Measuring Agricultural Sustainability

Dariush Hayati, Zahra Ranjbar, and Ezatollah Karami

Abstract Sustainability in agriculture is a complex concept and there is no common viewpoint among scholars about its dimensions. Nonetheless various parameters for measuring agricultural sustainability have been proposed. This manuscript reviews some aspects of agricultural sustainability measures by referring to measuring difficulties, components of sustainability measurement and their interaction. Criteria to select sustainability indicators are discussed. Agricultural sustainability scales at national level and farm level are reviewed. A large number of indicators have been developed but they do not cover all dimensions and levels. Therefore, indicators used for agricultural sustainability should be location specific. They should be constructed within the context of the contemporary socioeconomic and ecological situation. Some recommendations to select indicators in order to better measure agricultural sustainability are presented.

Keywords Agricultural sustainability • Measuring sustainability • Sustainability indicators • Sustainability components

1 Introduction

For any study on sustainable agriculture, the question arises as to how agricultural sustainability can be measured. Some argue that the concept of sustainability is a "social construct" (David 1989; Webster 1999) and is yet to be made operational (Webster 1997). The precise measurement of sustainability is impossible as it is site-specific and a dynamic concept (Ikerd 1993). To some extent, what is defined

D. Hayati (✉), Z. Ranjbar and E. Karami
Department of Agricultural Extension and Education, College of Agriculture, Shiraz University, Shiraz, Iran
e-mail: hayati@shirazu.ac.ir

E. Lichtfouse (ed.), *Biodiversity, Biofuels, Agroforestry and Conservation Agriculture*, Sustainable Agriculture Reviews 5, DOI 10.1007/978-90-481-9513-8_2,

as sustainable depends on the perspectives of the analysts (Webster 1999). Although 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" (Pretty 1995).

Practices that erode soil, remove the habitats of insect predators, and cut instead of plant trees can be considered unsustainable compared to those that conserve these resources. According to Altieri (1995), farmers can improve the biological stability and resilience of the system by choosing more suitable crops, rotating them, growing a mixture of crops, and irrigating, mulching and manuring land. According to Lynam and Herdt (1989), sustainability can be measured by examining the changes in yields and total factor productivity. Beus and Dunlop (1994) considered agricultural practices such as the use of pesticides and inorganic fertilizers, and maintenance of diversity as measures of sustainability. For sustainable agriculture, a major requirement is sustainable management of land and water resources.

Reviewing the aspects of agricultural sustainability measures, by referring to measuring difficulties, components of sustainability measurement and criteria for indicators selection were the main objectives of this manuscript. It should be declared that the article has inevitably had to take a bias toward cropping because of the huge amount of literature on sustainability indicators in various disciplines.

2 General Issues

Considerable efforts have been made to identify appropriate indicators for agricultural sustainability. In the realm of practice, the most influential model of environmental reporting is the causality chain of Pressure-State-Response (PSR). Although its conceptual development can be traced back to the 1950s, the PSR model was pioneered by the Organisation for Economic Cooperation and Development (OECD) (OECD 1991). The PSR model and variants have been extensively used to organise a menu of indicators. Examples of applications include the State-of-Environment (SOE) reporting (Australia, Canada and New Zealand) and the set of sustainability indicators proposed by the United Nations Commission on Sustainable Development (CSD). The latter has been tested in selected developed and developing countries. This sets a new precedent of cross-nation sustainability indicator comparability which has been followed recently by other international initiatives such as the Environmental Sustainability Index and OECD Environmental Performance Review. In effect, indicators become a policy instrument to exert peer pressure among nations to perform better.

Recently, OECD has developed a common framework called "driving force state response" (DSR) to help in developing indicators. Driving force indicators refer to the factors that cause changes in farm management practices and inputs use. State indicators show the effect of agriculture on the environment such as soil, water, air, biodiversity, habitat and landscape. Response indicators refer to the actions that are taken in response to the changing state of environment. Using the DSR framework, OECD (1997) identified 39 indicators of issues such as farm financial resources, farm management, nutrient use, pesticide use, water use, soil quality, water quality, land conservation, greenhouse gases, biodiversity, landscape, wildlife habitats, and farm's contextual information, including socioeconomic background, land-use, and output. Similarly, the British Government suggested 34 indicators under 13 themes such as nutrient losses to fresh water, soil P levels, nutrient management practices, ammonia emissions, greenhouse gas emissions, pesticide use, water use, soil protection, and agricultural land resource, conservation value of agricultural land, environmental management systems, rural economy and energy (MAFF cited in Webster 1999).

Most of the indicators mentioned above are suitable to evaluate agricultural sustainability at aggregate level. They cannot, however, be used to assess sustainability at the farm level, although individual farmers take the major decision in land-use including mode of use and choice of technology (Webster 1999). Sands and Podmore (2000) used environmentally sustainability index (ESI) as an indicator of assessing agricultural sustainability and applied it to farms in the United States. ESI represents a group of 15 sustainability sub-indices including soil depth, soil organic carbon, bulk density and depth of ground water. Tellarini and Caporali (2000) used the monetary value and energy value to compare the sustainability of two farms, high-inputs and low-inputs in Italy. Gowda and Jayaramaiah (1998) used nine indicators, namely integrated nutrient management, land productivity, integrated water management, integrated pest management, input self-sufficiency, crop yield security, input productivity, information self-reliance and family food sufficiency, to evaluate the sustainability of rice production in India. Reijntjes et al. (1992) identified a set of criteria under ecological, economic and social aspects of agricultural sustainability. Ecological criteria comprise the use of nutrients and organic materials, water, energy, and environmental effects, while economic criteria include farmers' livelihood systems, competition, factor productivity, and relative value of external inputs. Food security, building indigenous knowledge, and contribution to employment generation are social criteria (Rasul and Thapa 2003). Various parameters for measuring agricultural sustainability have been proposed by scholars. Their emphasis and tendency has been classified in three groups of components (social, economic, and ecological) as part of a review of literature and the result has been presented in Table 1.

Theoretical discussions are attending the challenges of disciplinary and methodological heterogeneity. The quest to define sustainability through biophysical assessment has brought distributional issues to the fore, initiating preliminary interaction with the social sciences and humanities (see Hezri 2005; Miller 2005). Another important theoretical output is the availability of various methodologies in aggregating raw and incongruent sustainability variables through indices development.

The existing indicator systems in the realm of policy are becoming instrumental in mainstreaming sustainable development as a policy goal. Following persistent applications across time at various levels of government, the PSR model has pooled

Table 1 Classification of scholars' emphasis and their tendency toward three components of agricultural sustainability according to a review of literatures

