Systematic evaluation of indicator sets for farming system diagnosis and design

G. Cesare Pacini[a], Jeroen C.J. Groot[b], Franca Bacigalupe[c], Concetta Vazzana[a] and Santiago Dogliotti[c]

[a]*Department of Plant, Soil and Environmental Science, Florence University, Italy; gaiocesare.pacini@unifi.it*
[b]*Biological Farming Systems Group, Wageningen University and Research Centre, The Netherlands*
[c]*Department of Plant Science, Faculty of Agronomy, Uruguay*

Abstract: *Indicators of farming system performance are pertinent for the diagnosis of the sustainability of farming systems and to evaluate alternative options in a systems design context. However, methodologies to define, to prioritize and to select indicators in a systematic way are scarce. The objectives of this paper are to present a conceptual approach to systematically evaluate indicator sets for assessment of the sustainability of farming systems (FSs) and discuss its possible application by analysing two indicator frameworks used for FS design (MESMIS and AESIS). The formulation and functioning of the indicator frameworks was related to their use in case-studies in Uruguay and Italy. Main features of the approach are (a) separation of entities in agroecosystems from their associated economic and cultural values; (b) categorization of entities into four dimensions (physical, ecological, productive and social); and (c) a distinction between indicators representing functional properties (for diagnosis) and structural properties (for causal relations and design of adjustments). The points of emphasis of the indicators sets could be readily found for the case studies in Italy (environmental assessment) and Uruguay (productivity and livelihood of small family farmers). The overview of the sets of indicators and their apparent omissions should feed into the stakeholder discussions to determine whether the differences in emphasis were as intended or should lead to adjustments in the indicator sets.*

Keywords: *sustainability indicators, farming system diagnosis and design, conceptual framework, agro-ecosystem dimensions and properties, MESMIS, AESIS.*

Introduction

Many authors have conducted research into the requirements for sustainable farming, and most agree that food sufficiency, environmental preservation, socio-economic viability, and equity are the major components of sustainable farming. However, establishing the definitions and operational methodologies that enable their application in the decision-making process has proved to be a very difficult task.

Indicators are commonly the first, most basic, tools for analyzing change in social-ecological systems. Indicators provide important data for analyses for several reasons. Firstly, they can work as a basis for assessment by providing information on conditions and trends of sustainable development. Secondly, on the basis of such assessments, indicators can provide input to decision-making processes. Thirdly, by presenting several data in one number that commonly is simpler to interpret than complex statistics, they can facilitate communication between different groups, for example between experts and non-experts, as well as farmers, scientists, technicians and policy-makers (Segnestam, 2002). Thus, indicators are suitable to quantify the sustainability of farming systems (FSs), and can support design and implementation in the process of building sustainable FSs.

Methodologies to define, to prioritize and to select indicators in a systematic way in projects are scarce. This limits the effective use of sustainability indicators in participative innovation and adaptive management projects or policy/decision making processes aiming to enhance system sustainability. A crucial starting point for the identification of appropriate indicators is an explicit system definition, which has to facilitate the representation of diverse perspectives on the system under study by stakeholders with contesting view-points and interests. Moreover, the purpose of the indicators has to be agreed upon, and a distinction is needed between (1) indicators that can be used for monitoring the characteristics and dynamics of the system, and (2) indicators that represent relations and processes in the system at an explanatory level, which can be used to effectively make structural changes to the system to improve overall system performance.

