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SAFE—A hierarchical framework for assessing the sustainability of agricultural systems

N. Van Cauwenbergh [a,*], K. Biala [b,e], C. Bielders [a], V. Brouckaert [b], L. Franchois [c], V. Garcia Cidad [b], M. Hermy [d], E. Mathijs [c], B. Muys [d], J. Reijnders [a], X. Sauvenier [b], J. Valckx [d], M. Vanclooster [a], B. Van der Veken [d], E. Wauters [c], A. Peeters [b]

[a] Unité de Génie Rural, Université catholique de Louvain, Croix du Sud 2 bte2, 1348 Louvain-la-Neuve, Belgium
[b] Laboratoire d'Ecologie des Prairies, UCL, Croix du Sud 5 bte1, 1348 Louvain la Neuve, Belgium
[c] Centrum Voor Landbouw-en Milieu Economie, KULeuven, Willem de Croylaan, 42, 3001 Leuven, Belgium
[d] Division Forest, Nature and Landscape, KULeuven, Celestijnenlaan 200^{E}, 3001 Leuven, Belgium
[e] Institute for Land Reclamation and Grassland Farming, DOB Wroclaw, ul. Krainskiego 16, 50-153 Wroclaw, Poland

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Abstract

Sustainable development and the definition of indicators to assess progress towards sustainability have become a high priority in scientific research and on policy agendas. In this paper, we propose a consistent and comprehensive framework of principles, criteria and indicators (PC&I) for sustainability assessment of agricultural systems, referred to as the Sustainability Assessment of Farming and the Environment (SAFE) framework. In addition we formulate consistent and objective approaches for indicator identification and selection. The framework is designed for three spatial levels: the parcel level, the farm level and a higher spatial level that can be the landscape, the region or the state. The SAFE framework is hierarchical as it is composed of principles, criteria, indicators and reference values in a structured way. Principles are related to the multiple functions of the agro-ecosystem, which go clearly beyond the production function alone. The multifunctional character of the agro-ecosystem encompasses the three pillars of sustainability: the environmental, economic and social pillars. Indicators and reference values are the end-products of the framework. They are the operational tools that are used for evaluating the sustainability of the agro-ecosystems. The proposed analytical framework is not intended to find a common solution for sustainability in agriculture as a whole, but to serve as an assessment tool for the identification, the development and the evaluation of agricultural production systems, techniques and policies.

Keywords: Sustainability assessment; Sustainable agriculture; Principles criteria and indicators; Decision support

1. Introduction

Ever since the Brundtland definition of sustainable development (World Commission on Environment and Development, 1987), the concept of agricultural sustainability has gradually evolved (Schaller, 1993). Lewandowski et al. (1999) defined sustainable agriculture as the management and utilization of the agricultural ecosystem in a way that maintains its biological diversity, productivity, regeneration capacity, vitality, and ability to function, so that it can fulfil – today and in the future – significant ecological, economic and social functions at the local, national and global levels and does not harm other ecosystems. The implementation and evaluation of sustainable agriculture has become a principal challenge for agricultural research, practice and policy.

For sustainability evaluation of production systems, a variety of assessment tools has been developed in the past, including Life Cycle Assessment (LCA), Cost–Benefit

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* Corresponding author. Tel.: +32 10473690; fax: +32 10473833.
E-mail address: vancauwenbergh@geru.ucl.ac.be
(N. Van Cauwenbergh).

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Analysis (CBA), Environmental Impact Assessment (EIA) and Sustainability Standards with Principles, Criteria and Indicators (PC&I). While these methods may use the same indicators, their procedure and field of application are quite different (Baelemans and Muys, 1998). PC&I is the most universal and versatile among these tools, as it is nothing else than a thematically structured list of principles and criteria with a corresponding checklist of indicators. PC&I can be used for a wide range of applications such as eco-certification at the management unit level, policy evaluation at the regional or national level (Holvoet and Muys, 2004), or as a generic assessment tool for specific sustainability issues.

For the evaluation of sustainability in agro-ecosystems at national and international levels sets of agri-environmental indicators have recently been designed (e.g. Smith and Dumanski, 1994; Piveteau, 1998; NRC, 2000; MAFF, 2000; Wascher, 2000; OECD, 2001; Delbaere, 2002; de Angelis, 2002). At the management unit level (i.e. the farm scale) different environmental assessment tools have been developed, such as Écopoints (EP; Mayrhofer et al., 1996), Environmental Management for Agriculture (EMA; Lewis and Bardon, 1998), SOLAGRO (Initiatives pour l'énergie, l'environnement, l'agriculture; Pointereau et al., 1999), ECOFARM (Peeters and Van Bol, 2000), agro-ecological indicators (AEI; Girardin et al., 2000) and PROP'EAU SABLE (Lambert et al., 2002). However, as stated by Bossel (2001) ''defining an appropriate set of indicators for sustainable development is a difficult task''. If too few indicators are monitored, crucially important developments may escape attention, and when focusing on a particular area of the system trade-offs are not properly taken into account (von Wirén-Lehr, 2001). Conversely, if too many indicators are considered, data collection and data processing become difficult to handle at a reasonable cost, redundancies might appear and the message expressed by the indicator set becomes difficult to understand. Therefore, the difficulty is to come up with a set of ''essential'' indicators (Mitchell et al., 1995; Bossel, 2001). In the early times, this obstacle was overcome by using an intuitive judgement of experts familiar with a particular discipline (e.g. ecology or economy), which introduced some important biases due to ''an overly dense indicator specification or gaps for some critical issues'' (Bossel, 2001).

It is in this context that frameworks for indicator sets have progressively evolved. The role of the framework has changed from the organization of a core set of indicators (e.g. Piveteau, 1998; OECD, 1999; Wascher, 2000) towards a sound basis to facilitate the formulation of exhaustive indicator sets and to ensure the selection of a core, coherent and consistent list of indicators in a particular system. Two types of frameworks can be distinguished (after von Wirén-Lehr, 2001): system-based frameworks, primarily providing systemic indicators describing key attributes (general functions or processes) of systems as a whole (e.g. Conway, 1994; Smith and Dumanski, 1994; Bossel, 2001; López-Ridaura et al., 2005) and content-based disciplinary frameworks providing specific indicators that characterize single parts (related to specific functions or processes) of the system of concern (e.g. CIFOR, 1999). A recent overview of the conceptual approaches used in sustainability evaluation is given by López-Ridaura et al. (2005). Although both approaches provide a good structure to derive indicators, the existing frameworks show limitations when applied to the agricultural production systems. Indeed, system-based frameworks, that evaluate sustainability based on general attributes of the system (such as productivity, stability, resilience, etc.), provide a good thinking structure for indicator derivation, but the lack of a specific content for the different attributes requires an extensive knowledge of the system under investigation to formulate indicators. Furthermore, due to the highly complex nature of systemic indicators, these indicators remain qualitative rather than quantitative parameters (von Wirén-Lehr, 2001). On the other hand, content-based frameworks (such as PC&I) facilitate the translation of functions into specific objectives and quantitative parameters, yet the lack of a holistic approach in most frameworks for agriculture does not allow for the evaluation of the system as a whole.