Sources	Component	Parameters
Herzog and Gotsch (1998); Van Cauwenbergh et al. (2007)	**social**	• The education level of the household members
Herzog and Gotsch (1998)		• Housing facilities
Herzog and Gotsch (1998)		• Work study
Herzog and Gotsch (1998); Rasul and Thapa (2003); Van Cauwenbergh et al. (2007)		• Nutritional/health status of the family members
Ingels et al. (1997); Pannell and Glenn (2000); Horrigan et al. (2002); Rasul and Thapa (2003)		• Improved decision making
Karami (1995); Ingels et al. (1997); Rezaei-Moghaddam (1997); Norman et al. (1997); Lyson (1998); Van Cauwenbergh et al. (2007)		• Improved the quality of rural life
Ingels et al. (1997); Van Cauwenbergh et al. (2007)		• Working and living conditions
Becker (1997); Ingels et al. (1997); Van Cauwenbergh et al. (2007)		• Participation/social capital
Becker (1997); Rigby et al. (2001); Rasul and Thapa (2003); Rasul and Thapa (2004)		• Social equity
Hayati (1995); Nambiar et al. (2001); Rasul and Thapa (2003)	**Economic**	• Average of crop production
Becker (1997); Herzog and Gotsch (1998)		• Expenses for input
Herzog and Gotsch (1998); Van Cauwenbergh et al. (2007)		• Monetary income from outside the farm
Herzog and Gotsch (1998); Pannell and Glenn (2000); Nijkamp and Vreeker (2000); Van Cauwenbergh et al. (2007)		• Monetary income from the farm
Becker (1997); Herzog and Gotsch (1998); Nijkamp and Vreeker (2000); Van Cauwenbergh et al. (2007)		• Economic efficiency
Karami (1995); Herzog and Gotsch (1998); Lyson (1998); Smith and McDonald (1998); Comer et al. (1999); Pannell and Glenn (2000); Rigby et al. (2001); Koeijer et al. (2002); Rasul and Thapa (2003); Van Passel et al. (2006); Gafsi et al. (2006)		• Profitability
Herzog and Gotsch (1998)		• The salaries paid to farm workers
Herzog and Gotsch (1998); Rasul and Thapa (2003)		• Employment opportunities
Smith and McDonald (1998); Van Cauwenbergh et al. (2007)		• Market availability
Karami (1995); Nijkamp and Vreeker (2000); Van Cauwenbergh et al. (2007)		• Land ownership
Hayati (1995); Becker (1997); Ingels et al. (1997); Bouma and Droogers (1998); Pannell and Glenn (2000); Sands and Podmore (2000); Bosshard (2000); Nambiar et al. (2001); Horrigan et al. (2002); Rasul and Thapa (2003); Van Cauwenbergh et al. (2007)		• Soil management

(continued)

Table 1 (continued)

Sources	Component	Parameters
Hayati (1995); Ingels et al. (1997); Gafsi et al. (2006); Van Cauwenbergh et al. (2007)	**Ecological**	• Improve water resource management
Hayati (1995); Rezaei-Moghaddam (1997); Ingels et al. (1997); Norman et al. (1997); Pannell and Glenn (2000); Rasul and Thapa (2004)		• Usage of pesticides, herbicides and fungicides
Saltiel et al. (1994); Hayati (1995); Norman et al. (1997); Bosshard (2000)		• Usage of animal/organic manures
Senanayake (1991); Saltiel et al. (1994); Hayati (1995)		• Usage of green manures
Ingels et al. (1997); Herzog and Gotsch (1998)		• Physical inputs and efficient use of input
Herzog and Gotsch (1998); Rasul and Thapa (2003)		• Physical yield
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)		• Crop diversification
Saltiel et al. (1994); Rasul and Thapa (2003)		• Use of alternative crop
Saltiel et al. (1994)	**Ecological**	• Usage of fallow system
Saltiel et al. (1994); Hayati (1995); Comer et al. (1999); Horrigan et al. (2002); Rasul and Thapa (2003)		• Crop rotation
Nijkamp and Vreeker (2000); Rasul and Thapa (2003); Rasul and Thapa (2004)		• Cropping pattern
Smith and McDonald (1998); Van Cauwenbergh et al. (2007)		• Trend of change in climatic conditions
Hayati (1995); Rezaei-Moghaddam (1997);Ingels et al. (1997)		• Usage of chemical fertilizer
Hayati (1995); Ingels et al. (1997); Comer et al. (1999); Horrigan et al. (2002);		• Conservational tillage (no/minimum tillage)
Hayati (1995); Ingels et al. (1997); Rasul and Thapa (2003); Gafsi et al. (2006); Van Cauwenbergh et al. (2007)		• Control erosion
Senanayake (1991); Pannell and Glenn (2000)		• Microbial biomass with in the soil
Senanayake (1991);); Ingels et al. (1997); Norman et al. (1997); Nambiar et al. (2001); Van Cauwenbergh et al. (2007)		• Energy
Ingels et al. (1997); Norman et al. (1997); Comer et al. (1999); Horrigan et al. (2002); Rasul and Thapa (2003)		• Cover crop/Mulch
Pannell and Glenn (2000); Sands and Podmore (2000); Van Cauwenbergh et al. (2007)		• Depth of groundwater table
Pannell and Glenn (2000)		• Protein level of crops
Comer et al. (1999); Praneetvatakul et al. (2001); Horrigan et al. (2002); Rasul and Thapa (2003)		• Integrated pest management

an enormous amount of data previously inaccessible, a prelude for the much needed long-term trend monitoring that is important for governments to prioritize actions. The recent global interest in ecological monitoring not only contributes in improving information accessibility, but in generating more data for environmental policy-making (Hezri and Dovers 2006).

3 Measuring Difficulties

The multifaceted nature of sustainable agriculture, with three interdependent and interactive components (ecological, social, and economic) causes difficulty in monitoring. Therefore, a number of indicators are currently emerging the measurement of the different components. Norman et al. (1997) noted, at least three major challenges remain:

- The measures currently available generally fall short in terms of assessing the interactions and interdependencies among the three components and the trade-offs of pursuing one component at the expense of another.
- Many of the measures or indicators currently available are not particularly useful to farmers or are too time-consuming to measure in their day-to-day work, making it difficult for them and their families to monitor progress in terms of agricultural sustainability. This is particularly regrettable because many of the issues relating to sustainable agriculture are location or situation specific.
- Most indicators show progress or no progress towards specific components of sustainability, but they fall short in terms of helping to determine cause/effect relationships to help assess current problems and provide ideas on what needs to be done to ensure continued progress towards sustainability. An additional complication is that some strategies relating to sustainable agriculture require 5–10 years (e.g., a full crop rotation) of implementation before they result in visible or measurable signs of payoff.

Although a large number of indicators have been developed, they do not cover all dimensions and those levels noted in Table 2. Due to variation in biophysical and socioeconomic conditions, indicators used in one country are not necessarily applicable to other countries (Rasul and Thapa 2003). Therefore, indicators should be location specific, constructed within the context of contemporary socioeconomic situation (Dumanski and Pieri 1996).

Moreover, sustainable agriculture is a dynamic rather than static concept. What may contribute towards sustainability today may not work as the system changes, thus requiring a high level of observation and skills that can adapt to change. Consequently, sustainability is a direction/process and does not by itself result in a final fixed product, making it even more difficult to monitor and/or measure (Norman et al. 1997).

Table 2 Basic dimensions and conforming levels to assess agricultural sustainability

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

von Wirén-Lehr 2001

4 Components of Sustainability Measurement

System theory has proven valid for sustainability assessment. First, it contributes to clarifying the conditions of sustainability. By definition, system theory forces one to define the boundaries of the system under consideration and the hierarchy of aggregation levels. In agricultural land use systems the most relevant subsystems (or levels) are the cropping system (plot level); farming system (farm level); watershed/village (local level); and landscape/district (regional level). Higher levels (national, supranational, and global) influence agriculture more indirectly by policy decisions or large-scale environmental changes (e.g., acid rain or global warming).

By identifying the system hierarchy, externalities between levels and tradeoffs among components can be traced and explicitly taken into consideration. For example, in an agro-ecological system analyzed at the farm level, the effects of national policies are externalities as long as they are outside the decision context of the farmer (Olembo 1994). Typical tradeoff among components within a farming system includes unproductive fallow lands in a rotation system for the sake of soil recovery for future use. In resource economics the aspect of externalities has gained great importance in that methodologies are being developed to convert such externalities into accountable quantities (Steger 1995), as well as the assignment of "opportunity costs" to tradeoff effects.

Similarly, the "tragedy of the commons" i.e., individual use of common resources can be analyzed adequately only by considering the higher system level to find proper policies for sustainable use e.g., the case of overgrazing in pastoral societies. Such conflicting interests among different groups – or hierarchical levels of the system – is a typical problem in sustainability strategies. Problem analysis is greatly facilitated by system theory to derive alternative scenarios of future development, depending on the policy chosen (Becker 1997).