In order to guide decision-makers in taking choices coherent with the sustainability principles, indicators can be embedded in a framework wherein sets of indicators are identified and monitored in a logical sequence of phases. There is currently a vast range of indicator-based frameworks to evaluate sustainability of farming systems and land-use in the literature. Some focus on environmental impact (see, for an example, the critical review of 12 indicator-based methods reported by Van der Werf and Petit, 2002), others consider socio-economic aspects as well (e.g., Smith and Dumanski, 1994; Vereijken, 1999; Van Mansvelt and Van der Lubbe, 1999; Weersink et al., 2002; López-Ridaura et al., 2002; Meul et al., 2008; Pacini et al., 2009). In many frameworks much attention is paid to select indicators that are able to communicate the state of the agro-ecosystem regarding on-going sustainability problems, while discarding the others. On the other hand, trying to keep a holistic perspective and considering the complexity of cross-relations between environmental, social and economic processes of the agro-ecosystem can give cause for highly complex FS design architectures based on scarcely transparent definitions of indicators, attributes, criteria and other categories, which are often not harmonised between different disciplines and are not understood by farmers, policy makers and other stake-holders.

The objectives of this paper are to present a conceptual approach to systematically evaluate sets of indicators identified for evaluation of the sustainability of farming systems (FS) and discuss its possible application by analysing and evaluating two indicator frameworks used for FS design (MESMIS and AESIS). The formulation and functioning of the indicator frameworks will be related to their use in case-studies in Uruguay and Italy. The presented approach was devised with the specific aim of combining the need for a holistic approach, addressing the multiple dimensions and hierarchical levels of agroecosystems (to allow for detection of missing information), with the need of stimulating direct involvement of stakeholders in the processes of farm diagnosis and design to build sustainable FSs. Application of the method to MESMIS and AESIS is discussed with special attention to transparency for stake-holders in the two case-studies.

Conceptual approach

The aim of the evaluation of indicator sets as proposed in this paper is to check if all problem domains have been included (or have been excluded for clear reasons), if contrasting interests and perspectives can be addressed, and if there are no unintended unbalances in the indicator set. For this purpose, a set of views on the agroecosystem is defined. The main principles underlying the conceptual approach are as follows:

- Separate views are defined on the entities and the values in the system.
- Values can have a cultural or financial dimension.
- The entities are categorized in four different dimensions: physical, ecological, productive and social.
- Some indicators are used to quantify functional properties (capacity, stability and resilience), and contribute to the monitoring of agroecosystems and can be used to inform policy makers.
- Other indicators are more complex and quantify interrelations among entities within the system and relations with the environment; these indicators address the structural properties (diversity, coherence and connectedness) and play an important role during the participatory diagnosis and modification of agroecosystems management strategies.

Dimensions

We propose to define separate views on the concrete components or entities in the agroecosystem and on the values that can be associated with the entities (Figure 1). A value system can be understood as 'the ordering and prioritization of a set of values that an actor or society of actors holds' (Abreu and Camarinha-Matos 2006). It reflects that components of the agroecosystem have a certain value attached based on societal priorities and rules, which can be expressed in a cultural (or socio-ethical) importance; besides, an economic or financial value can be attached to commodities that are traded in markets. The economic value depends on human demand and local supply of products and services.

The second proposal concerns the classification of the components of the agroecosystem into four sustainability dimensions as a starting point of the assessment (Figure 1). In particular the productive dimension is often omitted from evaluation frameworks used for sustainability assessment (Gomez Sal et al., 2003). It includes not only products harvested from ecological systems, but also artefacts from industrial or human cultivation processes that use both ecological and physical resources. These products can be transformed into other products (milk into cheese; engines, dashboards and other components into tractors).

It can be argued that breaking the system and the problems of the system down in clearly distinctive dimensions will facilitate the identification of context specific problems. Subsequently, these can be translated into critical properties and relevant indicators in a rather straightforward fashion. In this manner the evaluation process is more concrete from the start and this would make the identification of the indicators less abstract, thereby increasing the opportunities for contributions of non-scientific stakeholders. These proposals do not imply that involved participants would immediately embark on mono-disciplinary approaches, since the dimensions are highly interrelated and adjustments with respect to one of the dimensions will have repercussions for other dimensions.

