agricultural sustainability indicators in this research were:

Economic

1. Productivity:
   - labour productivity
   - capital productivity
   - land productivity
   - animal productivity
   - animals per working unit
2. Profitability
   - labour profitability
   - return on equity
   - return on assets

Social

1. Internal social sustainability
2. External social sustainability
3. Disposable income

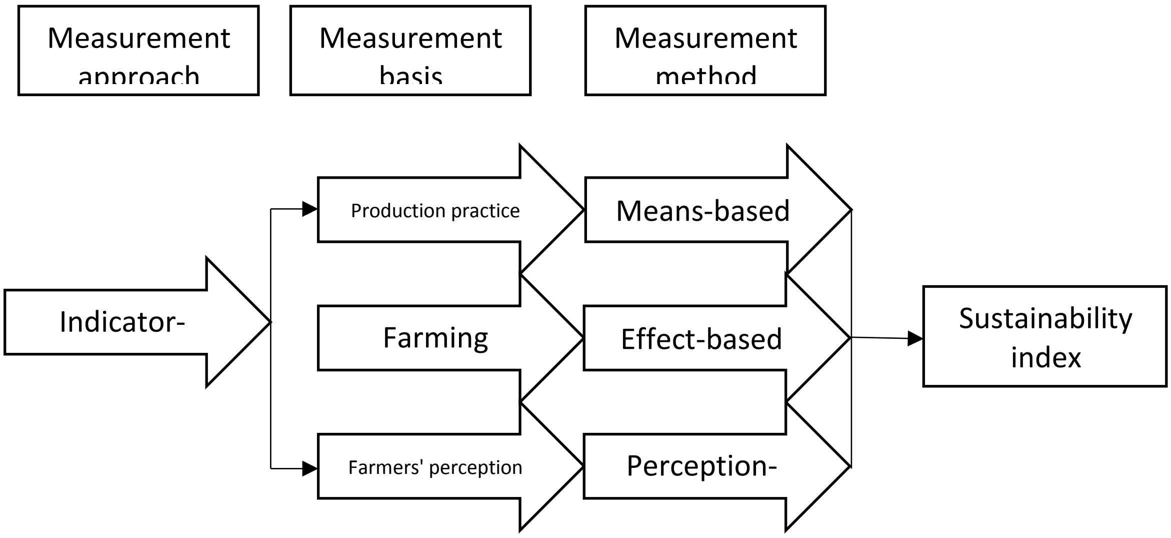
Ecological

1. Use of inputs
   - pesticides
   - energy
   - nutrients
2. Quality of natural resources
   - soil quality
   - air quality
   - water quality
   - biodiversity

10. Proposing data-collection methods for measuring agricultural sustainability

In collecting data and designing measurements to assess agricultural sustainability, some researchers worked from a methodological perspective. Van der Werf and Petit (2002), for example, note that agricultural emissions and pollution of the environment depend primarily on the state of the farming system, which depends largely on climatic factors such as rainfall and temperature and on farming practices, which in turn depend on farmers' perceptions of the environmental effects of their activities. Given the interdependence of these agro-ecological factors, there is clearly a need for an indicator-based approach to measuring and monitoring agriculture that aggregates a range of indicators drawn from means-based, effect-based and perception-based measurement (see Figure 5).

Figure 5. Method for collecting data and measurements (Sabiha *et al*., 2016)



Sabiha *et al*. (2016) observe that means-based methods are applied to the environmental indicators related to farming practices, effects-based methods to the environmental indicators related to farming systems and perception-based methods to the environmental indicators related to farmers' perceptions. Applying a proportion of a recommended amount of chemical fertilizer to assess agro-chemical risk is a means-based indicator, whereas the chemical reactivity of soil – soil alkalinity and acidity are examples – is an effect-based indicator, and farmers' perceptions of loss of soil fertility as a result of applying larger amounts of chemical fertilizer constitute a perception-based indicator.

The sustainability of agriculture depends largely on farm production practices. The link is indirect, however, because emissions to the environment depend on the state of the farming system, which depends on farm production practices and on variable factors such as rainfall and temperature. Hence indicators of agricultural sustainability may be based on farm production practices – means-based – or on the effects of such practices on the farming system or emissions to the environment – effect-based. With regard to the quality of groundwater, for example, indicators concerned with fertilization such as amounts of nitrogen applied, or those concerned with the planting cover crops to minimize leaching, are means-based. On the other hand, indicators reflecting nitrate in the soil at harvest or nitrate lost to groundwater are effect-based (Van der Werf and Petit, 2002).