Thus, agricultural sustainability not only is a difficult concept to define but also is difficult to implement and monitor/measure. This complexity is demonstrated in Table 3 which shows the expected interactions among the three components of sustainability and the five levels of influence. Although sustainability tends to be

Table 3 Interacting components of sustainability[a]

Levels influencing sustainability	Components of sustainability		
	Ecological	Economic	Social/institutional
International	Secondary	Secondary	Secondary
National	Secondary	Secondary	Primary
Community	Secondary	Primary	Primary
Farm	Primary	Primary	Primary
Field	Primary	Secondary	Secondary

[a]The ‘primary’ cells represent where the component of sustainability is mainly expressed, and the ‘secondary’ cells represent other factors that can influence sustainability (Norman et al. 1997)

locational or site specific (at the field, farm, and community levels), as Norman et al. (1997) noted, it is very much influenced by:

1. *What happens at the higher levels?* National policies have a great influence on ecological and economic sustainability at the field/farm levels. Other policies at that level related to social/institutional issues also can have major effects on the viability/welfare of communities and, hence, on quality of life. International markets and influences (particularly in smaller countries) are increasingly affecting what happens at the lower levels. Such influences tend to be relatively greater in countries that are poor (low income) and/or where agricultural production is influenced heavily by the export market. Thus, it is necessary to understand the interaction between these levels, because “each level finds its explanations of mechanism in the levels below, and its significance in the levels above” (Bartholomew 1964; Hall and Day 1977).
2. *Interactions among the sustainability components.* In the focus group discussions with Kansas farmers, some of them indicated that those who were in conventional agriculture were often on an economic treadmill e.g., having to raise enough money to service debts and hence had little time to consider ecological sustainability issues. They also had to make compromises concerning quality of life because of having to work very long hours. In fact, the prevailing attitude among the farmers was that all three components of sustainability (environmental, economic, and social) had to be pursued at the same time, if progress was to be achieved (Norman et al. 1997). A more extreme example of the potentially negative interactions among the components of sustainability occurs in many low income countries, where a close link has been established between poverty and ecological degradation. In parts of West Africa, for example, population pressures and low incomes are forcing farmers to cultivate land that is not suitable for agriculture. They are aware of the problems of doing this, but the short-run economic needs of survival are forcing them to sacrifice long-run ecological sustainability (Ibid). In such a situation, ensuring ecological sustainability without solving the problems of poverty and population pressure on the land is impossible (World Bank 1992).

According to three components of sustainability, Zhen and Routray (2003), proposed operational indicators for measuring agricultural sustainability. These indicators are summarized in Fig. 1:

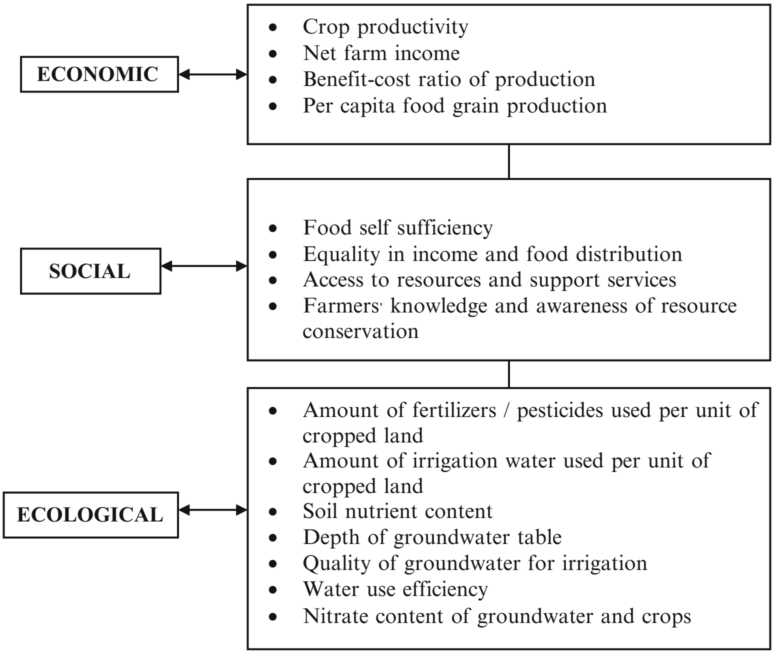

Fig. 1 Proposed agricultural indicators for measuring sustainability (Zhen and Routray 2003)

5 Criteria for Indicators Selection

Considering sustainable agriculture in the global context, preliminary indicators were developed for assessing agricultural sustainability. The preliminary indicators meet the following suitability criteria (Nambiar et al. 2001):

1. Social and policy relevance (economic viability, social structure, etc.)
2. Analytical soundness and measurability
3. Suitable for different scales (e.g. farm, district, country, etc.)
4. Encompass ecosystem processes and relate to process oriented modeling
5. Sensitive to variations in management and climate
6. Accessible to many users (e.g. acceptability)

Table 4, developed by Becker (1997), presents criteria for the selection and evaluation of sustainability indicators. The first demand on sustainability indicators is their scientific validity (BML 1995). Bernstein (1992) demanded that “the ideal trend indicator should be both ecologically realistic and meaningful and managerially useful.” These two key properties should be complemented by the requirement that appropriate indicators be based on the sustainability paradigm (cf. RSU 1994). This last property explicitly introduces the normative element, guiding selection of the indicator according to the value system of the respective author, institution, or society (Becker 1997).

Table 4 Criteria for the selection and evaluation of sustainability indicators (Becker 1997)

Scientific quality	Ecosystem relevance	Data management	Sustainability paradigm
• Indicator really measures what it is supposed to detect • Indicator measures significant aspect • Problem specific • Distinguishes between causes and effects • Can be reproduced and repeated over time • Uncorrelated, independent • Unambiguous	• Changes as the system moves away from equilibrium • Distinguishes agro-ecosystems moving toward sustainability • Identifies key factors leading to sustainability • Warning of irreversible degradation processes • Proactive in forecasting future trends • Covers full cycle of the system through time • Corresponds to aggregation level • Highlights links to other system levels • Permits tradeoff detection and assessment between system components and levels • Can be related to other indicators	• Easy to measure • Easy to document • Easy to interpret • Cost effective • Data available • Comparable across locus and over time quantifiable • Representative • Transparent • Geographically relevant • Relevant to users • User friendly • Widely accepted	• What is to be sustained? • Resource and efficiency • Carrying capacity • Health protection • Target values • Time horizon • Social welfare • Equity • Participatory definition • Adequate rating of single aspects

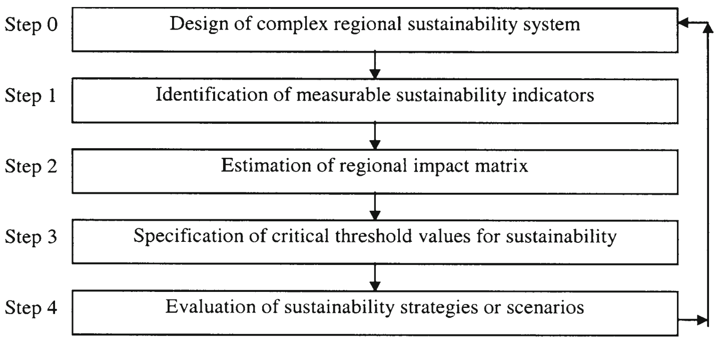

Fig. 2 Steps in a sustainability assessment procedure (Nijkamp and Vreeker 2000)

In the regional sustainability assessment Nijkamp and Vreeker (2000) presented the following steps (Fig. 2). Clearly, various feedback mechanisms and/or iterative steps may also be envisaged and included in this stepwise approach. It goes without saying that the above simplified and schematic general framework for a regional sustainability assessment study is fraught with various difficulties of both a theoretical/methodological and empirical/policy nature (Bithas et al. 1997).

