

Recent Developments in Indicators and Models for Agri-environmental Assessment

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Abstract

Over the years there has been a remarkable development in agricultural and environmental sciences and the public is growing increasingly concerned about the relations between agriculture and the environment, and about the sustainability of agricultural production systems in many parts of the world. Policy makers and the general public have asked the scientific community to make more information available, and a great wealth of research studies have been conducted and published in recent years. Many studies include in-depth analyses of agricultural systems based on simulation models for various purposes: understanding the mechanisms involved, comparing alternative scenarios and supporting and evaluating policy measures. Indicators are also frequently used to provide concise quantitative figures of various aspects (economic or productive performances, environmental impacts, etc.) and to communicate them to a broad audience. This paper offers a survey of the recent literature dealing with agri-environmental issues and, in particular, of those references presenting the use of models and indicators for the assessment of agricultural systems and their effects on environmental compartments (water, soil, air), from multiple disciplinary perspectives, and at various scales. The references examined for this paper have been classified in order to group the papers according to various criteria, thus facilitating the identification of relevant references, and to compare their contents. The methodological approaches are analysed and compared in order to highlight the contributions of the scientific literature to the assessment of agro-ecosystems and agri-environmental policies.

Key-words: agriculture, environment, indicator, model, assessment, policy making.

1. Introduction

The exploitation systems of natural resources for primary production have changed over time with the development of scientific and technological progress as well as under the effects of socio-economic changes. The continuous evolution of agricultural systems has provided food for an ever increasing world population, but has also caused various conflicts with the environment – e.g. erosion, salinisation, desertification phenomena – which have even caused the disappearance of whole civilisations in the past ages.

In recent years, the perception of relations between agriculture and the environment has remarkably changed and concerns have been raised about the sustainability of agricultural production systems in many parts of the world and the general public has asked the scientific community to make more information availa-

ble. Also, there is a need for new analysis and assessment approaches to acquire new, integrated knowledge.

Simulation models and indicators play a fundamental role in this context by providing methods and tools for the assessment of agro-ecosystems and their environmental effects and for communicating their performance in a concise and effective way.

There is an extensive literature about indicators falling within the broad field of sustainability science. Those specific for the problems in question are usually called agri-environmental indicators. Sustainability provides the general approach to deal with multidisciplinary analyses and in particular with those disciplines related to the 3 pillars of sustainable development – social, economic, environmental ones – or four, by including also an institutional dimension.

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The 1992 Earth Summit recognised the important role that indicators can play in helping countries make informed decisions concerning sustainability. This recognition is articulated in Chapter 40 of Agenda 21 which calls on governmental and non-governmental organisations to identify Indicators of Sustainable Development (ISD's) that can provide a solid basis for decision-making at all levels.

Indicators, in this context, can provide crucial guidance for policy-making in a variety of ways. They can in general translate physical and social science knowledge into manageable units of information that can facilitate the decision-making process. Another crucial role of ISD's is that of providing a means of measuring, monitoring and reporting on progress towards sustainability, which is still an open problem both for the academia and the decision makers.

The Organisation for Economic Co-operation and Development (OECD, 2002) defined three major functions of environmental indicators in agriculture. Firstly, they should provide information to policy makers and the general public about the state of the environment influenced by agriculture. Secondly, they have to help policy makers to better understand the cause-effect links and feedback loops between agricultural activity and the environment. Thirdly, they have to assist in the evaluation of the effectiveness of agri-environmental policy instruments.

Similarly to the indicators for sustainable development and in particular for the assessment of the sustainability of agricultural systems, there is a very broad literature that deals with simulation models for agri-environmental issues. Whenever the analysis of dynamic systems characterised by cause-effect chains and feedback loops is concerned, models present the solution for simulating development trajectories, analysing alternative scenarios, quite often calculating indicators' values as outputs.

Models and indicators are thus playing a very important role in the sustainability assessment of agricultural systems in various contexts usually related to policy support (e.g. *ex ante* or *ex post* evaluation of agri-environmental policy measures), or decision making (e.g. choice between alternative cultivation techniques with different environmental effects).

This paper aims at providing a review of the recent literature about agri-environmental indi-

cators and models. In particular it is intended to facilitate the identification of relevant references for those readers interested in knowing about available methods and operational tools, for carrying out agri-environmental assessments in order to support policy and decision making. For this purpose the references have been classified according to various criteria and reported in a synoptic table reported in Table 1.

The following pages include the definitions of the most important terms and provide an overall analysis of the role played by agri-environmental indicators and models in a theoretical analytical process of agricultural systems made of monitoring (with indicators), conceptual frameworks, analyses (with models) and assessment.

The third section of the paper briefly presents the method adopted in the review: sources of information, keywords examined, classification criteria, etc.

The fourth section presents a systematic review of the results of the literature, based upon several classification criteria, and in particular: the approaches adopted, the compartment of interest, their scales, the disciplines involved in the analysis and, in some cases, in the evaluation of agricultural systems.

The final section of the paper presents some concluding remarks.

2. Definitions and theoretical background

The sustainability analysis of agricultural systems should first of all identify proper ways to describe the phenomena to be assessed. Significant measurable variables should be identified and, very importantly, processed to transform the acquired data into information that can be used for communication with non experts, typically in the context of policy or decision-making processes.

According to the scheme proposed by the Organisation for Economic Co-operation and Development (OECD, 1991; 1994), variables which can be observed and measured can later be transformed into indicators, values whose significance extends beyond that of the variables themselves, with respect to specific purposes. Moreover, a set of aggregate or weighted indicators may produce a more concise and representative value, called an index. Combining re-

Table 1. Comparative analysis of the literature examined.