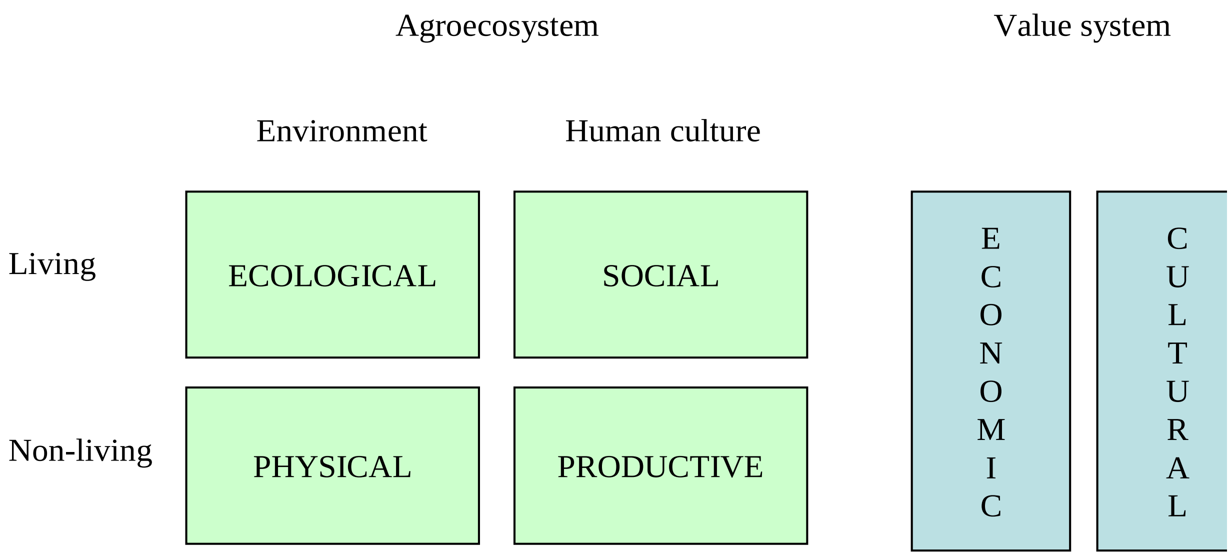

Figure 1. Dimensions of agroecosystems (green) and aspects of the value system (blue).

By overlaying the entities in the dimensions with the perspective on the economic value system, indicators representing the financial values are identified. These are predominantly found in the productive, social and physical dimensions (prices of products and inputs, income). In all four dimensions indicators that convey the cultural values of the system can be found. By overlying and combining views on the agroecosystem we can also specify questions such as: 'which ecological and physical entities in the agroecosystem hold a cultural value (and should therefore be protected)?'; 'is as much attention paid to the physical as to the ecological dimension (or is one of the dimensions more important or problem-prone?)'; 'which components of the productive system provide the most economic benefit (and should these be prioritized or are other sources of economic benefit needed)?'. In a next step we can determine if the proposed set of indicators addresses the issues that have been highlighted by the questions.

Properties

Properties of agroecosystems can be classified into two main categories, i.e. functional and structural. Functional properties (capacity, stability and resilience) contribute to the monitoring of agroecosystems and can be used to inform stakeholders of the status of the system and the changes therein, while structural properties (diversity, coherence and connectedness) play an important role during the detailed scientific diagnosis to understand causal relations, and for the design of modifications to agroecosystems management strategies.

Functional properties

The functional properties of capacity, stability and resilience describe the performance of the system in terms of variations and continuance of the state variables. *Capacity* is the average performance level of a state variable in the system. *Stability* is the capability of the system to remain close to stable states of equilibrium when facing 'normal' variations, and is reflected in the frequency and amplitude of fluctuations in the state variables. *Resilience* refers to the aptitude of the system to maintain its performance defined by capacity and stability after a disturbance or long-term or permanent changes in its environment or internal conditions. The resulting functional properties can be translated into corresponding indicators that are merely descriptive (e.g., like dashboard display in a car), can be used for monitoring of the sustainability of the agroecosystem, but are not useful to explain the underlying mechanisms or to design targeted adjustments aiming to improve the performance of the system and/or to innovate (redesign) the system.