Indeed, unlike in forestry (Lammerts van Bueren and Blom, 1997; CIFOR, 1999), remarkably few efforts have been made to develop holistic content-based frameworks of PC&I for sustainable agriculture (van der Werf and Petit, 2002). In this paper, we present such a content-based PC&I framework for assessing sustainability in agricultural systems, referred to as the Sustainability Assessment of Farming and the Environment (SAFE) framework, the content reflecting the functions of (agro-) ecosystems as developed by de Groot et al. (2002). Although content-based, SAFE differs from previous efforts in the agricultural domain by its holistic approach, covering all components of agricultural systems. In addition, several complications that may have hampered the development of content-based PC&I frameworks for agriculture are tackled in the SAFE framework: (1) problems with indicator selection, (2) scale problems for implementing such a framework and (3) lack of reference values for testing sustainability issues. These are further discussed below.

First, it should be considered that indicators are the basic element of any control system and should therefore sufficiently reflect the complexity of the system (Peet and Bossel, 2000). Operational indicators should meet a range of conditions related to quality and cost–benefit ratio. As discussed by Sauvenier et al. (2006), an objective and verifiable way of indicator selection is therefore needed. Several authors (OECD, 1999; Romstad, 1999; NRC, 2000) proposed requirements that a good indicator should meet, without providing practical guidelines concerning the selection procedure. In SAFE, such a procedure is proposed (Sauvenier et al., 2006).

Second, scaling problems appear throughout existing indicator sets. Aggregated data and indicators applicable at the national level lack a close link to the farm, which is the management unit level where agri-environmental measures need to be implemented (Pacini et al., 2003). Further, indicator sets that take into account both technical–economic and environmental–ecological trade-offs of production processes (e.g. Bockstaller et al., 1997; Pointereau et al., 1999; Girardin et al., 2000; Peeters and Van Bol, 2000; Lambert et al., 2002) are well performing, but the geographic specificity of these systems makes transferability to other systems difficult. Finally, the spatial scale for which indicators need to be designed depends on the sustainability criterion which is addressed. A difficulty in assessing the sustainability of agricultural systems is that the appropriate measurement scale varies both within and across the three pillars of sustainability (Rigby and Cáceres, 2001).

Third, problems occur with the definition of reference values. If absolute reference values (such as norms) are not available, then indicator values are scored using a relative scale, which is, for instance, based on time series analysis. Unfortunately, such relative scoring becomes problematic when data are scarce.

SAFE is designed for three spatial levels: the parcel level, the farm level and a higher spatial level that can be the landscape, the region or state, according to the indicator type. The SAFE framework is hierarchical as it is composed of principles, criteria, indicators and reference values in a structured way. Indicators and reference values are the end-products of the framework as well as the operational tools that are used for evaluating the sustainability of agro-ecosystems. The proposed analytical framework forms part of the evaluation path in agricultural sustainability (Fig. 1). It is not intended to find a common solution for sustainability in agriculture as a whole, but to serve as an assessment tool for the identification, development and evaluation of locally more sustainable agricultural production systems, techniques and policies. In this paper, the focus is on the development of the sustainability evaluation framework. Further details on the selection and aggregation of indicators and the practical implementation of the framework are given by Sauvenier et al. (2006).

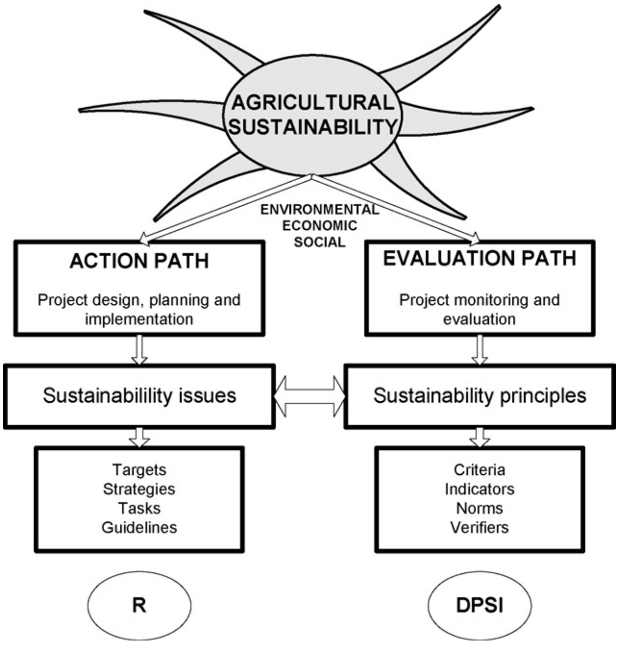

Fig. 1. Paths in sustainability research (after Madlener et al., 2003) and related DPSIR indicators.

2. Methodology of the hierarchical framework

2.1. System boundaries

The system boundaries of the SAFE framework are defined on the basis of the product life cycle, and have a spatial and a temporal component. Regarding the *product life cycle*, the framework is restricted to the on-farm activities of the production cycle. This means that impacts caused by off-stream activities such as transport, food transformation and packaging are not accounted for. Upstream activities such as fertilizer and biocides manufacturing and fossil fuel or phosphate extraction are also excluded, except for the calculation of the energy balance. Including these input-related issues in the energy balance is important because they reflect the sustainability of the farmer's choices in relation to external resource inputs. We acknowledge that to some extent we are inconsistent in defining system boundaries by making exceptions for the energy balance. However, we defend this choice because of the high importance of the energy balance for farm sustainability and because of the impact of farmers' decisions on the energy balance. Because the SAFE framework only focuses on the farming activity, this does not provoke double counting.