6 Indicators of Agricultural Sustainability

Two basic approaches to sustainability assessment have been developed: First, the exact measurement of single factors and their combination into meaningful parameters. Second, indicators as an expression of complex situations, where an indicator is “a variable that compresses information concerning a relatively complex process, trend or state into a more readily understandable form” (Harrington et al. 1993).

The term sustainability indicator will be used here as a generic expression for quantitative or qualitative sustainability variables. According to WCED (1987) and Conway’s (1983) definitions, which focuses on productivity trends, both quantitative and qualitative variables concentrate on the dynamic aspect of sustainability over time. Indicators to capture this aspect belong to the group of trend indicators, while state indicators reflect the condition of the respective ecosystem (Bernstein 1992). In developing environmental indicators for national and international policies it has become common practice to distinguish pressure, state, and response indicators (OECD 1991; Adriaanse 1993; Hammond et al. 1995; Pieri et al. 1995; Winograd 1995). An overview on current sustainability indicators is presented in Table 5.

Extensive set of indicators including biophysical, chemical, economic and social can be used to determine sustainability in a broader sense (Nambiar et al. 2001). These indicators are:

Table 5 Indicators and parameters for sustainability assessment (Becker 1997)

Economic indicators	Environment indicators
• Modified gross national product	• Yield trends
• Discount rates	• Coefficients for limited resources
– Depletion costs	– Depletion rates
– Pollution costs	– Pollution rates
• Total factor productivity	• Material and energy flows and balances
• Total social factor productivity	• Soil health
– Willingness to pay	• Modeling
– Contingent valuation method	– Empirical
• Hedonic price method	– Deterministic-analytical
• Travel cost approach	– Deterministic-numerical
	• Bio-indicators
Social indicators	Composite indicators
• Equity coefficients	• Unranked lists of indicators
• Disposable family income	• Scoring systems
• Social costs	• Integrated system properties
• Quantifiable parameters	
• Participation	
• Tenure rights	

6.1 Crop Yield

Long-term crop yield trends to provide information on the biological productive capacity of agricultural land and the ability of agriculture to sustain resource production capacity and manage production risks.

6.2 Agricultural Nutrient Balance

Excessive fertilizer use can contribute to problems of eutrophication, acidification, climate change and the toxic contamination of soil, water and air. Lack of fertilizer application may cause the degradation of soil fertility. The parameters of agriculture nutrient balance are gross nutrient balance (*B*) and input: output ratio (I/O). Gross nutrient balances of the total quantity of N, P and K, respectively, applied to agricultural land through chemical fertilizers and livestock manure, input in irrigation, rain and biological fixation minus the amount of N, P and K absorbed by agricultural plants, run-off, leaching and volatilization.

6.3 Soil Quality

Soil quality indicators include physical properties, e.g. soil texture, soil depth, bulk density, water holding capacity, water retention characteristics, water content, etc., chemical properties, e.g. total organic C and N, organic matter, pH, electrical conductivity, mineral N, extracted P, available K, etc., and biological properties, e.g. microbial biomass C and N, potentially mineralisable N, soil respiration, biomass C/total organic C ratio, respiration: biomass ratio, etc.

6.4 Agricultural Management Practices

Management and the type of fertilizers and irrigation systems will affect the efficiency of fertilizer, pesticide and water use. Agricultural management indicators here include efficiencies of fertilizer, pesticide, and irrigated water uses.

6.5 Agri-Environmental Quality

These agri-environmental indicators provide information on environmental impacts from the production process. Degrees of soil degradation and water pollution are included. The degree of soil degradation is measured by the effects of water and wind erosion, Stalinization, acidification, toxic contaminants, compaction, water logging and declining levels of soil organic matter. The quality of surface, ground and marine water is measured by concentrations in weight per liter of water of nitrogen, phosphorus, dissolved oxygen, toxic pesticide residues, ammonium and soil sediment.

6.6 Agricultural Biodiversity

Biodiversity of plants and livestock used for agricultural production is important to conserve the agro-ecosystem balance. However, the dependence on a limited number of varieties and breeds for agricultural production may increase their susceptibility to pests and diseases. Biodiversity measurement is reflected by the total number of varieties/breeds used for the production of major crops/livestock, and the number of animals and microorganisms in the production.

6.7 Economic and Social

Aspects and sustainable agriculture sustainability of agroecosystems is reflected not only in environmental factors but also in economic soundness and social considerations. These aspects are included as real net output (real value of agricultural production minus the real cost), and the change in the level of managerial skills of farmers and land managers in income and farming practice.

6.8 Agricultural Net Energy Balance

Agriculture not only uses energy such as sunlight and fossil fuels, but also is a source of energy supply through biomass production.

Principles and criteria derived from the function of the agro-ecosystem have been presented in Table 6. With respect to the “environmental pillar”, its function is 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).

Regarding the “economic pillar”, its function in the agro-ecosystem is to provide prosperity to the farming community. In addition, each agro-ecosystem has several social functions, both at the level of farming community and at the level of society. The definition of these functions is based on present-day societal values and concerns. Farming activities should be carried out with respect of the quality of life of the farmer and his family. The agro-ecosystem needs to

Table 6 List of principles and criteria derived from the functions of the agro-ecosystem

Principles	Criteria
	Environmental pillar
	Air
Air quality is maintained or enhanced.	Supply (flow) of quality air function
Wind speed is adequately buffered.	Air flow buffering function
	Soil
Soil loss is minimized.	Supply (stock) of soil function
Soil chemical quality is maintained or increased.	Supply (stock) of quality soil function
Soil physical quality is maintained or increased.	
Soil mass flux (mudflows, landslides) are adequately buffered.	Soil flow buffering function
	Water
Adequate amount of surface water is supplied.	Supply (flow) of water function
Adequate amount of soil moisture is supplied.	
Adequate amount of groundwater is supplied.	
Surface water of adequate quality is supplied.	Supply (flow) of quality water function
Soil water of adequate quality is supplied.	
Groundwater of adequate quality is supplied.	
Flooding and runoff regulation of the agro-ecosystem is maintained or enhanced.	Water flow buffering function
	Energy
Adequate amount of energy is supplied.	Supply (flow) of energy function
Energy flow is adequately buffered.	Energy flow buffering function
	Biodiversity
Planned biodiversity is maintained or increased.	Supply (stock) of biotic resources function
Functional part of spontaneous biodiversity is maintained or increased.	
Heritage part of spontaneous biodiversity is maintained or increased.	
Diversity of habitats is maintained or increased	Supply (stock) of habitat function
Functional quality of habitats is maintained or increased.	Supply (stock) of quality habitat function
Flow of biotic resources is adequately buffered.	Biotic resource flow buffering function
	Economic pillar
	Viability
Farm income is ensured.	Economic function
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.	

(continued)

Table 6 (continued)

Principles	Criteria
	Environmental pillar
	Social pillar
	Food security and safety
Production capacity is compatible with society's demand for food.	Production function
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
Labour conditions are optimal.	Physical well-being of the farming community function
Health of the farming community is acceptable.	
Labour conditions are optimal.	Psychological well-being of the farming
Health of the farming community is acceptable.	
Internal family situation, including equality in the man–woman.	Community function
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.	
Farmer's feeling of independence is satisfactory.	
	Social acceptability
Amenities are maintained or increased.	Well-being of the society function
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.	
Educational and scientific value features are maintained or increased.	Cultural acceptability Information function
Cultural, spiritual and aesthetic heritage value features are maintained or increased.	

Van Cauwenbergh et al. 2007

be organized in such a way that social conditions are optimal for the people who work on farms. This refers 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.