Authors	Year	Environmental compartment				Impacts	Approach	Acronym Name	Scale	Application area	Assessment discipline			
		water		air							technical	environmental	economic	human
		quantity	quality	soil	multiple									
Abrahamson P. et al.	2000		X	X		nutrients	Daisy	field			X			
Archer D.W. et al.	2001		X			pesticides	CEEPES	farm	Argentina		X		X	
Ares J.	2004		X			pesticides		farm	France, Germany, USA		X			
Arondel C. et al.	2000		X			nutrients, pesticides, irrigation	ELECTRE TRI	farm	Germany, USA, UK		X			
Aspinall R. et al.	2000				X	biodiversity		catchment			X			
Bayliss J.L. et al.	2005				X			catchment			X			
Bazzani G.M.	2005	X			X		DISSIR	farm/catchment			X			
Bazzani G.M. et al.	2005	X			X	sustainability	DISSIR	farm	Italy		X			
Berenzani N. et al.	2005				X	pesticides		landscape	Germany		X			
Berka C. et al.	2001		X			nutrients		catchment	Canada		X		X	
Bigras-Poulin M. et al.	2004		X			microbiological	AHPis	farm	Canada		X		X	
Bockstaller C. et al.	1997		X			nutrients, pesticides	AEIs	farm	Canada		X			
Bockstaller C. et al.	2003							farm			X			
Braband D. et al.	2003				X	biodiversity		field/farm			X			
Brisson N. et al.	2003	X				nutrients	STICS	field/regional	France		X			
Brown C.D. et al.	2003		X			pesticides	p-EMA (I)	farm	UK		X			
Büchs W.	2003		X		X	biodiversity		landscape			X			
Büchs W. et al.	2003		X		X	biodiversity		field			X			
Collentine D. et al.	2004		X			nutrients	LENNART	field	Sweden		X			
De la Torre Ugarte D. et al.	2000							national	US		X			
De Smet B. et al.	2005		X			biomass and energy	POLYSYS	regional	Belgium		X			
Ekholm P. et al.	2005		X			pesticides	ΣSeq	farm	Finland		X			
			X			nutrients	Soil surface P balance				X			
Freyer B. et al.	2000		X			environmental resources		national/landscape	England, Wales		X			
Gilbert J.C. et al.	2000		X			biodiversity	the habitat creation model	landscape/field			X			
Girardin P. et al.	2000						AGRO*ECO	field/farm			X			
Gömann H. et al.	2005		X		X	suitability	GROWA98, WEKU, RAUMIS	catchment	Germany		X			
			X			nutrients					X			
Gómez-Sal A. et al.	2003				X	nutrients	SOIL + SOIL-N	landscape	Spain		X			
Granlund K. et al.	2000		X			pesticides	SYNOPS 1.1	regional	Finland		X			
Gutsche V. et al.	1997		X			nutrients		landscape	Germany		X			
Haag D. et al.	2001		X			nutrients		landscape	Central Europe		X			
Halberg N.	1999		X		X	energy, biodiversity		farm	Denmark		X			
Halberg N. et al.	2005		X			nutrients, pesticides, energy		farm	Europe		X			
Hanley N. et al.	1999		X			nutrients		farm	UK		X		X	
Hansen B. et al.	2000		X			nutrients	“empirical nitrogen leaching”, “nitrogen balance”	farm	Denmark		X		X	

Table 1. Comparative analysis of the literature examined (cont.).

Authors	Year	Environmental compartment						Impacts	Approach	Acronym Name	Scale	Application area	Assessment discipline			
		Review			multiple								technical	environmental	economic	human
		quantity	quality	water	soil	air	multiple									
Hart	2003	X	X	X	X		pesticides	model	p-EMA (II)	farm field	UK	X	X			
Heathwaite A.L. et al.	2005	X	X	X	X		nutrients	model	TopManage	national/regional/local	Germany	X	X	X		
Herrmann S. et al.	1999	X	X	X	X			model				X				
Heuvelmans G. et al.	2005	X					water	model	LCA Methodology	farm	Canada	X				
Huffman E. et al.	2000		X				land quality	indicator	BSD	landscape	Switzerland	X				
Jeanneret P. et al.	2003			X		X	biodiversity	indicator		landscape		X				
Koo B.K. et al.	2006	X	X				nutrients	model	MCA	catchment/		X		X		
Kookana R.S. et al.	2005	X	X				pesticides	index		catchment/		X				
Kyllmar K. et al.	2005	X	X				nutrients	model	SOILNDB	regional	Australia	X				
Levitani L. et al.	1995	X	X				pesticides	model		field	Sweden	X	X	X		
Lewis K.A. et al.	1998	X	X	X		X	pesticides	model	EMA	farm	UK	X	X	X		
Morrison J. et al.	2000	X	X	X		X	agriculture	indicator			South Africa	X	X	X		
Moxey A. et al.	1998	X	X	X		X		indicator				X				
Onate J.J. et al.	2000	X	X	X		X	biodiversity	indicator			Spain, Denmark	X				
Oglethorpe D.R. et al.	1999							model	VEMM, SEUM	farm	UK	X	X	X		
Pervanchon F.	2002	X	X		X	X	energy	indicator		farm field/farm		X				
Pervanchon F. et al.	2005	X	X		X	X	nutrients	indicator	I_{En} $I_{N\ losses}$	field/farm	France	X				
Pierr H.-P.	2003							indicator		landscape	EU	X				
Primdahl J. et al.	2003							model		farm	EU	X				
Rao M.N. et al.	2000						nutrients	model	EPIC-View	farm	USA	X				
Rigby D. et al.	2001						sustainability	indicator	ISAP	farm	UK	X				
Sands G.R. et al.	2000						sustainability	index	ESI	field	USA	X				
Schou J.S. et al.	2000						nutrients	model	ESMERALDA	catchment	Denmark	X	X			
Schröder J.J. et al.	2003	X	X				nutrients	indicator	MINAS	farm	Denmark	X		X		
Schröder J.J. et al.	2004	X	X				nutrients	indicator		farm	Canada	X	X	X		
Sharma T. et al.	2006	X	X			X	sustainability	model	AgFutures	regional		X				
Simonta C. et al.	2005	X	X	X		X	erosion	model	SIDASS	local/regional		X				
Smith C.S. et al.	1998	X	X				sustainability	model		field/farm/	Australia	X				
Smith C. S., et al.	2000	X	X	X		X	sustainability	model	TIM	catchment		X				
Stein A. et al.	2001		X	X			heavy metals, nutrients	indicator			NL, UK, DK	X	X	X		
Tzilivakis J. et al.	1999	X	X	X		X	nutrients	indicator	SEAM			X				
Tzilivakis J. et al.	2004	X	X	X		X	pesticides	indicator		farm	England	X				
van Beek C.L. et al.	2003	X	X	X		X	nutrients	indicator	FGBs - SSBs	field/farm	Netherlands	X				
van der Werf H.M.G. et al.	2002	X	X			X		indicator		farm	Germany	X				
Waltz R.	2000							indicator		national	France	X				
Weinstoerffer J. et al.	2000					X		indicator	I_{land}	farm/ region		X		X		

levant indicators into a composite index presents the available evidence in a much more convincing fashion than would individual indicators (EEA, 2005; ICSU, 2002) and facilitates the use of such information by non experts. Indicators, and even more indices, are the values upon which the decision processes, including the development or assessment of policies, can be based.