For the *spatial* aspect, there is a horizontal and a vertical component. The horizontal component is dependent on the scale of application limited to the parcel, farm or landscape level (watershed, region or state), respectively. The parcel is the smallest scale level considered and is internally uniform with regard to management practices, except for the field margins. The farm is a management unit with a certain level of capital stock including a set of human, man-made, social and natural resource capital (Stern, 1997); it thus includes parcels, buildings, machines, livestock, etc. The highest spatial level is to some extent dependent on the issue to be analyzed: watershed for surface water-related issues, landscape/ecosystem for some soil, air, energy and biodiversity-related issues, and administrative units (region, state) for some environmental as well as for social and economic issues. The selected sustainability indicators are defined for one or more of these levels. The vertical component is limited to the biosphere. It is the thin layer at the earth surface colonized and influenced by organisms, including the soil profile as the actively rooted zone, here arbitrarily set to 1.5 m, the plant canopy and the atmosphere between and above the canopy (including birds and flying insects).

Effects on the higher layers of the atmosphere (e.g. CO_2 emissions inducing pressure on the climatic system) or the geosphere (e.g. nitrate leaching to the groundwater system) are taken into account through the fluxes across the system boundaries. Fig. 2 shows the product life cycle and the spatial component of the system boundaries.

The *time* scale over which to evaluate sustainability is difficult to define because indicators are often intrinsically static (being a snapshot measurement), while the agro-ecosystem is highly dynamic. Indicators must be used to compare the actual state of the system with sustainability reference values (sustainability assessment) or with the state of the same system in the past and in the future (sustainability monitoring). But for many indicators snapshot measurements are not accurate because of the cyclic behaviour of the agro-ecosystem and/or its rapid response to climatic and other sources of variation (e.g. market prices). For this reason many indicators should be time-integrated and/or have an adapted measurement frequency in order to observe changes in a dynamic system. The same applies to social and economic indicators. Because economic indicators are typically derived from book-keeping data, often their three-year average values are considered.

2.2. *Structure of the hierarchical framework: principles, criteria and indicators*

The SAFE analytical framework defines hierarchical levels to facilitate the formulation of sustainability indicators in a consistent and coherent way. The structure of the hierarchical framework is shown in Fig. 3 (adapted from Lammerts van Bueren and Blom, 1997). The general aim of the framework is to evaluate sustainability in agriculture and this aim is progressively reached by defining successively principles, criteria and indicators, following the PC&I theory as developed for assessing sustainability in forestry (Lammerts van Bueren and Blom, 1997). The PC&I theory is applied to the agro-ecosystem itself, defined at different scale levels by different system boundaries, as discussed above. The definition of the principles further rests on the normative theory of ecosystem functioning as defined by de Groot (1992).

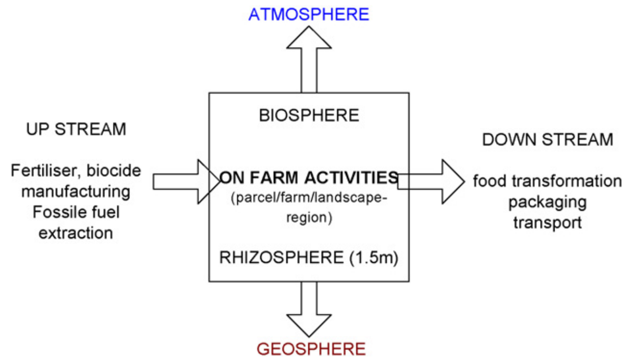

Fig. 2. Product life cycle and spatial component of the system boundaries.

The first hierarchical level of *principles* is related to the multiple functions of the agro-ecosystem, which go clearly beyond the production function alone (de Groot et al., 2002). The multifunctional character of the agro-ecosystem encompasses the three pillars of sustainability: the environmental, economic and social pillars. Principles are general conditions for achieving sustainability (which is the ultimate goal) and should be formulated as a general objective to be achieved.

A *criterion*, i.e. the second hierarchical level, is the resulting state or aspect of the agro-ecosystem when its related principle is respected. Criteria are specific objectives, more concrete than principles and relating to a state of the system, and therefore easier to assess and to link indicators to. The selection of criteria must be based on thorough knowledge of the system under evaluation. The formulation of a criterion must allow a verdict (Yes/No) on the compliance with the criterion in an actual situation.

Indicators form the third hierarchical level and are variables of any type that can be assessed in order to measure compliance with a criterion. Indicators describe features of the agro-ecosystem or elements of prevailing policy, management conditions and human driving forces indicative of the state of the system in an objectively verifiable way. A set of indicator values should provide a representative picture of the sustainability of agricultural systems in all its environmental, economic and social aspects. In order to obtain indicator values there is a need for measurement tools and/or calculation procedures (e.g. modelling or expert-based evaluation) to measure or estimate the indicator value. This set of measurement and calculation procedures is further referred to as ‘‘expression procedure’’.

Reference values form the fourth and lowest level of the hierarchical framework. Reference values describe the desired level of sustainability for each indicator. They give users guidance in the process of continuous improvement towards sustainability (Mitchell et al., 1995; Girardin et al., 1999; Wefering et al., 2000; Piorr, 2003). The choice of reference values is established on a scientific or empirical basis. The SAFE framework allows an assessment based either on the comparison of an indicator value with a previously defined absolute reference value (if it exists) or on the comparison of indicator values from different systems among each other (von Wirén-Lehr, 2001) (Fig. 4). Absolute reference values include scientific and legal reference values. Scientific values are brought forward by scientists based on state-of-the-art knowledge in combination with the precautionary principle (O'Riordan and Cameron, 1994). Legal values are also called norms and their compliance is compulsory. They are typically the result of negotiation, for instance, between policy makers, farmers' representatives, advisory organisms and scientists. Absolute reference values can also be divided into target and threshold values. *Target values* identify desirable conditions (Mitchell et al., 1995), while *threshold values* may be expressed either as minimum or maximum levels or ranges of acceptable values, that