Herrera *et al.* (2016) based on the FLINT (Farm-Level Indicators for New Topics in Policy Evaluation) project, introduced three sustainability monitoring systems that can be useful in collecting required data: (a) regulations-based measurement; (b) market-led measurements; and (c) own farm measurement system. Regulations-based monitoring systems have as a purpose compliance with government rules or policy evaluation, for example cross-compliance mechanisms. Market-led measurement initiatives request information based on the commercial arrangements between farmers and their customers, for example information that is requested by traders, retailers or consumers. Farm monitoring systems include all the data and information management (digitalized or not) managed within the farm.

The choice of method for collecting data depends on the type of data required and the subject matter of the indicator. The following sections give some guidelines for collecting primary, secondary or estimated data for the purpose of measuring or assessing agricultural sustainability.

Primary data

When primary data are to be collected by a third party or through an assessment tool, the data about a farm's activities may be in the form of audit reports, certificates or similar sources. There are many sustainability measurement tools that enable users to calculate information such as greenhouse gas emissions (FAO, 2013).

Secondary data

Users of the Framework and Methods for Measuring and Monitoring Agricultural Sustainability (FMMMAS) may not always be able to collect primary data for all indicators. In some cases secondary data may be a reliable basis for making assumptions about the performance of an enterprise: if so, the assessor should establish that the data obtained are current and published by a reliable source. Statistics or scientific information are preferable because the data will come from a peer-reviewed source. Because secondary data are likely to be at best of moderate or low quality, FMMMAS users will need to make assessments on the basis of their own judgment (FAO, 2013).

Estimates

Estimates of the performance of an enterprise may have to be used in FMMMAS; they will generally be made by enterprise managers or staff. The FAO (2013) guidelines make the important distinction that estimates are different from data collected in interviews: an assessor may, for example, estimate that a farm operation uses a certain amount of fuel per year and assess the effects of carbon emissions accordingly. In the absence of documentation or reliable secondary data, or where it is not possible to validate tools or calculations, estimates may be used to complete FMMMAS indicators – but they must be taken as low-quality data, and assessors should call for improvements in data quality.

Conclusion

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 and, more recently, innovation (Latruffe *et al.*, 2016). The review of the literature shows that agricultural sustainability has been understood largely in its environmental dimensions, that it is affected by socio-economic and biophysical conditions, and that obstacles to sustainable agriculture are different in different countries. The FMMMAS was developed in this context to enable assessments of the sustainability of agricultural activities such as farming, cropping and livestock raising to be made at the global level. By using FMMMAS, which considers sustainability in the social, economic and ecological dimensions, investigators in different countries can apply in their measurement tools the metrics that capture most accurately the priorities relevant to them. In short, the FMMMAS guidelines provide an internationally comparable and operationally cost-effective way of measuring and monitoring agricultural sustainability.

The literature on sustainability shows that the approach based on the three pillars – social, economic and ecological – is most commonly used in assessing and measuring agricultural sustainability, whereas FMMMAS constitutes a tool that enables national-level measurements and evaluations of agricultural sustainability to be compared and ranked with those of other countries.

The literature reviewed in this study of frameworks and methods for measuring and monitoring agricultural sustainability makes it clear that the three-pillar approach, which is a major trend in indicator-based analysis – is used for designing the indicators, a process in which features such applicability, cost-effectiveness, data availability and global applicability are considered. On the other hand, it should be kept in mind that social dimension of agricultural sustainability is poorly investigated in literature. In this regard, social pillar of agriculture is the dimension that requires more concentration in the future.

It should be noted the level of analysis can be a significant influence on the diagnosis of agricultural sustainability: i) at the field level soil-management, grazing and cropping practices will be the main determinants of sustainability; ii) at the farm level sustainable resource use is necessary to support a family farm business; iii) at the national level there may be pressures on the use of agricultural land from non-farming sectors; and iv) at the global level climate, international terms of trade and the distribution of resources become important determinants.

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