Many authors and institutions have developed proposals for an indicators list, and most of them emphasise the need to organise the selected indicators within a conceptual analytical framework. A document by the International Council for Science (ICSU, 2002) attempted to sketch a general scheme in which indicators and frameworks are integrated in four types of knowledge of a generic evaluation process of human-environmental relationships. *Indicators* represent the first component, functional to monitoring social and environmental developments at various scales in time and space. As previously stated they should be preferably organised within *conceptual frameworks*, the second type of knowledge, i.e. ordering mechanisms that help organise indicators logically. A third kind of useable knowledge derives from specific forms of *analysis* (e.g. models), to gain information and insight for a specific *assessment* purpose (the fourth kind of knowledge).

Indeed, indicators play a fundamental role at the communication interface between science and policy/decision making, while models provide methods and tools for supporting the analysis of the systems of interest, in this case the agro-ecosystems, or more generally the territorial systems in which agri-environmental issues are considered. Indicators allow better communication and accessibility to information by bridging the gap between producer and user of information, i.e. between the information available through scientific resources and the need of information for decision-making (Boisvert et al., 1998).

With de Witt (1986), we can define a system as the limited part of reality that contains interrelated elements of specific interest; a model is a simplified representation of a system, and simulation is the art of building mathematical models and studying their properties relative to those of the systems. Although it always simplifies reality, a model must contain all the essen-

tial features of the real system, in order to describe and resolve a given problem (Jørgensen, 1986). The balance between simplification and comprehensiveness depends upon the scope of the model, which may be very diverse, thus determining a wide range of possible model typologies (Giupponi, 1995), which can be classified as follows:

- type of model: abstract (formal, mathematical) versus physical (material); internal (cognitive, or mental), versus external (i.e. formal, computerised);
- time frame: static and dynamic;
- type of process description and algorithms: rule-based, empirical (statistical), causal (analysis of causes and effects);
- type of approach (within causal models): deterministic or stochastic;
- level of detail in system description: screening or detailed (system assessment);
- level of detail in spatial description: lumped and distributed;
- spatial scale: theoretically from single cell to the global scale;
- time scale: discrete event or continuous.

Abstract dynamic causal models (with some degree of empiricism), either deterministic or stochastic, are generally utilised for the analysis of agricultural systems, with remarkable variations in time and space scales.

Giupponi (1995) identified the characteristics of two main categories of models useful when dealing with agri-environmental issues. The first category includes crop production models, in which the following processes are simulated with varying emphasis: crop physiology and morphology; soil processes; pests; farm management; economics. They are usually aimed at focusing on the productive function, with yield estimation being one main output, from technical and in some cases economic viewpoints. The other category includes those models that focus instead on the relationships of agricultural systems with the environment. Many of them belong to the category of diffuse pollution models (Novotny and Olem, 1994) in which other processes may be simulated and in particular: surface runoff, leaching; erosion; soil adsorption and desorption of agrochemicals; dispersion in the air. According to the issues to be examined some modules can be lumped into parameters, while others could be particularly well develo-

ped, such as carbon dioxide fluxes of the soil-plant-air system, when dealing with climate change problems.

According to the definitions given above and following the general analysis framework proposed by the ICSU, the role of indicators can be defined within the context of providing effective and concise – but usually static – information about the phenomena of interest within conceptual frameworks, which could make explicit the complex network of cause-effect links within the systems of interest (i.e. the agro-ecosystems at various levels and scales). On the other hand, models provide the essential capability of dealing with dynamic systems and analysing their behaviour in various contexts and under different scenarios, thus providing also the capability of simulating alternatives, a fundamental feature, for example, for the *ex ante* assessment of policy options.

2.1 Agri-environmental indicators and conceptual frameworks

Indicators are classified in different ways, on the basis of the purpose they serve. The European Environmental Agency (EEA) distinguishes four categories of indicators (EEA, 1999): a first category of *Descriptive indicators* answers the question: “What is happening to the environment and to humans” presenting the situation as it is, without judgements about how it should be (typically used for the State of the Environment reports); *Performance indicators* answer the follow-up question “Does it matter?” by comparing the situation observed with reference conditions (e.g. distance to target); there is a third category of *Efficiency indicators*, answering the question “Are we improving?”; finally, a fourth category of indicators (*Total welfare indicators*) is connected with the question: “Are we on the whole better off?”, which asks for a balance between economic, social and environmental progress in comprehensive terms of sustainability.

The OECD and other international institutions have launched many activities in the past to foster the identification of a standardised list of agri-environmental indicators and the collection of relevant data. A comprehensive list is summarised in a recent work by the OECD (2002), in which four main categories are identified, the first dealing in general with “Agricul-

ture in the broader economic, social and environmental context”, with two sections about contextual information (e.g. Agricultural GDP; Land use) and one about farm financial resources. The second section is about “Farm management and the environment”, with indicators about land management practices and organic farming, for instance. The third section focuses on the “Use of farm inputs and natural resources” with three sub-sections with indicators about nutrients, pesticides and water uses. The last section includes the larger number of indicators dealing with the “Environmental impacts of agriculture” described by seven categories of indicators about soil quality; water quality; land conservation; greenhouse gases; biodiversity; wildlife habitats and the landscape.