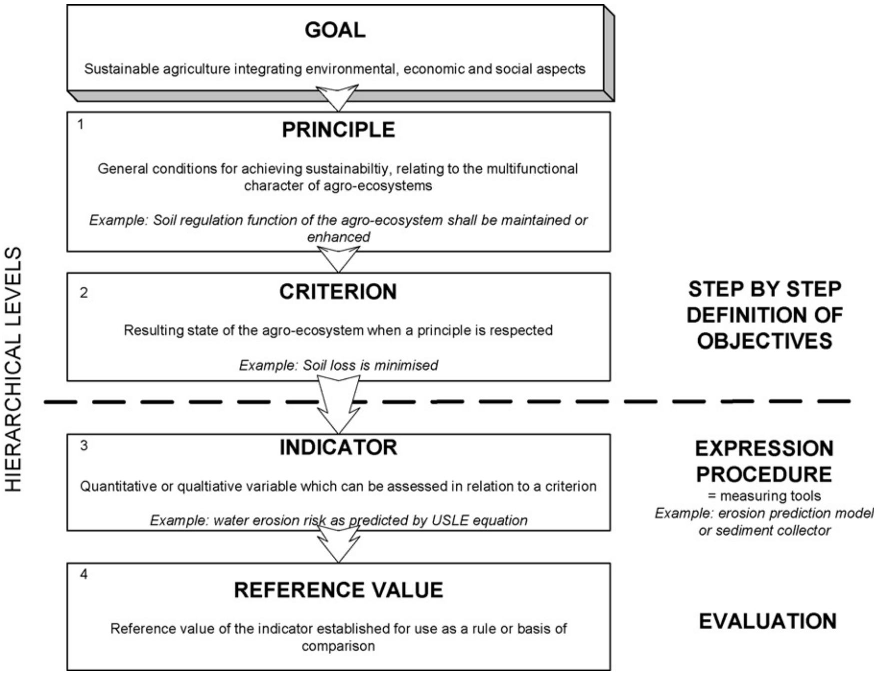

Fig. 3. Structure of the SAFE hierarchical framework (adapted from Lammerts van Bueren and Blom, 1997).

should not be exceeded taking into account the precautionary principle (e.g. Restrepo, 1998; Smith, 2000). As shown in Fig. 4 both target and threshold values can have a scientific source, although they are often politically oriented. Legal norms are typically represented by thresholds, although they can constitute targets in some cases. Examples of reference value types are given in Fig. 5.

For some criteria, e.g. economic criteria, it is meaningless to define absolute reference values at a local spatial scale. In such cases, the most adequate reference value should be established at larger spatial scales such as the regional average. Relative assessment can also be performed, based on a comparison between sectors. For other criteria, the evaluation of an indicator at a given moment in time makes not much sense. This applies, for instance, to the evaluation of plant or insect diversity. In such cases indicators and reference values should be defined in terms of a desirable trend (i.e. how does the trend in indicator values compare with the reference trend). Assessing changes in time may be achieved by presenting the time course of the system state variable from which trend indicators and reference values can be inferred. The above-mentioned types of reference values may be applicable to different scales such as the parcel, the farm or the landscape/watershed/administrative unit scale.

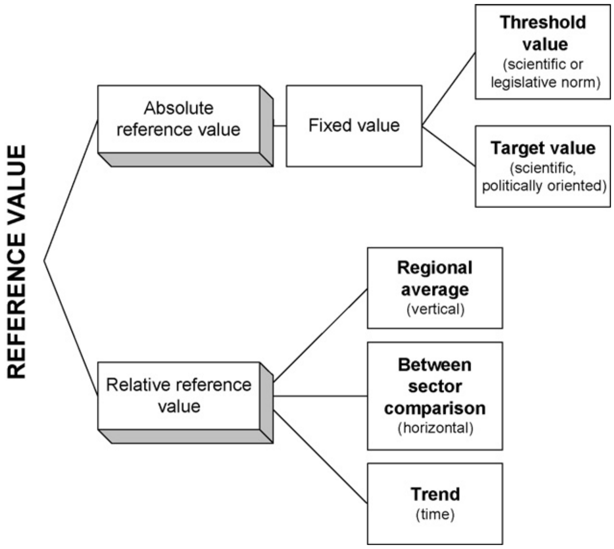

Fig. 4. Classification of reference values.

3. Description of the hierarchical framework

The principles and criteria of the SAFE framework are presented in Table 1. They are related to the functions of an agro-ecosystem (de Groot et al., 2002) and are grouped together according to the three pillars of sustainable agriculture.

3.1. Environmental pillar

Environmental functions are connected with the management and conservation of natural resources and fluxes within and between these resources. Natural resources provided by ecosystems are water, air, soil, energy and biodiversity (habitat and biotic resources).

Two main sets of agro-ecosystem functions are considered in SAFE (Table 2):

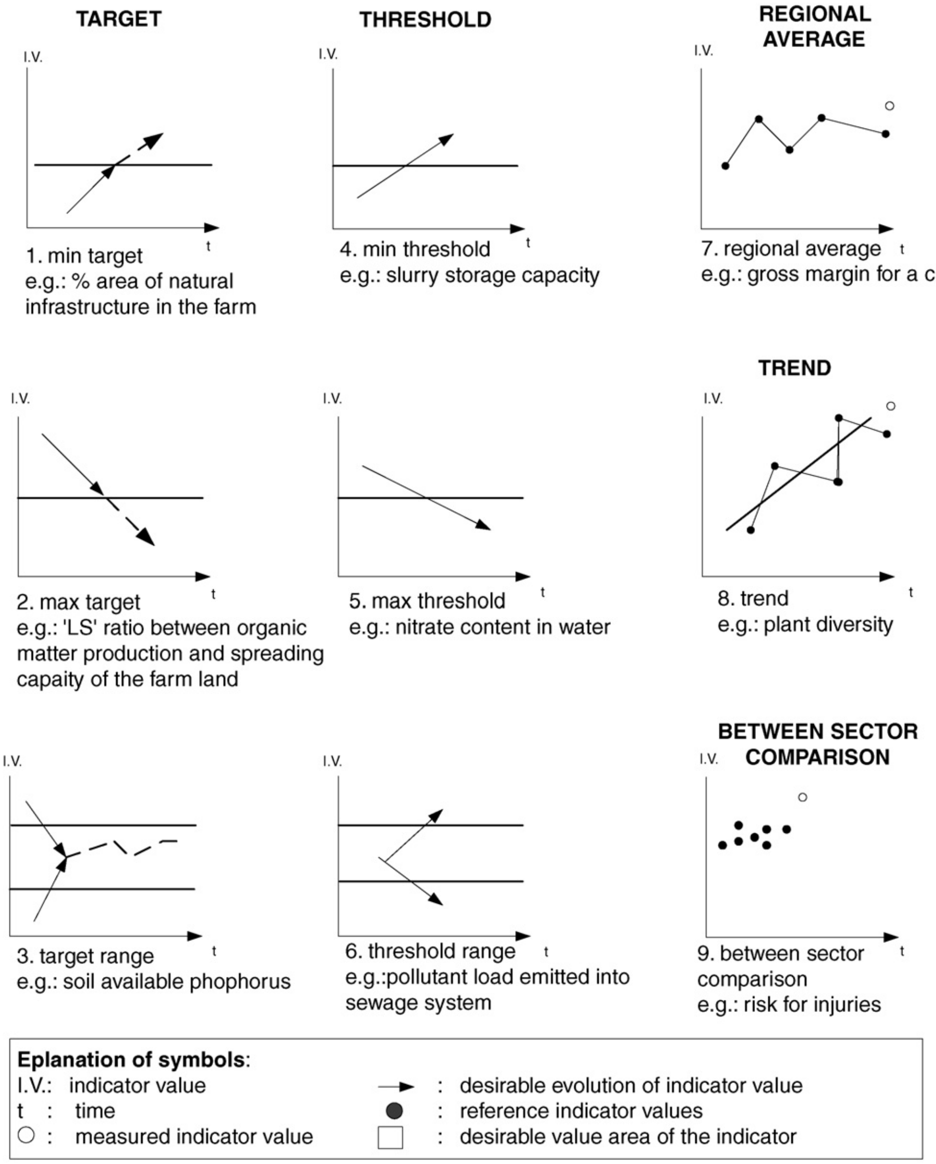

Fig. 5. Reference values—target, threshold, regional average and trend.

