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Review

Environmental impact assessment for a farming region: a review of methods

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Abstract

The methods currently used for assessing the environmental impact of agriculture on the scale of a farming region cover a wide range of objectives, users and concepts. To illustrate this variety, this article provides an analysis of six main types of method: environmental risk mapping, life cycle analysis, environmental impact assessment, multi-agent system, linear programming and agro-environmental indicators. Eleven case studies, in which one of the six methods was applied, are used as data in this review. All methods are based on a set of environmental objectives. Some methods also take account of economic and social objectives to produce a more wide-ranging assessment of the sustainability of the agricultural system studied. Each method relies on indicators serving as criteria to evaluate whether the objectives have been attained. These indicators take account of local impacts such as noise, regional impacts such as eutrophication, or global impacts like the greenhouse effect. The characteristics required to develop a method for the environmental impact assessment of a farming region are discussed. The analysis of the interactions between farms is indispensable at this scale of analysis. Indicators based on the environmental effects of farming practices should take precedence over those based on the practices themselves, which do not provide a direct evaluation of environmental impact. Indicators which express an impact both per kg of product and per unit of land area used bring together the essential functions of agriculture, namely production and the occupation of the countryside. The assessment methods should include an analysis of the uncertainty associated with the results. Lastly, the method should be validated with respect to (i) the conception of the method and its indicators, (ii) the consistency of the values of the indicators in relation to observed values, and finally (iii) the suitability of the indicators and more generally of the assessment method for the end users.

Keywords: Farming region; Evaluation methods; Sustainability; Environmental risk mapping; Life cycle assessment; Environmental impact assessment; Multi-agent system; Linear programming; Agro-environmental indicators

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1. Introduction

To be sustainable, an activity must be viable from both an economic and an environmental point of view, fair at the economic and social level, and tolerable from the social and environmental point of view (Barbier, 1987). From the environmental point of view, a farming activity is sustainable if its polluting emissions and its use of natural resources can be supported in the long term by the natural environment. Diagnosis of the environmental impact of agriculture therefore constitutes the first step in the overall assessment of the sustainability of agriculture. The environmental impact of agricultural activity can be analysed on a range of spatial scales, from the field to the national or indeed the supranational scale (OECD, 2001a). At each spatial scale there are favoured methods of assessment. The field or livestock building constitutes the basic unit of action of a farm. At this level farmers aim to optimise production, whilst minimising inputs and polluting emissions from a field (Benoît, 1992) or from a livestock unit (CORPEN, 2003).

The farm is the main management unit of the agricultural system. The variety of environmental assessment methods proposed at the farm level (van der Werf and Petit, 2002), illustrates the need for diagnosis at this scale. Methods for assessing a farm are based either on a synthesis of the results from individual fields (Benoît, 1992) or else on an approach to the farm as a whole, such as the nitrogen balance approach (Kristensen et al., 2003; Schröder et al., 2003).

At a higher level, the term ''regional evaluation'' of agriculture is used. A farming region[1] is an identified geographic entity, differentiated and structured by the activities and the social groups which occupy it and interact there (Papy, 2001). The geographical limits of a farming region are consequently extremely variable (from the scale of the landscape to the supranational scale), as they depend on the political, economic, social and environmental factors considered (Lemaire et al., 2003). The regional assessment of the environmental impact of agriculture is often associated with an evaluation of economic sustainability (Pretty et al., 2000). The latter can integrate macroeconomic and regulatory constraints and the assessment of the cost of environmental impacts.

Passing from the level of the farm to that of a farming region requires surveys, either exhaustive (by combining assessments of all farms concerned) or partial, defining a farm type classification, which will allow the results of a survey of a sub-set of farms to be extrapolated. Depending on the approach, the farming region thus considered may cover from several hundred hectares to several thousand square kilometres.

Analysis on the regional scale can allow the study of relationships, communication and competition between farms. In fact, these interactions constitute an emerging property of agriculture at this scale (Cristofini, 1985). Consequently, the evaluation of the environmental impact of a farming region cannot be reduced to the sum of the evaluations for each farm (von Wiren-Lehr, 2001). This scale therefore allows us to study the positive or negative impact of interactions between farms on the emissions of pollutants and on the consumption of resources in the geographical zone studied (Nielsen, 1999; Lemaire et al., 2003). Such interactions may consist of exchanges of services (e.g. field operations), exchanges of products (grain, straw, fodder, manure) or shared equipment for product transformation or waste treatment.

The object of this article is to analyse the different methods for evaluating the environmental impacts of a *farming region*; that is to say a set of farms in a given geographical zone. The analysis of the different methods is based on the concepts used, the objectives considered, the potential users, the type of indicators used and a consideration of the spatial and temporal variability of different impacts. This is followed by some thoughts about the necessary elements of an environmental assessment at the scale of a farming region.

[1] In France, the term ''farming territory'' is often used.