Structural properties

Indicators that reveal the structural properties of diversity, coherence and connectedness express the composition of an agroecosystem in terms of components and processes and their interrelations or the relations with the environment outside the boundaries of the system under analysis. Structural properties determine the functional responses of the system (like the engine of a car), and are particularly relevant to understand the mechanisms that govern agroecosystem performance (Ives and Carpenter, 2007), and to identify possible changes in the system to improve its sustainability. *Diversity* is related to the number of different components and processes present in the system and their relative abundance, whereas *coherence* provides measures of the numbers and strengths of the connections and flows among components and processes within the system. In some instances diversity and coherence have been combined in a term referred to as "*complexity*" (Okey 1996). *Connectedness* is similar to coherence, but concerns the connections with entities outside the agroecosystem. Examples of connectedness can be identified for connectivity with external waterways and habitats (physical and ecological dimensions), but also for integration of farm business in the supply chain (vertical integration system productive dimension) and the involvement of farmers in social networks and institutional arrangements (social dimension).

MESMIS and AESIS

The conceptual framework based on agroecosystem dimensions and properties was applied to analyse and evaluate two indicator frameworks used for FS design (MESMIS and AESIS) in case-studies in Uruguay and Italy.

Short description of MESMIS and the case-study of South Uruguay

An in-depth description of MESMIS is given in López-Ridaura et al. (2002). The MESMIS framework is based on the following premises: 1) sustainability is defined by seven general attributes of natural resource management systems (NRMS): productivity, stability, reliability, resilience, adaptability, equity, self-reliance (self-empowerment); 2) sustainability evaluations are only valid for a specific management system in a given geographic location, a previously circumscribed spatial scale (parcel, production unit, community), a previously determined time period; 3) the evaluation of sustainability is a participatory process requiring an evaluation team with an interdisciplinary perspective; 4) sustainability can not be measured per se, but rather can be seen through the comparison of two or more systems (López-Ridaura et al., 2002). The operational structure of the MESMIS is conceived as a cycle consisting of six steps. The first three steps are devoted to the characterisation of the systems (Step 1), the identification of critical points (Step 2) and the selection of specific environmental, social and economic indicators (Step 3). In the last three steps, the information obtained through the measurement and monitoring of indicators (Step 4) is integrated using quantitative and qualitative analysis techniques (Step 5), which allows obtaining a value judgment for the management systems evaluated and suggesting ways to improve the socio-environmental profile of these systems. Suggestions and recommendations (Step 6) trigger a new evaluation cycle that starts re-characterising the system (Step 1, Cycle 2) (López-Ridaura et al., 2002).

MESMIS was applied to a case-study in South of Uruguay (Departments of Canelones, Montevideo and South East of San José). This area has the highest concentration in the country of small or family farms (farms where most of the labour force is contributed by the farmer and his/her family). Around 88% of the farms with vegetable production as main source of income are family farms (Tommasino and Bruno, 2005). Between 1990 and 2000 the number of vegetable farms decreased by 20% (DIEA, 2001), and those who stayed in business had to produce more, cheaper and better quality to maintain their family income. The strategy followed by most farmers was to intensify and specialise their production systems. In the South of Uruguay the average vegetable cropped area per farm increased, while the average total area per vegetable farm stayed approximately the same. The average number of crops per farm also decreased. The observed increase in crop yields was explained by increasing use of irrigation, external inputs (fertilizers, biocides and energy), and higher quality seeds (Aldabe, 2005). The intensification strategy put more pressure in already deteriorated soils and on limiting farm resources. Increasing the crop area and narrowing the crop types without an adequate planning troubled farm operational functioning causing inefficient use of production resources, higher dependence on external inputs and higher impact on the environment. Consequently, the sustainability in the long term of most of the family farms in South Uruguay is threaten by incomes not enough to cover maintenance of the family and production infrastructure, and/or continued deterioration of the natural resource base (Dogliotti, 2009). In Table 1 attributes, diagnosis criteria and indicators of the MESMIS framework applied to the case-study in Uruguay are presented.