7 Agricultural Sustainability Scales at National Level

Assessing and implementing sustainability in agriculture can be undertaken by using goal-oriented strategy approaches according to von Wirén-Lehr (2001). These approaches outlined in Fig. 3 include four fundamental steps, which are:

7.1 Goal Definition

Since goal definition represents the basis of strategies, it determines all subsequent steps as well as the whole methodological framework. Corresponding to

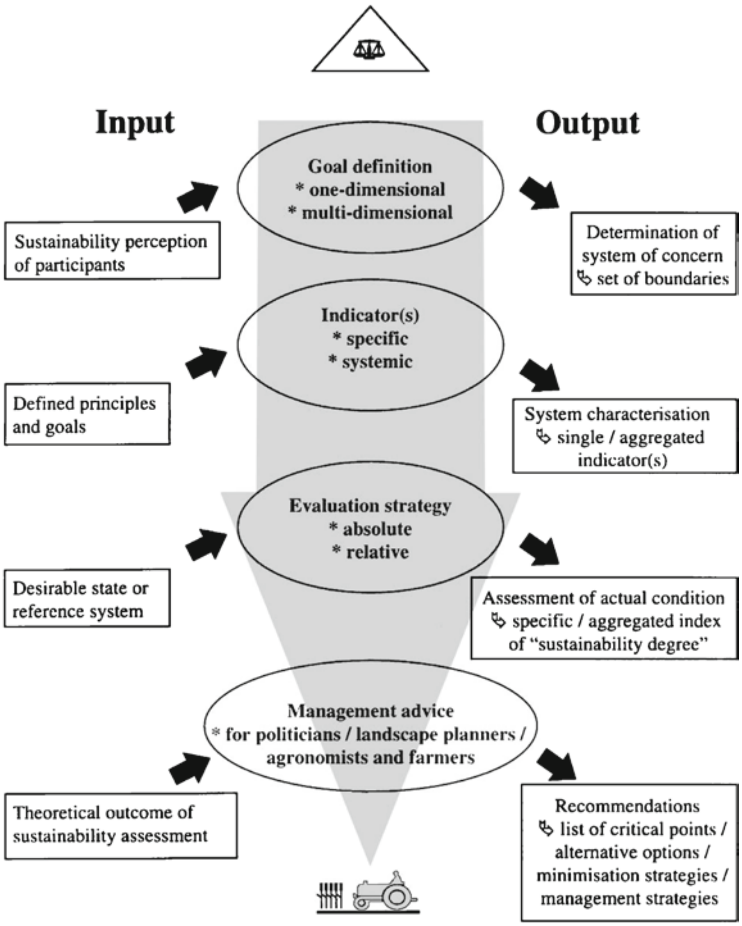

Fig. 3 Basic features of four-step strategies to assess and implement sustainability in agriculture. Frames present required data influx (*left frames*) and expected outcome (*right frames*) of feature derivation (von Wirén-Lehr 2001)

the general multidimensional sustainability paradigm, definitions of sustainable agriculture have to include ecological, economic and social aspects with respect to their diverse spatial and temporal scales (Allen et al. 1991; Herdt and Steiner 1995; Christen 1996). Even though this holistic approach integrates all principles of the theoretical term, its applicability is considerably reduced by the high complexity. Hence, a first step must be to condense the holistic sustainability perception, to restrain definitions on single selected principles and to define aims and systems of concern.

Depending on the priorities of participants and target groups, goal definitions may concentrate on one single (one-dimensional goal definition) or various selected dimensions (multidimensional goal definition). In the agricultural sector, the normative focus of sustainability perception is predominantly based on ecological and/or economic aspects (Crews et al. 1991; Dunlap et al. 1992; Neher 1992; Farshad and Zinck 1993). However, to ensure successful implementation of sustainable systems, management advice has to be strongly adapted to the requirements and abilities not only of target groups but of all groups concerned, for example, also political stakeholders or customers. They should be included in the conceptual work from the beginning. Consequently, concepts to assess and implement sustainability in agriculture have to enhance co-operation not only between different scientific sections but also between divergent socio-professional groups (Giampietro and Bukkens 1992; Flora 1995). Essential for this interdisciplinary work is a separate survey of normative options, e.g. setting of goals and objective parameters (e.g. agro-technical options) permitting every participant or user to verify the fundamental conditions of the work.

7.2 Indicators

All goal-oriented concepts deduce single indicators or indicator sets to 'translate' the defined principles. Indicators represent a powerful tool both to reduce the complexity of system description and to integrate complex system information (Giampietro 1997). Hence, indicators have to be deduced for different systems such as agricultural production systems or other ecosystems, e.g. forests or lakes and at diverse spatio-temporal scales. If the agricultural production system is considered as one compartment of a whole cultured landscape, indicator sets have to provide information not only on imbalances, e.g. releases and deficits of the agricultural production system itself, but also on the external deposition and off-site effects of emissions resulting from agricultural production, e.g. toxic effects in natural aquatic ecosystems due to pesticide residues. Two types of indicators can be distinguished according to their focus of characterization such as:

- Specific indicators, characterising single parts of the system of concern (Nieberg and Isermeyer 1994; Bockstaller et al. 1997)
- Systemic indicators, describing key functions and processes of systems as a whole (Beese 1996; Müller 1998; Xu et al. 1999)

7.3 Evaluation Strategies

Evaluation strategies enable the determination of the sustainability of systems under investigation. They are based on the previously characterised sustainability perception, goal definitions and selected indicators or indicator sets. The evaluation process represents one of the most delicate parts of the concept. First, evaluation ultimately depends on normative options concerning setting of goals, selection of systems of concern and deduction of threshold values or ranges of tolerance (Finnveden 1997). Second, the evaluation of systems based on sets of single indicators ultimately remains inadequate since systemic sustainability represents ‘more than the sum of the parts’.

Two strategies of sustainability evaluation may be distinguished – absolute and relative strategies.

- Absolute evaluation procedures exclusively investigate indicators and corresponding data derived from one single system. Hence, validation is based on a comparison with previously defined margins of tolerance or distinct threshold values for each selected indicator (Mitchell and McDonald 1995). These limits are determined either by estimation, e.g. resulting from expert interviews or referring to socio-political postulates for the reduction of emissions or by scientific deduction, e.g. elaboration of critical loads/levels based on eco-toxicological experiments. Therefore, absolute evaluation assesses distinct datasets e.g. the phosphorus content of the soil compared to the maximum tolerable content. This transparent presentation of results permits end-users to verify the assessment and – if necessary – to adapt the presented data to alternative threshold values.
- Relative evaluation procedures are established on a comparison of different systems among themselves or with selected reference systems. Due to this comparative assessment of systems, there is no need to define distinct margins of tolerance or threshold values. Frequently the results of a relative evaluation are presented as normative point scores.

7.4 Management Advice for Practical Application

The development of management advice for practical application represents the last step for adapting the theoretical outcome of sustainability assessments into implementation of agricultural practice. These recommendations support end-users either in planning new, sustainable production systems or to improve the sustainability of existing systems. The elaboration of management advice considerably varies with respect to the needs and knowledge of the target group, e.g. farmers, political stakeholders or landscape planners.