At the European level, the most recent effort is represented by IRENA (Indicator Reporting on the Integration of Environmental concerns into Agricultural policy), an initiative aimed at developing agri-environmental indicators for monitoring the integration between agricultural and environmental policies, thus contributing to analysing the progress towards sustainability in the agricultural sector. IRENA has identified a set of 35 detailed indicators, subdivided in five groups, according to the following selection criteria: policy relevance, responsiveness, analytical soundness, data availability, ease of interpretation and cost effectiveness. A report of the IRENA indicators for the EU-15 area has been recently released by the European Environmental Agency (EEA, 2005), with the state and trend of the selected indicators, grouped as follows: agricultural water use, agricultural input and the state of water quality, agricultural land use farm management practices and soils, climate change and air quality, and biodiversity and landscape.

Once a comprehensive set of indicators has been defined, there should be a clear structure that communicates to policy makers how each piece of information is related to the various human activities, environmental phenomena, and policy processes. To achieve this, conceptual frameworks that structure a collection of indicators and that communicate their application are developed.

In general, different analytical levels require different frameworks. That is to say, depending on the detail of analysis and the purpose of the

monitoring, different frameworks may provide the proper support and help.

Three commonly used frameworks are listed below (Segnestam, 2002):

1. The Input-Output-Outcome-Impact framework, which is used in the monitoring of the effectiveness of projects. Indicators are structured in terms of inputs, outputs and the overall project objectives.
2. The UNCSO's framework based on environmental (or sustainable development) themes, in which indicators are organised according to Major Areas, Themes and Sub-themes "(...) to support policy-makers in their decision-making at a national level" (UNCSO, 2000).
3. A series of frameworks for environmental reporting and monitoring at local, regional, national, and international levels proposed by various organisations. Relevant examples are the PSR scheme (Pressure – State – Response), adopted by the Organisation for Economic Co-operation and Development (OECD, 1994), the DSR system (Drivers, State, Response) proposed by the Commission on Sustainable Development of the United Nations (UNCSO, 2000) and the DPSIR framework (Driving Force – Pressure – State – Impact – Response), developed by European institutions: the EEA and Eurostat (EEA, 1999).

The DPSIR framework is broadly adopted, and many countries find it useful for state of the environment reporting. Core lists of environmental issues – and of relevant pressure-state-response indicators – have been, and are being, developed by several organisations to do this, building on initial work by the OECD. Italy, for example, publishes a national state of the environment report using this framework every two years, and is setting up a national monitoring system along the same lines.

A framework for organising the selection and development of indicators is essential. Nevertheless, it must be recognised that any framework, by itself, is an imperfect tool for organising and expressing the complexities and interrelationships encompassed by agri-environmental policies and, more generally, all the policies inspired by the principles of sustainable development. Frameworks can therefore be considered as a basis for analysis, to be inte-

grated into a structured assessment approach, defined for a specific use: e.g. for the evaluation of agri-environmental measures.

2.2 Models for the analysis and assessment of agricultural systems

Once indicators have been selected and structured in a manner that facilitates their interpretation, analysis may follow, in order to provide insights into the dynamics and interrelationships of phenomena to be investigated within the agricultural socio-ecosystem. Analytical tools for such a purpose range from mathematical models (e.g. basin scale hydrologic modelling), and Geographical Information Systems, to various forms of economic analyses, such as cost benefit analysis, risk-benefit analysis, or multi-criteria analysis methods.

Modelling provides descriptions of the inputs, outputs and processes of the systems under study (which may in turn provide quantitative values for the selected indicators) and allows for simulations of present, past or future states of the system, according to previously defined scenarios. Analyses, and thus models, support the assessment of agri-environmental issues, such as in the case of the Environmental Impact Assessment of alternative production systems (Heller and Keoleian, 2003), or in the context of – strategic or tactical – decision making, or for the assessment and evaluation of policy effects (*ex ante*) and/or effectiveness (*ex post*). In all these cases the knowledge of the causality between human activities (management systems, strategies, and policies) and their impacts on the outside world is required, and so are conceptual frameworks in which models of various kinds provide simulations and quantifications of indicator values. The ability to analyse "what if?" scenarios is essential in all cases, to understand past and current developments, to anticipate the future and to evaluate strategies.

The process of identifying effects is based upon scientific and social observation and analysis. Integrated Assessment Modelling (IAM) allows to link the mathematical representations of different components of natural and social systems (Risbey et al., 1996) at local, regional or global levels. Regarding the social aspects, a recent resource book on Sustainable Development Strategies (Dalal-Clayton and Bass, 2002), draws attention to the importance of including stakeholder analysis within the as-

assessment process. Such analysis, strongly supported by most of the recent European policies (see for instance Article 14 of the Water Framework Directive; EC, 2000) consists of the objective identification of stakeholders, their interests, powers and relations, and, in general of their involvement throughout the process of decision/policy making.

As previously stated, the assessment of agri-environmental issues typically involves the analysis of alternative options: scenarios, measures, policies, management systems. Agri-environmental indicators and models thus become functional for exploring, evaluating and possibly choosing, within a discrete or continuous set of alternative solutions to the given problem. In order to support the choice between alternative options, many methods have been proposed, that quite often belong to the broad category of Multi-Criteria Analysis (MCA) methods (Belton and Stewart, 2002). These methods are basically based on a mathematical procedure, which associates an index of attractiveness to each option, depending on the estimated values of the indicators providing quantification to the multiple criteria to be considered and on the subjective values of those participating in the evaluation.

In synthesis, a generic process aimed at agri-environmental assessment can thus be designed as the result of the integration of analytical modelling tools framed within a conceptual framework describing cause-effect links and correlations, and providing adequate information in the form of indicators, which provide in turn the quantification to a comprehensive set of decision criteria to be processed (for example by means of MCA methods), in order to provide judgements and/or choice between a set of alternative options. The vast majority of the papers examined and presented later in this paper can be ascribed to part or to the whole assessment scheme described above.

3. Literature review methods and criteria

The bibliographic review was conducted on different databases providing access to on-line refereed journals: ISI Web of Knowledge (CAB Abstract, Web of Science, Inspec), AGRIS, FSTA and Science direct. Papers were extrac-

ted according to combinations of keywords and filtered in order to select papers of the period 2000-2005.