2. Description of the approaches

A review of the methods for assessing the environmental impact of a farming region reveals a wide diversity of approaches from the point of view of objectives, concepts and potential users. To analyse this diversity, six types of method for assessing environmental impact and eleven case studies, in which one of the six methods was applied, have been selected (Table 1). Although not intended to be exhaustive, these six types enable us to cover a wide range of the methods frequently used. The assessment of the environmental impact of agriculture is the main purpose of these methods. The economic and social components of sustainability can also be evaluated with some of the approaches (Table 2). First an approach based on mapping (ERM) will be presented, followed by two formalised environmental assessment approaches (LCA and EIA) and two optimisation approaches (MAS and LP), and finally a group of approaches based on indicators (AEI).

2.1. Environmental risk mapping (ERM)

In this approach, the objective is to define an environmental risk associated with the farming practices of a region (ERM-1 and ERM-2, Table 1). ERM approaches are based on the idea that the environmental risk results both from human pressure and from the vulnerability of the environment. By human pressure we mean the occupation of land for farming, farming practices and pollutant emissions. Only the environmental aspect of sustainability is usually considered in this approach. ERM approaches generally deal with a single environmental impact, such as the risk of nitrate leaching (Assimakopoulos et al., 2003), the transfer of phosphorus (Bouchardy, 1992) or of pesticides (Finizio and Villa, 2002).

The risk is characterised by a combination of variables, indicators or simulation model results considered relevant to the phenomenon studied

Table 1
Six methods for regional environmental impact assessment, and case studies used for the analysis and comparison of these methods

Method	Case studies author(s)	Object and scope
ERM: environmental risk mapping	ERM-1: de Koning et al. (1997)	Modelling of the soil nutrient balance as a sustainability indicator: nation scale (Ecuador)
	ERM-2: Giupponi et al. (1999)	Modelling impacts on water quality of alternative land use scenarios with the GLEAMS model and calculation of environmental impact indices: lagoon of Venice catchment (Italy)
LCA: life cycle analysis	LCA-1: Biewinga and van der Bijl (1996)	Evaluation of ecological and economic sustainability of energy crops using a range of indicators, mainly based on LCA: Europe
	LCA-2: Geier and Köpke (1998)	Evaluation of a complete conversion from conventional to organic farming using LCA: extrapolation at the rural area scale (Germany)
EIA: environmental impact assessment	EIA: Rodrigues et al. (2003)	Evaluation of the sustainability of agricultural technology innovation by the EIA method: Field-Farm (Brazil)
MAS: multi-agent system	MAS-1: Petit et al. (2001)	Evaluation of the quantity and quality of groundwater by using hydrological, agronomic and socio-economic models in a multi-agent system: Beauce aquifer (France)
	MAS-2: Becu et al. (2004)	Modelling the impact of catchment irrigation management under social and agronomic constraints in a multi-agent system: catchment scale (Thailand)
LP: linear programming	LP-1: Zander and Kächele (1999)	Optimisation of different production systems described at the farm level with multiple goal linear programming: extrapolation to a regional scale (Germany)
	LP-2: Hengsdijk and van Ittersum (2003)	Optimisation of different production systems to maximise the production targets whilst minimising impacts: farm or regional scale (Mali)
AEI: agro-environmental indicators	AEI-1: ECNC (2000)	Development of “Driving force”, “State”, and “Response” indicators for environmental impact assessment mainly at macro-level: European agriculture
	AEI-2: Rasul and Thapa (2004)	Evaluation of farming sustainability by ecological, economic and social indicators: micro-regions (Bangladesh)

Table 2
Intended users, sustainability dimensions considered and scale of impacts for 11 case studies of regional environmental impact assessment

Case studies	Characteristics intended users	Sustainability dimensions considered	Scale of impacts considered		
			Local[a]	Regional	Global
ERM-1[b]	Researchers and policy makers	Environment	+/0	+	0
ERM-2	Policy makers and local government	Environment	+	+	0
LCA-1	Researchers and policy makers	Environment and economy	+/0	+	+
LCA-2	Local government and farmers' advisors	Environment	+/0	+	+
EIA-1	Policy makers	Environment	+	+	+/0
MAS-1	Stakeholders: policy makers, farmers	Environment and economy	+	+	0
MAS-2	Stakeholders: policy makers, farmers	Environment, economy and sociology	+	+	0
LP-1	Researchers, local government and non-governmental organisation	Environment and economy	+	+	+/0
LP-2	Researchers and local government	Environment and economy	+/0	+	0
AEI-1	Policy makers and stakeholders	Environment and economy	+	+	+
AEI-2	Researchers and stakeholders	Environment, economy and sociology	+	+	0

[a] Symbols indicate the extent to which an effect is taken into account, +: effect is considered; +/0: effect is considered to a minor degree; 0: effect is not considered.
[b] See Table 1.

(Heathwaite, 2003). This kind of approach thus assumes routine use of Geographical Information Systems (GIS) to superimpose several sets of spatial information (Chen et al., 2001). The choice of techniques for weighting the different criteria used to evaluate the risk is a key stage in these approaches. These techniques can range from simple weighted linear combinations to fuzzy combination approaches (Assimakopoulos et al., 2003). This kind of assessment can be rapidly applied to obtain a qualitative characterisation of risk. However, the weighting techniques inevitably introduce an element of subjectivity into the mapping of risk.