Table 1. Attributes, diagnosis criteria and indicators of the MESMIS framework applied in South Uruguay.

Attribute	Diagnostic criterion	Indicator
Productivity	Production efficiency	Commercial yield per cropped area Commercial yield per unit of labor Animal production per grazed area Animal production per unit labor
	Economic efficiency	Return to labour Degree of satisfaction of family income needs Family income Net income
Stability	Natural resource cocnservation	Soil loss Soil organic matter balance Net income/water use Balance NPK Evolution of biological activity in the topsoil Environmental impact of pesticides in soil, water and air Evolution of weed population
Reliability Adaptability Resilience	Diversification	Income distribution along the year Income distribution among commercial channels Expertise diversification
	Stability of labor use	Ginni Index on monthly labor demand and availability
	Life quality	Life quality, access to social support and level of participation
	Production system fragility	Harvested fraction Commercialized fraction
	Vertical integration	Vertical integration Percentage of the final price received by the farmer at farm-gate
	External dependency	Dependency from external inputs Relevance of off-farm income
	Biodiversity	Ecological infrastructure area Crop rotation blocks Field size and field max width/max length ratio Crop diversity at farm level
Self-reliance	Self-sufficiency of economic resources	Indebtedness level Percentage of total costs covered by external funds

Short description of AESIS and the case-study of Tuscany

An in-depth description of AESIS is given in Pacini et al. (2009). Main features of the indicator AESIS are the relevance given to different spatial scales (farm, site and field), production and pedo-climatic factors, and a systemic view of the agro-ecosystem. The framework has been conceived to tackle different purposes ranging from detailed scientific analyses to farm-level management systems and policy monitoring. Besides, the framework has been designed and tested to be coherent with the current European financial accounting model (FADN). The AESIS has been developed from previous experiences dating since 1991, aiming at finding the right balance between a range of different application purposes and the level of complexity of indicators. Agro-environmental indicators can be calculated, simulated with models or directly measured with different levels of detail, proportionally to the aims of the evaluation exercise. The procedural steps to apply the framework are collected in three phases, i.e. definition of sustainability issues (Phase 1), identification of potential solutions (Phase 2) and evaluation of alternative farming systems (Phase 3). In Phase 1 issues are identified together with detailed critical points connected to farm environmental and production systems and relevant indicators are selected. In Phase 2 a comparison layout is settled (e.g., comparisons between farms, comparisons of different management systems/techniques on the same farm, comparisons of farms with thresholds, comparisons between farm model simulation results), indicator thresholds (or critical limits, sustainability targets) are identified and alternative management systems are defined (e.g., organic, integrated, environmentally-friendly, best available technologies etc.) together with relevant potential policy measures. In Phase 3 calculation methods of indicators are selected proportional to the evaluation purpose, indicators are measured and integrated in a farm simulation model and results are finally presented. Case-study farms include small, medium and large enterprises, as well as experimental stations, and range from arable to mixed cattle-arable, dairy, vineyard, olive, vegetable, fruit and ornamental plant nursery production. Pedo-climatic conditions of case-studies under survey, although belonging to the same Region, range from pre-mountain climates with a mean annual rainfall of 1000 mm (Mugello, northern Tuscany) to dry Mediterranean climates with a mean annual rainfall of 625 mm (Maremma, southern Tuscany), including a number of different soil types. Such a broad range of tests allowed to calibrate the AESIS in order to cope with diversity of agro-environmental impacts. In Table 2 the AESIS complete list of environmental critical points, systems and indicators applied in Tuscany is reported.