The following keywords were utilised for searching in the contents of the paper title, abstract and keywords. Below is the list of keyword combinations, with the number of papers found included in brackets:

- indicator AND model AND environment (172);
- agro-ecological AND indicator (AEI) (70);
- agri-environment AND indicator (84);
- agri-environment AND model (127);
- agri-environment AND indicator AND model (13);
- environment AND indicator AND model (286);
- environment AND indicator AND model AND agri* (79);
- environment AND model AND indicator AND impact assessment (10);
- farm model AND environment (5);
- sustainable rural development (17);
- sustainable rural development AND model (20);
- sustainable agriculture AND indicator (30);
- sustainable agriculture AND model (51);
- sustainable agriculture AND model AND indicator (9).

A first screening of the articles was based on the contents of the abstracts. Selected papers were read and evaluated considering their specific aims, and those relevant for agri-environmental assessment, with a relevant role played by indicators and models, were retained.

A total of seventy articles were selected and stored in a bibliographic database by means of the Endnote® software.

The papers were subsequently catalogued according to the following criteria:

- the main topic, i.e. the environmental compartment considered;
- the source(s) of environmental externalities analysed;
- the main methodological approach, i.e. models and/or indicators;
- the spatial scale;
- the geographical area considered;
- the disciplinary approach(es) of the assessment.

Table 1 shows the papers classified according to these criteria. Three environmental compart-

ments were considered: i) water, subdivided into quality and quantity, ii) soil and iii) air; "multiple" environmental compartment is attributed to those papers that have an integrated approach considering at least two compartments and/or considering the topic discussed in a more comprehensive manner without focussing on a single compartment.

The environmental externalities considered, and in particular the impacts discussed in the selected articles, were categorised as follows: water, soil, nutrients, pesticides, energy, biodiversity.

Papers were also classed in three groups based on their methodological approach, i.e. whether they either utilised or proposed models, indicators or comprehensive indices. A column of Table 1 also shows the acronym of the approach or tool present in the papers, in order to facilitate the identification of the contents.

The papers are further classified according to the scale at which the work is presented, by adopting the following possible levels: field, farm, landscape, catchment, region, and nation. A column in Table 1 shows the geographical area of reference.

The last classification criterion adopted and reported in Table 1 refers to the disciplinary approach of the papers: technical, environmental, economic or social, with the last category also including those papers focusing on the externalities affecting human health.

4. Results of the review according to the classification criteria

4.1 Environmental compartments

The first classification criterion was the main topic of the papers in terms of environmental compartments. Four categories of papers were identified, according to the environmental compartment they dealt with:

1. Water (quality and quantity).
2. Soil.
3. Air; or.
4. Multiple.

The vast majority of papers examines one or more compartments, thus focusing on the different kinds of environmental externalities produced by agricultural systems at various scales. Most papers focus on the impacts of agricultural activities on water resources and in particu-

lar on the chemical processes causing diffuse pollution phenomena. Nutrients (nitrates in particular) and pesticides releases are considered for the assessment of water quality in the majority (41) of papers. Half of them deal only with water quality, focusing on nutrients, while six of them deal with pesticides. One example of integrated approach dealing with both nutrients and pesticides can be found in Arondel (2000). In that case MCA methods are applied (ELECTRE TRI method) to analyse jointly the two sources of pollution, together with other indicators, for the assessment of environmental impacts of alternative cultivation systems on groundwater. Five papers deal with water from a quantitative viewpoint, in particular irrigation systems are considered.

Water quality and quantity are considered together in a study about the assessment of agricultural pressures on landscape ecological functions (Freyer, 2000) and also in a work focusing on rural planning integrated in a GIS modelling tool (Herrmann and Osinski, 1999). In both cases also the soil compartment was studied.

Many papers consider multiple compartments and 31 provide an integrated approach in which water quality issues are analysed jointly with other impacts, e.g. on biodiversity. The broader concept of sustainability analysis is also applied with an integrated approach in three papers, including variables regarding nutrients (Tzilivakis, 1999; Rao et al., 2000); and pesticides (Tzilivakis, 2004).

Agricultural impacts on the soil are discussed in 16 papers, while eight focus on air quality indicators. Only in two papers the soil compartment is considered alone (Huffman et al., 2000; Simota et al., 2005), and the focus is on the physical processes affecting land quality and erosion, respectively.

In three papers water quality, soil and air indicators are considered together (Bockstaller, 1997; Gutsche and Rossberg, 1997; Abrahamsen and Hansen, 2000).

As previously stated the processes analysed are mainly chemical pollution processes due to nutrients and pesticides, but also biological processes related to biodiversity. The exploitation of resources (utilisation and impact on natural resources and energy consumption) are also examined. The physical processes considered are related to erosion, water and land quality

but find limited attention in the papers examined. One of them is about water depletion with the Life Cycle Assessment (LCA) methodology (Heuvelmans et al., 2005), another one deals with land quality assessment, trying to identify trends in soil cover, wind erosion and soil salinity (Huffman et al., 2000). Finally, erosion is considered by the SIDASS model, utilised to predict losses due to mechanical and hydrologic processes (Simota et al., 2005).

Papers focusing on the analysis of agricultural impacts can be grouped as follows:

- nutrients (20 papers);
- pesticides (11 papers);
- biodiversity (7 papers);
- sustainability in general (7 papers).

Five papers dealing with nutrients consider also other impacts, particularly those related to pesticide inputs in three papers (Bockstaller, 1997; Arondel, 2000; Halberg et al., 2005). The other two works deal with resource utilisation and heavy metals in the Netherlands (Halberg, 1999; Stein et al., 2001).

Two papers propose an energy indicator (I_{En}) (Pervanchon, 2002) while another (Halberg, 1999) deals with energy consumption but also with resource utilisation and environmental impact.

4.2 Methodological approach

The various authors adopt very diversified approaches for agri-environmental assessment, that can be grouped in two main types, not always clearly distinguished:

1. Indicators and indices.
2. Models.

According to this classification criterion, 27 papers deal with indicators, while 37 present approaches based upon the use of simulation models. Several papers use the terms indicator and index without a clear distinction between the two, and two of them propose indices, as intended in this work, as the result of the combination of a set of aggregate or weighted indicators.

Regarding the temporal dimension, the majority of papers propose a static approach, while only thirteen are dynamic. Indicators are in general static, while models are often dynamic and continuous. Two papers provide a literature review dealing with the importance of the temporal dimension in general (Smith and McDonald, 1998; Haag and Kaupenjohann, 2001).