Table 7 Applied indicators in the agricultural policy scenario analysis (Lehtonen et al. 2005)

Applied indicator	Measured quality	Indicator reflecting	Strategic goal of indicator
Total number of animal units up to 2020	Animal units	The scales and long-term economic viability of aggregate animal production	To conclude the relative economic viability of animal production in different policy scenarios
Number of bovine animal units	Animal units	The scales and long-term economic viability of dairy and beef production	To conclude the relative economic viability of dairy and beef production in different policy scenarios
Number of pig animal units	Animal units	The scales and long-term economic viability of pig production	To conclude the relative economic viability of pig production in different policy scenarios
Number of poultry animal units	Animal units	The scales and long-term economic viability of poultry production	To conclude 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 abandoned agricultural land due to unprofitable production	Changes in the share of abandoned land due to unprofitable production in different policy scenarios
Grass area	Hectares	The scales of gross feed production; incentive for gross feed use and bovine animal production	Changes in scales 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[a]	Kilogram per hectare	Nitrogen leaching potential from cultivated land	Changes in nitrogen leaching potential in different policy scenarios
Phosphorous balance on cultivated area[a]	Kilogram per hectare	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

(continued)

Table 7 (continued)

Applied indicator	Measured quality	Indicator reflecting	Strategic goal of indicator
Profitability coefficient[b]		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 per hour	Economic and social welfare of farmers	Changes in the economic and social viability of agriculture in different policy scenarios

[a]The soil surface nitrogen and phosphorus balances 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
[b]The Profitability coefficient is a ratio obtained when the agricultural surplus is divided by the sum of the entrepreneur family's salary requirement and the interest requirement on capital invested

Further management advice is provided by lists of critical points indicating parts of systems which diverge from the desired state and consequently should be improved. However, lists of critical points which result from a separate evaluation of selected indicators represent case- and site-specific information with limited transferability to different agricultural systems. Since they do not provide any information on how to improve the indicated 'hot spots', their direct applicability in agricultural practice is considerably restricted. It obligates end-users, e.g. farmers and agronomists to interpret and weigh by themselves the presented set of results to develop a corresponding improvement strategy. 'One-solution strategies' resulting from lists of critical points (like strategies exclusively improving nutrient balances) are considered inappropriate to reflect the systemic aspect of sustainability. To enhance successful implementation, case- and site-specific advice should be provided indicating alternative management strategies to optimise the system under investigation.

The most elaborate assistance to the target group is supplied by the formulation of entire improved management strategies. Since the management of agricultural systems is strongly dependent on variable natural conditions, e.g. soil or climate but also on socio-political constraints, e.g. subventions of certain crops or statutory limitations of factor input, final design of these management strategies has to be performed in a case- and site-specific manner in co-operation with end-users (von Wirén-Lehr 2001).

A set of applied indicators for sustainability in different agricultural policy scenarios at the national level is presented by Lehtonen et al. (2005). Their purpose is to provide material for an interactive policy dialogue rather than assemble a comprehensive and conclusive assessment of sustainability of various agricultural policy alternatives (Table 7). They also present what kind of agricultural development each indicator is reflecting and the strategic goal of each specific indicator. It is important to realize that not only the numerical values of the calculated indicators but also their relative changes over time are important when evaluating the sustainability of alternative agricultural policies.

8 Agricultural Sustainability Scales at Farm Level

The indicators discussed here draw on Taylor et al. (1993). In their paper the index is constructed for a sample of 85 agricultural producers in Malaysia with points scored under the headings of (i) insect control, (ii) disease control, (iii) weed control, (iv) soil fertility maintenance and (v) soil erosion control. Gomez et al. (1996) also construct a farm level index of sustainability where six aspects of sustainability are monitored: (i) yield, (ii) profit, (iii) frequency of crop failure, (iv) soil depth, (v) organic C and (vi) permanent ground cover. The following indicators were then constructed for a sample of ten farms from the Guba region of the Philippines (Rigby and Caceres 2001):

– Improved farm-level social and economic sustainability
  - Enhances farmers' quality of life (US Farm Bill 1990)
  - Increases farmers' self-reliance (Pretty 1995)
  - Sustains the viability/profitability of the farm (Pretty 1995; US Farm Bill 1990; Ikerd 1993)

– Improved wider social and economic sustainability
  - Improves equity (Pretty 1995), 'socially supportive' (Ikerd 1993)
  - Meets society's needs for food and fiber (US Farm Bill 1990)

– Increased yields and reduced losses while
  - Minimising off-farm inputs (Hodge 1993; Pretty 1995; US Farm Bill 1990)
  - Minimising inputs from non-renewable sources (Hodge 1993; Ikerd 1993; Pretty 1995; US Farm Bill 1990)
  - Maximising use of (knowledge of) natural biological processes (Pretty 1995; US Farm Bill 1990)
  - Promoting local biodiversity/'environmental quality' (Hodge 1993; Pretty 1995; US Farm Bill 1990).

Senanayake (1991) proposed that agricultural systems have varying degrees of sustainability according to the level of external inputs required to maintain the system that the state of the biotic community within a system operates. His index was in the shape of an equation:

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

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 possible states ranging from two to three. For instance, the three possible states of E_i 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 are such that only two possible states exist, namely zero and one. In the zero state the farming category is unsustainable no matter what its 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:

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

where
$v_e = f(S_e, P_r)$
$V_d = f(E_i, E_r, P_e)$

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

Hayati and Karami (1996) suggested an operational index to measuring agricultural sustainability trend in farm level. The parameters measured in that method are those factors that intervene in the crop production process and could have positive effect in the process. The measurement is summarized in below equation:

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

S = Trend of sustainability
X_1 = Average of crop production per hectare
X_2 = Execution of crop rotation
X_3 = Usage of organic manures
X_4 = Usage of green manures
X_5 = Usage of crop stubble
X_6 = Usage of conservational plough
X_7 = Trend of change in water resources (at the farm)
X_8 = Trend of change in soil resources (at the farm)
Y_1 = Amount of pesticides, herbicides, and fungicides consumption in the farm in one cultivational season
Y_2 = Amount of nitrate fertilizer consumption per 1 t of crop production
Y_3 = Amount of phosphate fertilizer consumption per 1 t of crop production

In fact, parameters of X_1 till X_8 could lead to more sustainability if they increase and parameters of Y_1 till Y_3 could lead to unsustainability if they increase. Thus the below equation is established:

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

In order to measure agricultural sustainability at the farm level, Saltiel et al. (1994) presented an index which is constituted of seven components. They are: cultivation of sustainable crops, conservational cultivation, crop rotation, diminishing of pesticides and herbicides usage, soil mulching, and use of organic fertilizers.

9 Conclusion

The main difficulty in measuring and monitoring agricultural sustainability is that it is a dynamic rather than static concept and needs high level of observation and skills that can adapt to change. Whereas most agricultural scholars believe that measuring sustainability at the farm level is the most precise method, policies at the higher levels (such as national) are increasingly affecting at the lower levels (such as farm). It is necessary to understand the interaction between all levels because each level finds its explanation of mechanism in the level below, and its significance in the levels above.

Moreover, the level of analysis chosen can be a significant influence on the diagnosis of sustainability. At the field level, particular soil management, grazing and cropping practices will be the most important determinants of sustainability. At the farm level, sustainable resource use practices need to support a sustainable farm business and family household. At the national level, there may be broader pressures on the use of agricultural land from non-farming sectors, and at the global level, climatic stability, international terms of trade and distribution of resources also become important determinants.

Although sustainability is a global concept and a farm is only a small subsystem that interacts in various ways with surrounding systems, indicators are needed to know whether a farm system is moving towards or away from sustainability. Indicators can also be used to educate farmers and other stakeholders about sustainable production. Furthermore, indicators provide farmers with a tool to measure their achievements toward sustainability. Further, indicators allow for comparisons between farms' performance in the economic, social and environmental aspects of their production. Indicators also inform policy makers about the current state and trends in farm performance or sector performance. Sustainability performance measures can be used as input for policy tools and stimulate better integration of decision-making. Finally, sustainability indices can encourage public participation in sustainability discussions.

While no measure of sustainability can be perfect, the sustainable value is a useful measure and describes the current sustainability performance. On the other hand, the 'sustainable efficiency' indicator can be used to compare and rank farms. Besides, in view of the fact that biophysical and socioeconomic conditions of countries are different to each other, those indicators which are developed and used in one country may not applicable to other countries.