Table 2. AESIS complete list of environmental critical points, systems, indicators applied in Tuscany (modified from Pacini et al., 2009)

Critical point	**Environmental system**	**Indicator**
Water demand, water-table level	Water	Water balance
Flood risk, water stagnation, landscape conservation		Drainage system length
Soil erosion	Soil	Soil erosion
Soil quality		Soil salinity, Heavy metals
Loss of organic matter		Soil organic matter content
Agro-ecological identity of fields	Production activities	Field size Field max width/length ratio Rotation years
Landscape diversity		Crop diversity at farm level
Livestock biodiversity		Livestock biodiversity
Livestock intensity		Livestock load Manure management
Refuse		Dangerous waste load Percent of recycling waste
Associated biodiversity of flora	Biodiversity	Herbaceous plant biodiversity and richness Hedge biodiversity Arboreous plant biodiversity and richness Semi-natural habitat area Insect biodiversity and richness
Nitrogen cycle	Flow system	Nitrogen leaching Nitrogen run-off Soil Nitrates Ammonium emissions
Phosphorous cycle		Phosphorus sediment Soil phosphates
Biocide pollution		Environmental potential risks of pesticide use
Energy demand		Energy balance

Application of the conceptual framework to MESMIS and AESIS

A re-systematisation of indicators could allow for detection of aspects that receive no attention in the assessment either due to lack of erroneous omission or as a result of deliberate prioritization within the projects. In Table 3 the result of the re-systematisation of MESMIS and AESIS sustainability indicators based on agroecosystem dimensions and properties is reported.

For applications of MESMIS in Uruguay a total of 35 indicators were employed, whose 15 are performance indicators to account for capacity, stability and resilience of the FSs, and the rest describes the structural properties. The MESMIS set of indicators in the Uruguay case-study covers most agroecosystems properties and sustainability dimensions (Table 3), but the emphasis is on the productive and social dimensions with 24 indicators. Apparently, the vegetable farmers near Montevideo are in a vulnerable position and the project focuses primarily on maintaining productive capacity and income and quality of life for the farmers' families. Thus, many indicators are related to the economic values as expressed in product revenues, labour return and family income. The indicators in the physical and ecological dimensions relates to the structural properties of coherence and connectedness that would support the level of production, in particular organic matter build-up and reduction of soil loss through erosion to maintain fertility.

For applications of AESIS 31 indicators were employed, of which 4 are performance indicators. AESIS applications in Italy show more coverage of the environmental dimensions (i.e., physical and ecological, only physical diversity is disregarded) but hold limited information on the production and social dimensions (only production diversity is considered). This is in line with the original AESIS environmental vocation. In previous studies AESIS has been often applied in combination with microeconomic indicator sets but they were not formally included in the framework, as AESIS comprises explicit links and information entry points from financial accounting. Performance indicators such as farm gross margin, production variable costs and yields were calculated but no information was collected on agroecosystems properties of the social dimension, on production coherence (e.g., vertical integration, on-farm processing of products, animal feed self-supply), and connectedness (e.g., supply chain integration, percentage of the final price received by the farmer at farm gate, indebtedness level).

In MESMIS indicators are explicitly selected based on diagnostic criteria and the phase of design is left to step 6 “Conclusions and recommendations”, where results of indicators are displayed in an AMOEBA graph to allow to judge how the different systems compare in terms of sustainability, and this is also what basically happens in AESIS applications. In addition, AESIS anticipates the integration of indicators in farm simulation models that can be used in combination with scenario analysis to develop farm strategies and design new FSs based on the change of the state of the environment calculated with stock and flow indicators. However, both frameworks lack an explicit consideration of causal relationships between indicators and explicit links between the phases of diagnosis and design for building sustainable FSs.