Another useful criterion for classifying the papers is the type of process description and algorithms in which models can be grouped into: rule-based, empirical (statistical), causal (analysis of causes and effects): a clear distinction is often difficult, but 27 papers can be grouped as empirical (statistical), 10 as rule-based and 5 as causal.

4.3 Spatial scale

A great diversity of spatial scales was found in the literature examined. Only two papers are at national scale, one presents the application of a simulation model for bioenergy from agricultural products (De La Torre Ugarte and Ray, 2000) and another one is about the development of a comprehensive environmental indicator system for Germany (Walz, 2000). Three papers focus specifically with the regional scale, two adopting a modelling approach and the other one presenting a risk indicator (see Table 1).

Several papers approach agri-environmental issues at multiple scales. One of them considers a model for planning suitable land use with an holistic approach at different spatial levels from national to local (Herrmann and Osinski, 1999). The SIDASS model, a tool for recommendations of site-specific land use and management practices and for the evaluation of agriculture policies, is presented for use at the local and regional scales (Simota et al., 2005). The landscape indicator " I_{land} ", proposed by Weinstoerffer (2000), can be applied at the catchment scale and also to small regions, to evaluate impacts of land use patterns and intensities on the landscape. The TIM (Threat Identification Model) utilises different types of information at different scales: field scale for information about land unit, farm scale for socio-economic analysis, while other biophysical and socio-economic analyses of land use are examined at the catchment scale (Smith et al., 2000).

Six papers specifically approach agri-environmental assessment at the catchment, or river basin, scale. Five of them adopt models, and only one proposes an indicator. In one paper, DSIRR, a DSS focussing on irrigation, is proposed to consider the problem both at the farm and catchment scales and also touches the issue of up- and down-scaling (Bazzani, 2005).

Seven papers focus on landscapes as a spatial unit, four of them are about indicators, the

others are about models, while a remarkable number of papers (21) form a “farm scale” group, with a rather balanced use of models or indicators, most of them focusing on the management and impacts of nutrients and pesticides (see Table 1 for details).

Twelve papers analyse phenomena with the detail of the field scale and several of them aggregate the data to provide a synthetic characterisation of the whole farm. Examples can be found for biodiversity issues in Brabant et al. (2003), Girardin et al. similarly propose the comprehensive AGRO*ECO indicator set for farm sustainability assessment with calculations made at the field level (Girardin et al., 2000), while Pervanchon proposes two studies on an energy indicator (I_{En}) evaluating the environmental impact of arable farming systems helping the management of energy input at the field level (Pervanchon, 2002), and an environmental indicator related to nitrogen releases ($I_{N\ losses}$) for risk assessment (Pervanchon et al., 2005).

4.4 *Disciplinary approach of the assessment*

All the papers selected provide analyses and assessments from the environmental viewpoint except for one focused only on human health, i.e. the Agroenvironmental hygienic pressure indicators (AHPs) considering the microbiological impacts on water quality (Bigras-Poulin et al., 2004).

The majority of papers are not limited to environmental assessment and adopt a multi-disciplinary perspective, by combining technical or socio-economic components, but only four papers present a comprehensive multi-disciplinary approach including technical, environmental, and socio-economic analyses, at spatial scales broader than the farm. It is worth mentioning the review for the development of an holistic approach for pesticide assessment (Levitan et al., 1995), the holistic approach proposed in a GIS context for sustainability assessment in Germany (Herrmann and Osinski, 1999), and the decision support tool “AgFutures” for exploring alternative futures for agricultural sustainability (Sharma et al., 2006).

4.5 *General remarks about the contents of Table 1*

Some general considerations could be made with a synoptic analysis of the contents of Ta-

ble 1. First of all a comparison of the scales and approaches clearly shows that models are used at detailed scales while indicators are preferred in broader geographical contexts.

The same number of papers dealing with impacts on biodiversity or sustainability was examined, and within this group, the combination of multi-disciplinary approaches based upon indicators is clearly preferred. Multiple environmental compartments are also examined, as logically required when biodiversity and sustainability issues are considered. The reasons why there is a preference for indicators instead of models when dealing with those issues can be twofold: on the one hand, given the complexity of the issues, indicators may provide the means for synthesising information and communicating the results to a broader audience; on the other hand, the complexity itself may limit the possibility of developing comprehensive mechanistic models.

Papers that focus on the impacts of nutrients and pesticides are generally at farm or field scale, which are the scales at which farmers take strategic and tactical decisions regarding the management of agro-chemicals. At higher scales these sources of impact are usually considered from a different perspective, in relation to policy makers and with the aim of supporting decisions at different levels, in a more comprehensive manner.

Considering the water quality environmental compartment, indicators are applied in only 26% of papers. Given the above, one could deduce that this theme is adequately covered by a wealth of modelling approaches. Along this line a further consideration could be made regarding the high number of modelling approaches proposed, which do not correspond to a parallel diversity of theoretical approaches, thus evidencing some sort of redundancy in the efforts to provide modelling tools which are built upon the same theories and, in many cases, the same algorithms.

5. **A proposed categorisation according to IRENA**

In order to provide an interpretation of the significance of the indicators proposed for the IRENA initiative, aimed at defining an indica-

tor framework at the European level, papers were further classified according to the five IRENA groups listed below:

- agricultural water use;
- agricultural input and the state of water quality;
- agricultural land use, farm management (practices) and soils;
- climate change and air quality;
- biodiversity and landscape.

Climate change and air quality is the group with fewer papers, because the key words utilised for the literature search were not suitable to select papers that deal specifically with those issues. One paper by Pervanchon focuses specifically on energy use and can be attributed to this group (Pervanchon, 2002), other papers, attempting the analysis of agricultural systems also approach the issue from a holistic perspective, for example greenhouse gases emissions (Huffman et al., 2000).

For the same reason only three papers can be categorised in the *Agricultural water use* group: the DSIRR model to assess the sustainability of irrigated systems (Bazzani, 2005; Bazzani et al., 2005) providing the estimation of indicators to optimise crop water needs and land use, and quantifying other aspects related to pesticide risk, nitrogen, energy and socio-economic performances (income, public support, value added, farm employment); and a work that utilised the LCA (Life Cycle Assessment) methodology to deal with improvements of methods for water management issues at farm level, with indicators related to water inputs and outputs for the regional water balance (Heuvelmans et al., 2005).