(1) The supply function to ensure an adequate quantity and quality of the various resources for use by living organisms.
(2) The buffer function to ensure that environmental fluxes (e.g. radiation, water, wind) are sufficiently tempered so as to minimize damaging effects to the agro-ecosystem.

The supply function can be expressed equally as a stock or as a flow. Indeed, whenever a balance can be established for a given component (e.g. mass balance, energy balance, etc.) both stocks and flows can be identified. In addition, all resources can be evaluated in terms of their quantity or quality (Table 2). Resources can be described as a stock when the emphasis is on conservation and, in some cases, enhancement of the existing quantity (and associated quality) of the resource. They can also be described as a flow when the emphasis is on regulating flows, such that at any time a sufficient amount of resource (of satisfactory quality) is available to ensure proper functioning of the ecosystem. For instance, "soil mass is maintained" and "soil loss is minimized" refer to the stock function and flow function, respectively, yet they are equivalent statements, the end result being the same in both cases (conservation of soil mass). Except for habitat that exists only as a stock, the choice between the two ways of expressing ecosystem functions is therefore largely arbitrary. In SAFE, the choice between one or the other way of expressing the functions was made on the basis of the relative importance of the stocks versus the flows.

The buffer function relates to the ecosystem's control over the fluxes of natural resources with the purpose of avoiding undesirable effects in or outside the system. Here, the regulation seeks to maintain fluxes of a given component

Table 1
List of principles and criteria derived from the functions of the agro-ecosystem

Principles	Criteria
Environmental pillar	
Air	
Supply (flow) of quality air function	Air quality is maintained or enhanced
Air flow buffering function	Wind speed is adequately buffered
Soil	
Supply (stock) of soil function	Soil loss is minimized
Supply (stock) of quality soil function	Soil chemical quality is maintained or increased
	Soil physical quality is maintained or increased
Soil flow buffering function	Soil mass flux (mudflows, landslides) are adequately buffered
Water	
Supply (flow) of water function	Adequate amount of surface water is supplied
	Adequate amount of soil moisture is supplied
	Adequate amount of groundwater is supplied
Supply (flow) of quality water function	Surface water of adequate quality is supplied
	Soil water of adequate quality is supplied
	Groundwater of adequate quality is supplied
Water flow buffering function	Flooding and runoff regulation of the agro-ecosystem is maintained or enhanced
Energy	
Supply (flow) of exergy function	Adequate amount of exergy is supplied
Energy flow buffering function	Energy flow is adequately buffered
Biodiversity	
Supply (stock) of biotic resources function	Planned biodiversity is maintained or increased
	Functional part of spontaneous biodiversity is maintained or increased
	Heritage part of spontaneous biodiversity is maintained or increased
Supply (stock) of habitat function	Diversity of habitats is maintained or increased
Supply (stock) of quality habitat function	Functional quality of habitats is maintained or increased
Biotic resource flow buffering function	Flow of biotic resources is adequately buffered
Economic pillar	
Viability	
Economic function	Farm income is ensured
	Dependency on direct and indirect subsidies is minimized
	Dependency on external finance is optimal
	Agricultural activities are economically efficient
	Agricultural activities are technically efficient
	Market activities are optimal
	Farmer's professional training is optimal
	Inter-generational continuation of farming activity is ensured
	Land tenure arrangements are optimal
	Adaptability of the farm is sufficient
Social pillar	
Food security and safety	
Production function	Production capacity is compatible with society's demand for food
	Quality of food and raw materials is increased
	Diversity of food and raw materials is increased
	Adequate amount of agricultural land is maintained
Quality of life	
Physical well-being of the farming community function	Labour conditions are optimal
	Health of the farming community is acceptable
Psychological well-being of the farming community function	Education of farmers and farm workers is optimal
	Internal family situation, including equality in the man–woman relation is acceptable
	Family access to and use of social infrastructures and services is acceptable
	Family access to and participation in local activities is acceptable
	Family integration in the local and agricultural society is acceptable

Table 1 (*Continued*)

Principles	Criteria
	Farmer's feeling of independence is satisfactory
Social acceptability	
Well-being of the society function	Amenities are maintained or increased
	Pollution levels are reduced
	Production methods are acceptable
	Quality and taste of food is increased
	Equity is maintained or increased
	Stakeholder involvement is maintained or increased
Cultural acceptability	
Information function	Educational and scientific value features are maintained or increased
	Cultural, spiritual and aesthetic heritage value features are maintained or increased

All principles of the agro-ecosystem shall be maintained or enhanced.

(be it of stocks or flows) within a certain range of values outside which damage could occur. For instance, one of the possible functions of the agro-ecosystem is to temporarily retain surface runoff so as to keep river discharge below a certain threshold above which serious flooding problems may occur downstream.

3.1.1. Air

With respect to air, the agro-ecosystem serves two main functions: to regulate air flow velocity (wind) so as to minimize damaging effects, and to ensure an adequate supply of quality air, the quantity of air present not being influenced by the agro-ecosystem. Plants have a major impact on air quality through oxygen production and CO_2 absorption. In addition, the air quality-related criteria considered in the framework include all significant gaseous emissions from the agricultural sector. We distinguish four main categories of gaseous production: (1) greenhouse gases, e.g. N_2O, CH_4 and CO_2, (2) emissions provoking acidifying or euthrophicating depositions, e.g. NH_3, (3) emissions of eco-toxic pollutants, e.g. biocides and (4) emissions of particulate matter, e.g. dust production during tillage operations or wind erosion and particulate matter emissions from engines. The risks related to concentrations of ammonia in livestock buildings are considered in the social pillar under the criterion for acceptable production methods.