Figure 2 reports on an example of the use of the conceptual framework including functional and structural indicators for farming system diagnosis and design. Relations between indicators and dimensions are highlighted by arrows; hence properties are transversal through dimensions. Correspondence between functional properties and diagnosis on the one hand, and structural properties with design on the other hand can support the construction of sustainable FSs. Functional properties reveal how the farming system responds in terms of performances to farm strategies. Structural properties are those on which the farmer should intervene in the course of strategy design. Farm design (devised through indicator-based analysis of structural properties) follows-up diagnosis (run through indicator-based analysis of functional properties) in an iterative fashion.

Conclusions

The proposed conceptual framework showed to be useful to identify differences in priorities in the two indicator systems that were applied in different case study areas. The overview of emphases should be discussed in another round of stakeholder interaction, to verify if it corresponds to the perspectives on crucial limitations in the performance of agroecosystems and the potential threats to economic viability and environmental sustainability. In this sense, the conceptual approach seems to offer a promising avenue to further broaden and deepen participatory processes and to strengthen the holistic perspective on analysis of agroecosystems sustainability.

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Table 3. Re-systematisation of MESMIS and AESIS sustainability indicators based on agroecosystem dimensions and properties. Performance indicators are used to assess capacity, stability and resilience properties. AESIS indicators are reported with a light grey background, MESMIS indicators with white background.

Property	**Dimensions**			
	Physical	**Ecological**	**Production**	**Social**
Diversity	M	1) Herbaceous plant biodiversity and richness; 2) Hedge biodiversity; 3) Arboreous plant biodiversity and richness; 4) Insect biodiversity and richness	1) Rotation years; 2) Crop diversity at farm level; 3) Livestock biodiversity	M
	M	M	1) Income diversification; 2) Crop rotation blocks; 3) Crop diversity at farm level	1) Expertise diversification
Coherence	1) Soil fertility due to soil loss; 2) Water balance; 3) Drainage system length; 4) Manure management; 5) Percent of recycling waste	1) Semi-natural habitat area; 2) Field size and field width-length; 3) Hedge length; 4) Energy balance	M	M
	1) Net income/water use; 2) Balance NPK; 3) Decrease of soil fertility due to soil loss	1) Soil organic matter balance; 2) Ecological infrastructure area; 3) Field size and field width-length	1) Vertical integration	M
Connectedness	1) Erosive sediment yield; 2) Livestock load; 3) Dangerous waste load; 4) Nitrogen leaching; 5) Nitrogen run-off; 6) Ammonium emissions; 7) Phosphorous sediment; 8) Environmental potential risks of pesticide use	1) Energy balance	M	M
	1) Dependency from external inputs – physical; 2) Environmental impact of pesticides in soil, water and air	1) Dependency from external inputs – organic	1) Percentage of the final price received by the farmer at farm-gate; 2) Indebtedness level; 3) Percentage of total costs covered by external funds	1) Access to social support, 2) Level of participation; 3) Off-farm income
Performance (capacity, stability, resilience)*	1) Soil nutrient contents; 2) Soil salinity; 3) Heavy metals	1) Soil organic matter content	M	M
	M	1) Biological activity in the topsoil; 2) Weed population	1) Net income; 3) Commercial yield per cropped area; 4) Commercial yield per unit of labour; 5) Animal production per grazed area; 6) Animal production per unit labour; 7) Harvested fraction; 8) Commercialised fraction	1) Return to labour; 2) Degree of satisfaction of family income needs; 3) Ginni index of labour; 4) Family income; 5) Life quality

Legend: M = missing information, i.e. detection of aspects that receive no attention in the assessment. Note1: due to space limitations names of indicators of Tables 1 and 2 can be simplified. Note 2: in few cases explicit information already available for calculations in AESIS and MESMIS has been included in the form of indicators.