Some recommendations to selecting indicators in order to more appropriate measuring of agricultural sustainability are:

– Necessity to adoption of a systemic approach
– Establishment and gathering appropriate data base and other necessary information in shape of time series in developing countries
– More emphasis on determining of sustainability trend instead of precision determining amount of sustainability, especially with respect to lack of accessing such data in developing countries
– Launch of professional institutes to monitoring and measuring sustainability of agricultural and industrial systems
– Develop those indicators which be feasible to implementing, meanwhile responsive and sensitive toward any stresses and manipulation on system

References

Adriaanse A (1993) Environmental pool performance indicators. A study on the development of indicators for environmental policy in the Netherlands. Uitgeverij, The Hague
Allen P, van Dusen D, Lundy J, Gliessman S (1991) Integrating social, environmental and economic issues in sustainable agriculture. Am J Altern Agric 6:34–39
Altieri M (1995) Agroecology: the science of sustainable agriculture. West View Press, Boulder, CO
Bartholomew GA (1964) The role of physiology and behavior in the maintenance of homeostatic in the desert environment. In: Hughes GM (ed) Homeostasis and feedback mechanism. A symposium of the society for experimental biology, vol 18, Cambridge University Press. Cambridge, UK, pp 7–29
Becker B (1997) Sustainability assessment: a review of values, concepts, and methodological approaches. Consultative Group on International Agricultural Research, The World Bank, Washington, DC, USA, p 70
Beese F (1996) Indikatoren für eine multifunktionelle waldnutzung. Forstw Cbl 115:65–79
Bernstein BB (1992) A framework for trend detection: coupling ecological and managerial perspectives. In: McKenzie DH, Hyatt DE, McDonald VJ (eds) Ecological indicators, 2 vols. In: Proceedings of the international symposium on ecological indicators, Ft. Lauderdale, Florida, 16–19 Oct 1990. Elsevier, London/New York, pp 1101–1114
Beus CE, Dunlop RE (1994) Agricultural paradigms and the practice of agriculture. Rural Sociol 59(4):620–635
Bithas K, Nijkamp P, Tassapoulos A (1997) Environmental impact assessment by experts in cases of factual uncertainty. Proj Apprais 12(2):70–77
BML (Bundesministerium fur Ernahrung Landwirtschaft und Forsten) (1995). Synoptic portrait of similarities of the contents of existing criteria and indicator catalogues for sustainable forest management. Background paper by the Federal Ministry of Food, Agriculture, and Forestry, Bonn, prepared with assistance from the Federal Research Center for Forestry and Forest Industry

Bockstaller C, Girardin P, van der Werf HMG (1997) Use of agro-ecological indicators for the evaluation of farming systems. Eur J Agron 7:261–270

Bosshard A (2000) A methodology and terminology of sustainability assessment and its perspectives for rural planning. Agric Ecosyst Environ 77:29–41

Bouma J, Droogers P (1998) A procedure to derive land quality indicators for sustainable agricultural production. Geoderma 85:103–110

Christen O (1996) Nachhaltige landwirtschaft (sustainable agriculture). Ber Landwirtschaft 74:1–21

Conway GR (1983) Agroecosystem analysis. Imperial College of Science and Technology, London

Comer S, Ekanem E, Muhammad S, Singh S, Tegegne F (1999) Sustainable and conventional farmers: a comparison of socio-economic characteristics, attitude, and beliefs. J Sustain Agric 15(1):29–45

Crews TE, Mohler CL, Power AG (1991) Energetic and ecosystem integrity: the defining principles of sustainable agriculture. Am J Alter Agric 6:146–149

David S (1989) Sustainable development: theoretical construct on attainable goal? Environ Conser 16:41–48

Dumanski J, Pieri C (1996) Application of the pressure-state-response framework for the land quality indicators (LQI) program. In: Land quality indicators and their use in sustainable agriculture and rural development, p 41. Proceedings of the workshop organized by the Land and Water Development Division FAO Agriculture Department, Agricultural Institute of Canada, Ottawa, 25–26 Jan 1996

Dunlap RE, Beus CE, Howell RE, Waud J (1992) What is sustainable agriculture? an empirical examination of faculty and farmer definitions. J Sustain Agric 3:5–39

Farshad A, Zinck JA (1993) Seeking agricultural sustainability. Agric Ecosyst Environ 47:1–12

Finnveden G (1997) Valuation methods within LCA – where are the values? Int J LCA 2:163–169

Flora CB (1995) Social capital and sustainability: agriculture and communities in the great plains and corn belt. Res Rural Sociol Dev: A Res Annu 6:227–246

Gafsi M, Legagneux B, Nguyen G, Robin P (2006) Towards sustainable farming systems: effectiveness and deficiency of the French procedure of sustainable agriculture. Agric Syst 90:226–242

Giampietro M, Bukkens SGF (1992) Sustainable development: scientific and ethical assessments. J Agric Environ Ethics 5:27–57

Giampietro M (1997) Socioeconomic pressure, demographic pressure, environmental loading and technological changes in agriculture. Agric Ecosyst Environ 65:201–229

Gomez AA, Kelly DE, Syers JK, Coughlan KJ (1996) Measuring sustainability of agricultural systems at the farm level. Methods Assess Soil Qual SSSA Special Publication 49:401–409

Gowda MJC, Jayaramaiah KM (1998) Comparative evaluation of rice production systems for their sustainability. Agric Ecosyst Environ 69:1–9

Hall CA, Day JW (1977) Ecosystem modeling in theory and practice: an introduction with case studies. Wiley, New York

Hammond A, Adriaanse A, Rodenburg E, Bryant D, Woodward R (1995) Environmental indicators: a systematic approach to measuring and reporting on environmental policy performance in the context of sustainable development. World Resources Institute, Washington, D.C

Harrington L, Jones IG, Wino M (1993) Indicators of sustainability. Report brad. Measurements and a consultancy team. Centro International de Agricultural Tropical (CIAT), Cali, Colombia, p 631

Hayati D (1995) Factors influencing technical knowledge, sustainable agricultural knowledge and sustainability of farming system among wheat producers in Fars province, Iran. M.Sc. thesis presented in College of Agriculture, Shiraz Univ., Iran

Hayati D, Karami E (1996) A proposed scale to measure sustainability at farm level in socio-economic studies. Paper presented at first agricultural economic conference of Iran, Zabol, Iran, 5–7 April

Herdt RW, Steiner RA (1995) Agricultural sustainability: concepts and conundrums. In: Barnett V, Steiner R (eds) Agricultural sustainability: economic, environmental and social considerations. Wiley, Chichester/New York/Brisbane/Toronto/Singapore, p 257