Table 2
Principal functions of the agro-ecosystem's natural resources

	Supply function				Buffer function
	Stocks		Flows		
	Quantity	Quality[a]	Quantity	Quality[a]	
Air					
Atmosphere	/	/	No	Yes	Yes
Soil air	/	/	Yes	Yes	na[b]
Water					
Surface water	/	/	Yes	Yes	Yes
Soil water	/	/	Yes	Yes	na[b]
Groundwater	/	/	Yes	Yes	na[b]
Soil (solid)	Yes	Yes	/	/	Yes
Energy	/	/	Yes	na	Yes
Biodiversity/biotic					
Planned	Yes	na	/	/	Yes
Spontaneous	Yes	na	/	/	Yes
Biodiversity/habitat					
Planned	Yes	Yes	na	na	na
Spontaneous	Yes	Yes	na	na	na

Symbol (/) denotes stock (or flow) function relatively not important; na: not applicable.

[a] Physical and chemical quality only; biological quality is taken into account under biotic diversity.

[b] Because flow rates never reach damaging levels.

3.1.2. Soil

The soil component in the framework refers to the solid phase of the soil, the air and water components being considered as part of air and water resources.

The agro-ecosystem has three functions with respect to soil: to supply quantity and quality of soil material and to buffer soil mass fluxes. The first function is translated into one criterion, the minimization of soil loss by water, wind, tillage and harvest erosion and by mass movements, in order to conserve the soil resource. The second soil criterion relates to soil physical (e.g. bulk density or water holding capacity) and chemical quality (e.g. pH, adsorbed pollutants or nutrient content), respectively, soil biological quality being included under biotic biodiversity. The last function refers to the minimization of damage due to soil mass movement (e.g. from landslides and mudflows). As opposed to mudflows which are a form of mass movement, muddy floods, being dilute suspensions, are under the water buffering function. The habitat function of soil is considered under biodiversity/habitat.

3.1.3. Water

Three principles describe the functions of an agro-ecosystem related to water. First, surface water, soil water and groundwater have to be present in an adequate amount and second, be of satisfying quality. Third, the surface flow of water (run-off or even flooding) in the agro-ecosystem has to be buffered. An adequate amount of water implies that: (i) intra-annual variations of surface water have to be reasonable; (ii) the quantity of soil moisture has to permit a continuous occupation of the soil; and (iii) the use of groundwater should not exceed the recharge rate. The physical and chemical properties that have to be considered for water quality include: (i) load of agro-chemicals, (ii) load of nitrates for surface and groundwater, (iii) load of phosphates for surface water, (iv) sediment load and (v) load of pathogen micro-organisms in water. Other living organisms living in water are considered under biotic biodiversity. The habitat function of water is considered under biodiversity/habitat.

3.1.4. Energy

For the sake of simplicity, we use in this context the term energy instead of exergy, although the latter, referring to useful energy able to do work, would be more appropriate (Dewulf et al., 2000; Cornelissen and Hirs, 2002). Energy can be both renewable and non-renewable. Contrary to a complete Life Cycle Impact Assessment, including the impact categories abiotic resources (mainly non-renewable resources), biotic resources (mainly renewable resources) and land use (Lindeijer et al., 2002), the SAFE framework is only concerned with the land use impact, caused by agricultural practices. The impact category "biotic resources" (sensu Lindeijer et al., 2002) is not relevant in the context of man-made agricultural systems since "extraction" of wild populations does not take place (cf. wild populations of fish are caught in fisheries and need to replenish naturally to sustain their populations, but harvested crops can hardly be looked at as being part of wild populations). As to the impact category "abiotic resources" (fossil fuels, phosphate and metal extraction for fertilizer manufacturing, ...), this category is not applicable here either, because of the definition of the SAFE system boundaries restricting the sustainability evaluation to inside the farm borders, except for the energy balance as explained above.

The agro-ecosystem serves two main functions with respect to energy: to provide sufficient energy for the agro-ecosystem to perform its other functions, and to buffer energy flow. Farming systems can produce direct energy, for example, with bio-energy crops, by bio-methanization of crop residues, or by allocating agricultural land to other energy producing facilities such as wind mills. Indirect energy is produced through biomass and food production in general. The direct energy consumption component comprises the use of fossil fuel and electricity for field and farm operations, animal breeding and drying of the harvest. Indirect energy consumption includes the energy consumption for the production of inputs (mainly nitrogen fertilizers), in as far as the decision to use these inputs is taken at the farm level.

3.1.5. Biodiversity

The concept of biodiversity in agriculture can be defined at three main levels: the genetic diversity within individual species, the number of species within a community and the diversity of communities in the local environment. For each of these three levels, planned and spontaneous biodiversity can be identified.

Planned or agricultural biodiversity (Vandermeer et al., 1998; Maljean and Peeters, 2001) at the gene level measures the diversity of plant varieties and animal breeds, or even strains of micro-organisms, which are deliberately used by the farmer. At species level, it considers the diversity of cultivated plants or livestock species. At community level, it characterizes the diversity induced by the different land cover types, plot sizes, the presence of planted hedgerows, distinct field margins, orchards, etc.

Spontaneous biodiversity consists of gene, wild species and community diversity that appear spontaneously within production systems. It can be called associated biodiversity (Vandermeer et al., 1998). Some of these species play a decisive role for the farming system functioning, forming what is known as functional or para-agricultural biodiversity (Altieri, 1999; Maljean and Peeters, 2001). They particularly include species that have a positive effect on production, such as photosynthetic organisms that produce fodder, micro-organisms that play a role in decomposition or nitrogen fixation, parasites and predators of crop enemies, pollinators and earthworms. Other functional species, such as weeds, diseases and pests, have a negative effect on agricultural production. At community level, functional biodiversity is mainly provided by the presence of spontaneous hedgerows, field margins and woodland strips. Other spontaneous taxa and communities, linked to varying degrees with the farming system, but with a less clear role in its general functioning, are defined as extra-agricultural biodiversity (Maljean and Peeters, 2001). Many species in this category have a major heritage value. Species include higher plants (e.g. orchids), insects (e.g. butterflies, dragonflies), birds, mammals and others. At the community level, this type of diversity includes wild flower communities, communities of copses, ponds and wetlands.

The biodiversity buffering function can be understood as avoiding the extinction of native species and regulating the migration of invasive species.

For the definition of the principles, a distinction is made between biotic (or genetic) resources on the one hand and habitats on the other hand. The latter serve as carriers for adequate development of this genetic patrimony. Analogue to the biotic resources, the quantity as well as the quality of habitats is considered. Habitats include the atmospheric (air), aquatic (water) and terrestrial (soil, land) part of the environment on which organisms depend, directly or indirectly, in order to carry out their life processes such as copses, ponds and wetlands. Habitats also include corridors, whose main function is to sustain the flow of biotic resources. When it comes to quantity, the diversity, the number and the total area of habitats are important as well. The functional quality of habitats refers to the area of core habitat and the degree of connectivity between habitats.