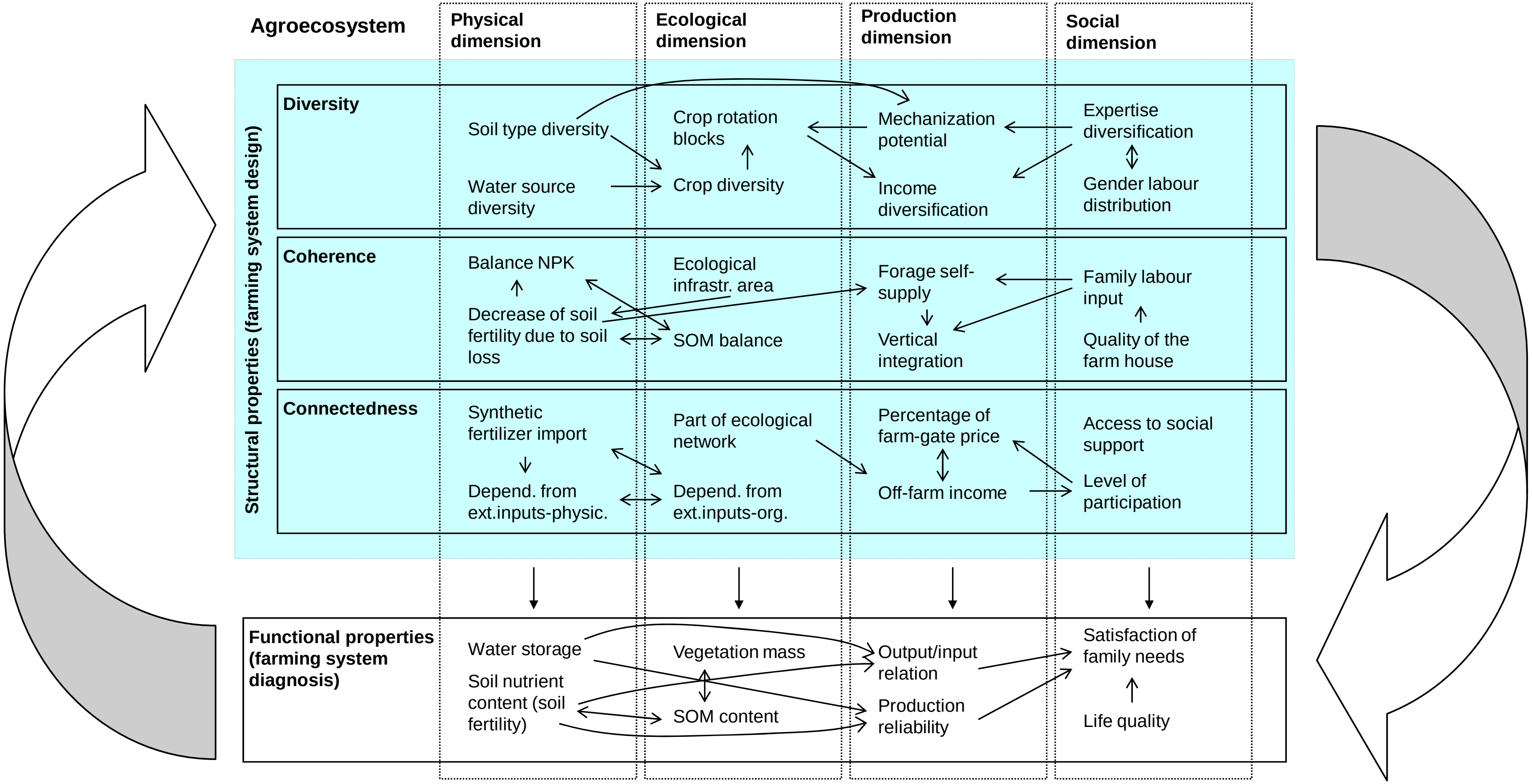

Figure 2. Example of the use of the conceptual framework including functional and structural indicators for farming system diagnosis and design. Legend: SOM: soil organic matter.