Herzog F, Gotsch N (1998) Assessing the sustainability of smallholder tree crop production in the tropics: a methodological outline. J Sustain Agric 11(4):13–37
Hezri AA (2005) Utilization of sustainability indicators and impact through policy learning in the Malaysian policy processes. J Environ Assess Policy Manage 7(4):575–595
Hezri AA, Dovers SR (2006) Sustainability indicators, policy and governance: issues for ecological economics. Ecol Econ 60:86–99
Hodge I (1993) Sustainability: putting principles into practice. An application to agricultural systems. Paper presented to `Rural Economy and Society Study Group', Royal Holloway College, December
Horrigan L, Robert SL, Walker P (2002) How sustainable agriculture can address the environment and human health harms of industrial agriculture. Environ Health Perspect 110(5):445–456
Ikerd J (1993) Two related but distinctly different concepts: organic farming and sustainable agriculture. Small Farm Today 10(1):30–31
Ingels C, Campbell D, George MR, Bradford E (1997) What is sustainable agriculture? www.sarep.ucdavis.edu/concept.htm. Last accessed: October 12, 2008
Karami E (1995) Agricultural extension: the question of sustainable development in Iran. J Sustain Agric 5(1/2):61–72
Koeijer TJD, Wossink GAA, Struik PC, Renkema JA (2002). Measuring agricultural sustainability in terms of effciency: the case of Dutch sugar beet growers. J Environ Manage 66:9–17. http://www.idealibrary.com
Lehtonen H, Aakkula J, Rikkonen P (2005) Alternative agricultural policy scenarios, sector modeling and indicators: a sustainability assessment. J Sustain Agric 26(4):63–93
Lynam JK, Herdt RW (1989) Sense and sustainability: sustainability as an objective in international agricultural research. Agric Econ 3:381–398
Lyson TA (1998) Environmental, economic and social aspects of sustainable agriculture in American Land Grant Universities. J Sustain Agric 12(2,3):119–129
Mitchell G, McDonald A (1995) PICABUE: a methodological framework for the development of indicators of sustainable development. Int J Sustain Dev World Ecol 2:104–123
Miller CA (2005) New civic epistemologies of quantification: making sense of indicators of local and global sustainability. Sci Technol Hum Values 30(3):403–432
Müller F (1998) Ableitung von integrativen indikatoren zur bewertung von Ökosystem-Zuständen für die umweltökonomischen Gesamtrechnungen. Metzler-Poeschel, Stuttgart
Nambiar KKM, Gupta AP, Fu Q, Li S (2001) Biophysical, chemical and socio-economic indicators for assessing agricultural sustainability in the Chinese coastal zone. Agric Ecosyst Environ 87:209–214
Neher D (1992) Ecological sustainability in agricultural systems: definitions and measurement. J Sustain Agric 2:51–61
Nieberg H, Isermeyer F (1994) Verwendung von Umweltindikatoren in der Agrarpolitik. Report No. COM/AGR/CA/ENV/ EPOC (94)96. OECD, Paris
Nijkamp P, Vreeker R (2000) Sustainability assessment of development scenarios: methodology and application to Thailand. Ecol Econ 33:7–27
Norman D, Janke R, Freyenberger S, Schurle B, Kok H (1997) Defining and implementing sustainable agriculture. Kansas Sustainable Agriculture Series, Paper #1. Kansas State University, Manhattan, KS
Organization for Economic Co-operation and Development (OECD) (1997) Environmental indicators for agriculture. OECD Publication, Paris
Organization for Economic Co-operation and Development (OECD) (1991) Environmental indicators: a preliminary set organization for economic cooperation and development. OECD Publication, Paris
Olembo R (1994) Can land use planning contribute to sustainability? In: Fresco LO, Troosnijder L, Bouma J, Van Keulen H (eds) The future of the land: mobilising and integrating knowledge for land use options. Wiley, Chichester, U.K., pp 369–376
Pannell DJ, Glenn NA (2000) Framework for the economic evaluation and selection of sustainability indicators in agriculture. Ecol Econ 33:135–149

Pieri C, Dumanski J, Hamblin A, Young A (1995). Land quality indicators. World Bank Discussion Paper 315. Washington, D.C.

Praneetvatakul S, Janekarnkij P, Potchanasin C, Prayoonwong K (2001) Assessing the sustainability of agriculture: a case of Mae Chaem Catchment, northern Thailand. Environ Int 27:103–109

Pretty JN (1995) Regenerating agriculture: policies and practice for sustainability and self-reliance. Earthscan, London

Rasul G, Thapa GB (2003) Sustainability analysis of ecological and conventional agricultural systems in Bangladesh. World Dev 31(10):1721–1741

Rasul G, Thapa GB (2004) Sustainability of ecological and conventional agricultural systems in Bangladesh: an assessment based on environmental, economic and social perspectives. Agric Syst 79:327–351

Reijntjes C, Bertus H, Water-Bayer A (1992) Farming for the future: an introduction to low external input and sustainable agriculture. Macmillan, London

Rezaei-Moghaddam K (1997) Agricultural extension, poverty, and sustainable agriculture in Behbahan county. Thesis presented for M.Sc. degree in agricultural extension, College of agriculture, Shiraz University, Shiraz, Iran

Rigby D, Caceres D (2001) Organic farming and the sustainability of agricultural systems. Agric Syst 68:21–40

Rigby D, Woodhouse P, Young T, Burton M (2001) Constructing a farm level indicator of sustainable agricultural practice. Ecol Econ 39:463–478

RSU (Der Rat von Sachverstandigen fur Umweltfragen) (1994) Umweltgutacbten 1994. Verlag Metzler-Poesche, Stuttgart

Saltiel J, Baunder JW, Palakovich S (1994) Adoption of sustainable agricultural practices: diffusion, farm structure and profitability. Rural Sociol 59(2):333–347

Sands GR, Podmore H (2000) A generalized environmental sustainability index for agricultural systems. Agric Ecosyst Environ 79:29–41

Senanayake R (1991) Sustainable agriculture: definitions and parameters for measurement. J Sustain Agric 4(1):7–28

Smith CS, McDonald GT (1998) Assessing the sustainability of agriculture at the planning stage. J Environ Manage 52:15–37

Steger U (1995) Nachhaltige und dauerhafte Entwicklung aus wirnchaftswissenschaftlicher Sicht. In: Fritz I, Huber J, Levi HW (eds) Nachhaltigkeit in naturwirsenschaJtlicber und sozialwissenschaftlicher perspektive. Hirzel, Stuttgart, pp 91–98

Taylor D, Mohamed Z, Shamsudin M, Mohayidin X, Chiew E (1993) Creating a farmer sustainability index: a Malaysian case study. Am J Altern Agric 8:175–184

Tellarini V, Caporali F (2000) An input/output methodology to evaluate farms as sustainable agroecosystems: an application of indicators to farms in central Italy. Agr Ecosys Environ 77:111–123 doi: 10.1016/S0167-8809(99)00097-3

U.S. Farm Bill. Food, agriculture, conservation, and trade act of (1990) Public low 101-624, title XVI, subtitle A, Section 1603. Government Printing Office, Washington DC

Van Cauwenbergh N, Biala K, Bielders C, Brouckaert V, Franchois L, Cidad VG, Hermy M, Mathijs E, Muys B, Reijnders J, Sauvenier X, Valckx J, Vanclooster M, der Veken BV, Wauters E, Peeters A (2007) SAFE – a hierarchical framework for assessing the sustainability of agricultural systems. Agric Ecosyst Environ 120:229–242

Van Passel S, Nevens F, Mathijs E, Huylenbroeck GV (2006) Measuring farm sustainability and explaining differences in sustainable efficiency. Ecol Econ 62(1):149–161

von Wirén-Lehr S (2001) Sustainability in agriculture: an evaluation of principal goal oriented concepts to close the gap between theory and practice. Agric Ecosyst Environ 84:115–129

World Commission on Environment and Development (WCED) (1987) Our common future The Brundtland Report. Oxford University Press, Oxford, UK

Webster JPG (1997) Assessing the economic consequences of sustainability in agriculture. Agric Ecosyst Environ 64:95–102

Webster P (1999) The challenge of sustainability at the farm level: presidential address. J Agric Econ 50(3):371–387

Winograd M (1995) Environmental indicators for Latin America and the Caribbean: towards land-use sustainability. GASE (Ecological Systems AnaIysis Group, Bariloche, Argentina), in collaboration with IICA (Instituto Interamerican de Cooperacibn para la Agricultura)-GTZ (Deutsche Gesellschaft fiir Technische Zusammenarbeit) Project, OAS (Organisation of American States), and WRI (World Resources Institute). Washington, D.C.

World Bank (1992) World development report 1992. Oxford University Press, New York

Xu FL, Joergensen SE, Tao S (1999) Ecological indicators for assessing freshwater ecosystem health. Ecol Model 116:77–106

Zhen L, Routray JK (2003) Operational indicators for measuring agricultural sustainability in developing countries. Environ Manage 32(1):34–46