Twelve papers regarding the literature proposals for indicators and models about *Agricultural land use, farm management (practices) and soils*, should be mentioned and are reported in Table 2. In order to contribute to the assessment of agricultural practices and the identification of suitable farming systems, useful materials can be found in the ecological and hydrological indicators proposed by Aspinall and Pearson (2000) at the catchment scale, in the STICS model (Brisson et al., 2003), in the AGRO*ECO method (Girardin et al., 2000) to assess the potential impact of agricultural practices on the environment utilising agro-ecological indicators to simulate crop growth, water and nitrogen ba-

lances. A wide list of indicators can be found in Halberg (1999) for analysing surplus and efficiencies of N, P, Cu, energy, and pesticides. Other sets of multi-sectoral indicators can be found in Herrmann and Osinski (1999) which support the planning of sustainable land use to define the potentials and sensitivities of regions, while the Policy Analysis System (POLYSYS) is a simulation model providing indicators in support of national biomass and bioenergy policies (De La Torre Ugarte and Ray, 2000). Other approaches to support policy at various scales can be found with specific reference to developing countries (Morrison and Pearce, 2000), or for the assessment of the effects of agri-environmental schemes of the E.U. (Primdahl et al., 2003), or for sustainability assessment in general (Smith et al., 2000).

Indicators related to land quality and resources management find rather comprehensive proposals in Huffman et al. (2000), while the SIDASS simulation model allows the simulation of soil physics dynamics (Simota et al., 2005).

Biodiversity and landscape indicators can find many interesting references in the selected literature. One work analyses seven tools considering relevant indicators subdivided into action-oriented and results-oriented indicators for bio-resource assessment (Braband et al., 2003) and state-of-the art development of biotic indicators is presented in Buchs (2003). Biodiversity can be assessed with species richness or quality of species communities, also considering changes in dominance positions (accompanied by a shifting of body size). Suitable habitat areas for threatened bird species are identified with two predictive models producing a map of habitat suitability by Bayliss et al. (2005). Several models assess agricultural pressures to landscape ecological functions and biodiversity by utilising resource indicators (Freyer, 2000; Freyer et al., 2000), or bioindicators (Jeanneret et al., 2003), or for scenario analysis (Gomez-Sal et al., 2003) with five assessment dimensions, ecological, productive, economic, social and cultural. (Hanley et al., 1999) Agri-environmental policy assessment for biodiversity conservation is proposed by means of an integration of ecological and economic models (Oglethorpe and Sanderson, 1999) or with a set of (OECD) indicators (Piorr, 2003), or with an aggregated sustainability index (Rigby et al., 2001; Sands and Podmore,

Table 2. Classification of the literature according to the Irena categories of indicators.

IRENA		References (Authors Year)
Number	Indicators	
<i>Agricultural water use</i>		
10	Water use (intensity)	
22	Water abstraction	
31	Ground water levels	
28	Population trends of farmland birds	Bazzani G.M. 2005; Bazzani G.M. et al. 2005
34.3	Share of agriculture in water use	
1	Area under agri-environment support	
2	Regional levels of good farming practices	
<i>Agricultural input and the state of the water quality</i>		
8	Mineral fertiliser consumption	Archer D.W. et al. 2001; Ares J. 2004; Arondel C. et al. 2000; Berenzen N. et al. 2005; Berka C. et al. 2001; Bigras-Poulin M. et al. 2004; Brown C.D. et al. 2003; Collentine D. et al. 2004; De Smet B. et al. 2005; Ekholm P. et al. 2005; Gömann H. et al. 2005; Gutsche V. et al. 1997; Hansen B. et al. 2000; Hart A. 2003; Heathwaite A.L. et al. 2005; Heuvelmans G. et al. 2005; Kookana R.S. et al. 2005; Kyllmar K. et al. 2005; Levitan L. et al. 1995; Schou J.S. et al. 2000; Schröder J.J. et al. 2003; Schröder J.J. et al. 2004; van Beek C.L. et al. 2003
9	Consumption of pesticides	
13	Cropping/ livestock patterns	
18	Gross nitrogen balance	
20	Pesticide soil contamination	
30	Nitrates/pesticides in water	
34.2	Share of agriculture in nitrate contamination	
1	Area under agri-environment support	
2	Regional levels of good farming practices	
3	Regional levels of environmental targets	
7	Area under organic farming	
<i>Agricultural land use, farm management (practices) and soils</i>		
12	Land use change	
13	Cropping/livestock patterns	
14.1	Farm management (practices) – tillage	Aspinall R. et al. 2000; Brisson N. et al. 2003; Girardin P. et al. 2000; Granlund K. et al. 2000; Halberg N. 1999; Herrmann S. et al. 1999; Huffman E. et al. 2000; Koo B.K. et al.; Lewis K.A. et al. 1998; Morrison J. et al. 2000; Primdahl J. et al. 2003; Simonta C. et al. 2005
14.2	Farm management (practices) – soil cover	
21	Use of sewage sludge	
24	Land cover change	
23	Soil erosion	
29	Soil quality	
1	Area under agri-environment support	
2	Regional levels of good farming practices	
7	Area under organic farming	
<i>Climate change and air quality</i>		
11	Energy use	
13	Livestock patterns	
8	Mineral fertiliser consumption	
14	Farm management (practices) — manure management	
18sub	Atmospheric emissions of ammonia from agriculture	Pervanchon F. et al. 2002
19	Emissions of methane and nitrous oxide from agriculture	
34.1	Share of agriculture in greenhouse gas emissions	
3	Regional levels of environmental targets	
27	Production of renewable energy (by source)	
<i>Biodiversity and landscape</i>		
12	Land use change	
15	Intensification/extensification	
16	Specialisation/Diversification	Bayliss J.L. et al. 2005; Braband D. et al. 2003; Büchs W. 2003; Büchs W. et al. 2003; De la Torre Ugarte D. et al. 2000; Freyer B. et al. 2000; Gómez-Sal A. et al. 2003; Haag D. et al. 2001; Hanley N. et al. 1999; Jeanneret P., et al. 2003; Oglethorpe D.R., et al. 1999; Onate J. J. Et al. 2000; Piorr H.-P. 2003; Rigby D. et al. 2001; Sands G.R. et al. 2000; Sharma T. et al.; Smith C.S. et al. 1998; Smith C.S. et al. 2000; Tzivilakis J. et al. 1999; Weinstoerffer J. et al. 2000
17	Marginalisation	
13	Cropping/livestock patterns	
24	Land cover change	
25	Genetic diversity	
28	Population of farmland birds	
26	High nature value (farmland) areas	
32	Landscape state	
33	Impact on habitats and biodiversity	
35	Impact on landscape diversity	
1	Area under agri-environment support	
2	Regional levels of good farming practices	
4	Area under nature protection	
7	Area under organic farming	