3.2. Economic pillar

The economic function of the agro-ecosystem is to provide prosperity to the farming community and thus refers to the economic viability of the agro-ecosystem. It must be noted that economic viability is often a precondition for several aspects of the social pillar as well (e.g. access to social activities depends on income level).

Basic farm economic activities cover three types of activities: (i) maintenance, production and product processing activities, (ii) marketing activities and (iii) financial activities. The combination of these activities results in the generation (or reduction) of income and financial capital.

Technical (or production) efficiency is achieved when the output is produced at minimum cost. This minimizes the inappropriate use (and thus waste) of inputs, such as fertilizer, pesticides, animal feed, energy, water, mechanical work, buildings, labour, land and information.

Market activities should be efficient. Allocative efficiency, which is the efficient allocation of resources, or price efficiency is reached when marginal returns equal marginal costs for all inputs and outputs. However, as mostly price takership is assumed, this criterion could be broadened with the condition that prices should be ‘‘fair’’ or ‘‘equitable’’. Sales can be realized in the spot market, on contract, through a marketing cooperative or directly to the final consumer, but the condition of the sale often depends on the relative bargaining power of the farmer, which is often to his disadvantage. The same holds for inputs, and particularly for land.

Financial activities should be efficient, that is, the dependency on external finance through credit or subsidies should be optimal, resulting in an optimal debt/equity ratio (solvency) and optimal investment. Subsidies may create a strong dependency, thus inhibiting innovation. Subsidies may be direct (direct income support, second pillar payments, etc.) and indirect (tax and VAT exemptions, indemnities for climatic and pandemic catastrophes, price support, etc.).

When technical, allocative and financial efficiency are all met at the same time, the farm is said to be economically efficient. The sum of the return on labour, the return on own capital and the net farm result equals to family income.

Two aspects which cannot be captured by production, market or financial activities are added to the framework. First, the farmer supplies and invests in human capital which is used to manage the farm. To be economically efficient, the farmer's professional training should be optimal. Second, the activities of the farm are influenced by whether or not the inter-generational transfer of the farm is ensured, e.g. through a higher incentive to invest. Furthermore the land tenure of the farm should be optimal in order for the farm to be sustainable and the farm should be adaptable to external changes through, for example, diversification of production.

3.3. Social pillar

The agro-ecosystem has several social functions, both at the level of the farming community and at the level of society. The definition of these functions is based on present-day societal values and concerns.

With respect to the former, farming activities should be carried out with respect of the quality of life of the farmer and his family. The agro-ecosystem needs to be organized in such a way that social conditions are optimal for the people who work there (that is, who perform an economic function). This refers both to the physical well-being (labour conditions and health) and the psychological well-being (education, gender equality, access to infrastructure and activities, integration and participation in society both professionally and socially, feeling of independence) of the farm family and its workers.

Society's demands with respect to farming activities are realized at three levels. Arranged from basic necessities to luxury goods these include: food security and safety, socially acceptable farming practices and cultural goods. First, the most basic function of the agro-ecosystem is to provide safe, sufficient and diverse food. Society acceptance depends on the externalities (both positive and negative) produced by the agro-ecosystem. Positive externalities include amenities (landscape, hedges and attractive farm buildings namely) and quality taste of food. Negative externalities include pollution (including odour and visual pollution), unacceptable production practices (e.g. animal welfare) and an unequal distribution of wealth. Finally, the agro-ecosystems may produce cultural goods pertaining to its information function: specific features may be of educational, scientific, cultural, spiritual and aesthetic value.

4. Discussion

Many indicator sets and frameworks for sustainable agriculture have already been presented in literature (e.g. Adriaanse, 1993; OECD, 1993; Hammond et al., 1995; Wascher, 2000). As stated in an overview by Lenz et al. (2000) these indicator sets have been generally developed based on the widely accepted ‘‘driving force–state–response’’ (DSR) framework and its variants as used by prominent organizations such as OECD (1997, 1999, 2001), UNEP (Hardi and Zdan, 1997), CSD (Mortensen, 1997) and EU-EEA (EEA, 1999).

Unfortunately, most of these classical content-based frameworks suffer from a series of drawbacks. Frequently encountered weaknesses of existing frameworks are partial coverage of sustainability issues, partial capture of the key factors and key processes, and partial reflection of the complex chain of causes and effects. In the DSR-related frameworks in particular, concepts such as ‘‘driving force’’ or ‘‘response’’ provide no structure to guarantee full

Table 3
Comparison of sustainability frameworks

	Framework				
	Framework for Evaluating Sustainable Land Management (FESLM)	Driving force–state–response (DSR)	Framework for Assessing Natural Resource Management Systems (MESMIS)	Bossel (2001)	Sustainability assessment of Farming and Environment (SAFE)
Stakeholders/target groups	Public, farmers, other land users	Decision makers and the wider public	Farmers, development workers, researchers, decision makers	Undefined	Farmers, decision makers, researchers
Hierarchical structure	Objective → means → evaluation factors → diagnostic criteria → indicators and thresholds	No	Attributes → critical points → diagnostic criteria → indicators	Definition of (sub-) system → expression of indicators following orientors	Principles → criteria → indicators → reference values
Topical organization	Five pillars: productivity, security, protection, viability, acceptability	Thirteen agri-environmental issues: contextual information, farm financial resources, farm management, nutrient use, pesticide use and risks, water use, water quality, soil quality, land conservation, greenhouse gases, biodiversity, wildlife habitats, landscape	Seven general attributes of natural resource management systems: productivity, stability, resilience, adaptability, equity, self-reliance (self-empowerment)	Coexisting subsystems and seven basic orientors: existence, effectiveness, freedom of action, security, adaptability, coexistence and psychological needs (human component)	Three pillars: environmental, social, economic. Ten topics: (environmental) air, soil, water, energy, biodiversity; (economic): viability; (social): food security and safety, quality of life, social acceptability, cultural acceptability
Indicator types following D(P)S(I)R	No	DSR	No	No	D(P)S(I)R (pressure and impact for environmental only)
Time scale	Evaluation over a stated period of time	Not specified	Case specific, no general time scale	Undefined	Case specific
Spatial scale	(Field to) large areas	National	From farm plot to local villages	Undefined	Field, farm, landscape, region
Use of reference system for defining thresholds	No: thresholds are defined by estimating future trends	No	Yes: cross-sectional or longitudinal comparison of systems	Undefined	Yes: absolute and relative reference systems