2000), or with a decision support tool that allows a systematic comparison of consequences of alternative futures through different indicators (Sharma et al., 2006). Relationships between landscapes, biodiversity and land use are examined by various authors, at various scales (Onate et al., 2000), in support to sustainability planning (Smith and McDonald, 1998), or considering supply in terms of the services offered by farmers and demand by social groups of beneficiaries (Weinstoerffer, 2000).

The most numerous group references can be referred to the IRENA classification, *Agricultural input and the state of the water quality* finding literature dealing with nutrient impacts on surface or groundwater, in particular concerning nitrogen, but also about pesticides. Eleven papers deal about nutrient impact, ten about pesticide and only one deals about both impacts. There is only one paper that deals about microbiological risk subsequent to livestock activities. A brief presentation of papers subdivided into the previous subgroups follows.

Eleven papers about nutrients and the state of water quality should be mentioned, most of them dealing with nitrogen and only two focusing on phosphorus. Nitrogen fluxes and emissions are considered at different scales in the review paper provided by Haag and Kaupenjohann (2001). The papers present diversified solutions with varying complexity: the SOIL-N (Granlund et al., 2000) and SOILNDB (Kyllmar et al., 2005) models are proposed for the calculation of nitrate leaching resulting from changes in cultivation practices, similar solutions can be found in Hansen et al. (2000), while a combination of integrated modelling and multi-criteria analysis (MCA) methodology is used for the multi-disciplinary assessment of alternative land uses (Koo and O'Connell, 2006). Spatial heterogeneity is analysed by Heathwaite et al. (2005) at the field scale, while at broader scales a GIS combined with nutrient mass balance is proposed (Berka et al., 2001), or LENNART, a net-based DSS (Collentine et al., 2004), or the integration of hydrological models (GROWA and WEKU) with an economic one (RAUMIS) in order to analyse policy options to reduce the diffuse pollution of nitrogen (Gomann et al., 2005). Another paper (Schou et al., 2000) focuses on economic instruments and presents two types of nitrogen taxes, compared with co-

st-effectiveness analysis considering different scenarios.

The effects of nutrient losses (N and P) on ground and surface water quality are discussed with indicators at various levels (e.g. livestock number, total nutrient input or surplus, water quality at different level, atmospheric quality, ecosystem quality) by Schroeder et al. (2004). N and P balances are approached at various levels, in particular at "farm gate" and soil surface to calculate nutrient surplus as a proxy of risk potential over various nutrient loss pathways (van Beek et al., 2003). The only paper examined dealing only with P, presents mass balance calculations to examine potential diffuse losses (Ekholm et al., 2005) and focuses on the role played by soil analyses of available P as an indicator useful for reducing P inputs.

A review of pesticide impact assessment approaches can be found in Levitan et al. (1995), but more recently many other proposals have been published. One of them is an integrated approach focusing on risk-indexed herbicide taxes (Archer and Shogren, 2001) with the CEEPES modelling approach. Similarly, Ares proposes a fugacity model for the integrated scenario analysis of crop re-conversion in Argentina (Ares, 2004). Many modelling solutions with a great diversity of complexities and degrees of empiricism are proposed to predict pesticide concentrations in the various environmental compartments: the OECD "simplified formula for indirect loadings caused by runoff" (Berenzen et al., 2005), the p-EMA(I) risk assessment system (Brown et al., 2003) and p-EMA(II) model (Hart, 2003), the risk indices LI, EYP, REXTOX and SyPEP (De Smet et al., 2005), the indices sPEC (short-term predicted environmental concentration) and IPEC (long-term predicted environmental concentration) (Gutsche and Rossberg, 1997), or the indicator-based risk assessment package proposed by Kookana et al. (2005), or the indicator approach presented in Lewis and Bardon (1998).

6. Conclusions

The literature examined evidences the availability of a great wealth of methodological proposals in different contexts and scales, which could all be framed within the broader multi-discipli-

nary context of sustainability science, thus providing the theoretical background for:

- the identification of indicators and their role in agri-environmental assessment;
- the development of common conceptual frameworks;
- the role of analytical tools relying on the use of models and indicators that are best selected through the use of sound conceptual frameworks;
- the definition of integrated assessment approaches.

The 4-step process described above may contribute to provide methodological support to cope with the problem mentioned above, focusing in particular on:

- the complexity of decisional contexts typical of agri-environmental issues;
- the large amounts of multi-sectoral and multidisciplinary information;
- the need for efficient communication between the scientific and the policy sectors and between decision/policy makers and the stakeholders involved.

The papers presented in this review deal in general with the relationships between agricultural systems and the environment, but given the keywords selected for the literature search, they tend to focus more on diffuse pollution, biodiversity and landscape. Other relevant themes for a comprehensive sustainability assessment are thus set aside, in particular those related to air pollution and climate change and resource depletion from a quantitative viewpoint.

It is worth noticing the high number of modelling approaches proposed, which do not correspond to a parallel diversity of theoretical approaches, thus evidencing some sort of redundancy in the efforts to provide modelling tools which are built upon the same theories and, in many cases, the same algorithms.

Finally, a remark should be made about the relationships between research and policy, and in particular the issues related to the potential usefulness of the proposed approach which is functionally linked to some aspects that are not always deeply considered in the scientific literature, namely, the ease of communication, the transparency of the algorithms, the potentials for misuse, the reproducibility, in general the credibility of those research efforts in order to support improved practices in decision and policy making and planning.

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