coverage of sustainability issues besides the generally accepted subdivision of sustainability into its three social, economic and environmental dimensions. Within each pillar, the selection of appropriate indicators therefore follows a more or less arbitrary choice due to a lack of a solid, holistic organizational basis. System-based frameworks provide a more solid organizational basis for selecting indicators, yet the complex system attributes that are at the heart of such systems are difficult to express in quantitative terms. Content-based approaches, by taking a component rather than a systemic approach, facilitate the quantitative assessment of sustainability. When combined with the PC&I, such content-based approaches offer a structured, hierarchical means of identifying indicators. However, the quality of the framework's structure depends largely on the proper definition of system functions at the level of ‘‘principles’’. If no further hierarchical levels are introduced, there is still a wide scope for introducing bias or partial coverage in the criteria and indicator selection procedure. In SAFE, besides the PC&I, three additional hierarchical levels have been introduced. The first level, which is commonly introduced, pertains to the three sustainability pillars. The second level is introduced by considering five resources in the environmental pillar and four attributes in the social pillar, the economic pillar requiring only one attribute. The last level applies only to the environmental pillar and stems from considering the quantity and quality of each resource and an adequate buffering of their related fluxes. Through this structured, holistic approach, all key agro-ecosystem functions are captured in SAFE and the selection of criteria and their related indicators is performed in a much more systematic way than has been classically done.

Many existing frameworks have a problem-based character concentrating on the lack of sustainability in a particular area rather than analysing the whole system. Consequently, one acts to solve the specific problem rather than the general one (von Wirén-Lehr, 2001). SAFE addresses this issue by developing a content-based framework, applied to the entire agro-ecosystem. Hence, it combines the advantages of the system-based approaches (holistic approach) with the facility of use of content-based approaches. In addition, among the numerous published initiatives, only a few studies deal with sustainability assessment of agro-ecosystems at the field or farm levels. Most studies work at larger scales, mainly the national or international levels (Smith and Dumanski, 1994; Piveteau, 1998; NRC, 2000; MAFF, 2000; Wascher, 2000; OECD, 2001; Delbaere, 2002; de Angelis, 2002; López-Ridaura et al., 2002). Important links between management by the farmer and impacts and effects on the agro-ecosystem and its sustainability levels that were not addressed in those frameworks are therefore addressed explicitly in SAFE.

Finally, only few existing frameworks for agricultural sustainability evaluation are universally applicable. While universal applicability is not a strict requirement for sustainability frameworks, the elaboration of one or a few generally applicable frameworks is definitely worthwhile. In particular, system-based frameworks (such as NRMS; López-Ridaura et al., 2005; Bossel, 2001) assure universal applicability through their system analysis and flexibility is assured through leaving the content ‘‘undefined’’ at a higher organizational level. Although content-based, SAFE may also be considered universally applicable to agro-ecosystems, at the level of principles, thanks to its holistic approach and, in particular, its link to the de Groot et al. (2002) agro-ecosystem functions. In this context, it should be noted that, whereas the framework should have a general, comprehensive character, selected sustainability indicators could and/or should be site- and scale-specific. Indeed as stated by López-Ridaura et al. (2005) ‘‘one fixed set of indicators for each and every natural resource management system is inappropriate, as every system is unique, and specific criteria and indicators may or may not be relevant for all cases’’. This flexibility is introduced through a participative indicator selection procedure at the indicator level (Sauvenier et al., 2006). It should also be accepted that frameworks themselves may change over time, when scientific knowledge increases and societal values and concerns evolve.

The SAFE framework presented in this paper offers some solutions to the main drawbacks encountered for sustainability analysis in agricultural systems, maintaining a clearly defined content of its attributes. Table 3 shows the main characteristics of the SAFE framework in comparison to other ecosystem-related multidimensional and multilevel frameworks (FESLM, Smith and Dumanski, 1994; MESMIS, López-Ridaura et al., 2002), the DSR framework developed by the OECD (1997, 1999, 2001) and a general system-based framework developed by Bossel (2001). The Framework for Evaluating Sustainable Land Management (FESLM) was designed by the FAO in 1993 as a structured, logical pathway for decision making with respect to land management. Although it is based on general properties of natural resource systems, its undefined content, and national application scale make it unsuitable for use in the agro-ecological domain. The DSR framework was developed by the OECD to structure the development of environmental indicators for agriculture following three major divisions: driving forces, state and response. This framework has a clear content and linking indicators to the issues seems straightforward, nevertheless it clearly lacks holisticity to perform a sustainability analysis of the agro-ecosystem as a whole. The MESMIS framework allows evaluating sustainability through a six step multi-criteria analysis and is explored as a practical example of system-based sustainability frameworks for natural resource management. This framework is designed for small-scale assessment and can be easily transferred to the agro-ecosystem domain. Nevertheless, the complexity of its basic attributes turns the definition of indicators into a difficult task. This comment also applies to the ‘‘Bossel-framework’’ that presents the generalized system-based approach where development is seen as a coevolutionary process involving interacting systems in a common environment. Indicators have to be found to describe the performance of each individual system and its contribution to the performance of the other system(s) related to seven basic orientors: existence, effectiveness, freedom of action, security, adaptability, coexistence and psychological needs (for humans and for systems with humans as components). Although theoretically sound, the practical application of this framework in the agricultural domain forms a clear challenge.

5. Conclusion

In this paper a holistic, hierarchical methodology, SAFE, is proposed to structure information about the agro-ecosystem in order to assess its sustainability level. SAFE starts from defining sustainability as maintaining or enhancing the environmental, economic and social functions of an agro-ecosystem as formulated in a set of principles and criteria. Environmental principles are derived by considering in a systematic way the quantity, quality and fluxes of all natural resources. Social and economic principles rest on present-day societal values and concerns. This structured, holistic approach ensures both the embracement of all key agro-ecosystem functions and a systematic selection of criteria and their related indicators. SAFE combines the advantages of system-based frameworks by analysing the system as a whole, thereby ensuring its universal applicability to agro-ecosystem sustainability analysis, and of content-based approaches by defining functions or attributes for specific components of the system, thereby facilitating quantification. SAFE operates at three spatial scales: the field, the farm and landscape/administrative unit. Consequently, important links between management by the farmer and impacts and effects on the agro-ecosystem and its sustainability levels are addressed explicitly in SAFE, unlike in previous frameworks. The step-by-step definition of sustainability and the strong theoretical basis of each concept ensure a broadly applicable system that could be used by several actors: farmers, farmer advisers, researchers and decision makers.

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