2.2. Life cycle analysis (LCA)

The aim of this approach is to evaluate the environmental impact of the production, the use and the disposal of a product. The central concept of LCA is to combine, in a small number of indicators, the polluting emissions and resources utilised during the course of the life of a product. This method has been the subject of considerable efforts to standardise the calculation of impacts (ISO/DIS, 2000a) and the interpretation of results (ISO/DIS, 2000b). Originally developed for industrial processes, the use of LCA to evaluate the environmental impact of farming activity is growing, both for plant production (Mattsson, 1999; Brentrup et al., 2001) and animal production (Haas et al., 2001; Cederberg, 2002).

Generally, the environmental aspect is the only component of sustainability studied (LCA-2, Table 2). Economic and social viability can be partially analysed by including a production cost analysis and by estimating, for example, the number of workers involved in the production system (LCA-1, Table 2). Local, regional, and global impacts are considered, depending on the distance between the source of the emission and the area affected by each type of impact (LCA-1 and LCA-2, Table 2, Gaillard et al., 1997). Hence, smell and noise are regarded as local impacts, as they are perceptible over a few kilometres. Eutrophication and acidification are both local and regional, since they can affect the environment close to the source of the emission but also several hundred kilometres away from it. The greenhouse effect and the use of non-renewable energy constitute global impacts.

On the scale of the farming region, the overall environmental impact is often assumed to be equal to the sum of the impacts for each farm. In practice, a system of classification is often used us to extrapolate the results obtained at the farm scale to the level of the farming region by assuming uniformity of farmer practices and production systems within a class (Dalgaard et al., 2004). On the regional scale, the environmental impacts of a given crop can be assessed by relating specific emissions, expressed as quantities per ha, to the total area of the crop considered (Biewinga and van der Bijl, 1996).

2.3. Environmental impact assessment (EIA)

The main aim of this method is to assess the environmental impacts of a new localised pollution source, such as an industry or highway, on its surroundings. Applied to agriculture, EIA has been used to study the environmental impact of new cultural practices (EIA, Table 1). It can also be used as a way of alerting farmers in developing countries to the lack of sustainability of their practices (Duffy, 1992). The method rests on the concept that the impact of a human activity depends on the pollution associated with that activity and the sensitivity of the environment in terms of biodiversity, housing, tourism, etc. Like LCA, this method of environmental assessment is standardised and consists of several stages from the recording of the emissions to decision-making by the authorities. The three aspects of sustainability – environmental, economic and social – are taken into account, as one tries to evaluate the impact of a new activity on the environment, the population and the attractiveness of the neighbourhood of the site. From the environmental point of view, local impacts like noise, smell, dust or smoke production, and to a lesser extent regional impacts, are given priority (EIA, Table 2). Unlike the LCA approach, the global impacts resulting from the new activity are rarely taken into account (Lenzen et al., 2003).

2.4. Multi-agent system (MAS)

Applied to the environment, the objective of MAS approaches is to represent the behaviour of a group of users or other agents towards a limited resource (MAS-1 and MAS-2, Table 1). MAS approaches fall within the scope of this study because they attempt to determine whether the utilisation of a resource is sustainable, both from the environmental but also from the social and economic points of view. They are based on the concept that the behaviour of each agent towards the other agents and towards the coveted resource can be modelled. In agriculture, MAS can be used to study the impact of irrigation practices (MAS-2, Table 1) or the management of manure (Courdier et al., 2002). Compared with the three previous approaches, the analysis of the interactions between farms lies at the heart of the method. The three aspects of sustainability can be considered, since the interactions between agents can be analysed under economic, social and environmental constraints. This approach generally only takes account of a single environmental impact. Only local or regional impacts are analysed (MAS-1 and MAS-2, Table 2). To estimate the consumption of natural resources, this type of approach can include the use of models, for example to simulate changes in the level of a water table resulting from water extraction for agriculture (ERM-1, Table 1).

2.5. Multiple linear programming (LP) approaches

Applied to a farming region, this method aims to optimise the total production of the zone in relation to its technical options and economic and social aspirations, while minimising the environmental impact (LP-1 and LP-2, Table 1; Stoorvogel, 1995; Bouman et al., 1999). LP approaches are based on the concept that a farm can be described by a set of indicators which one tries to maximise or minimise according to the case. This approach involves three stages. First, each type of animal or plant production is described in terms of its inputs and its emissions as an input–output matrix (Stoorvogel, 1995). Next, a set of environmental, agronomic, social and economic constraints is defined to limit the possible management methods. Finally, linear optimisation techniques are used to find the management methods which maximise revenue and employment and minimise polluting emissions and use of resources, whilst satisfying the system of constraints. On the scale of the farming region, the application of LP approaches usually involves a classification of farms, in order to extrapolate the emissions of a sub-set of farms to the whole of the region studied. This type of assessment may include a single environmental impact such as erosion (Agrell et al., 2004), or several, such as pesticides, eutrophication and greenhouse gases (Bouman et al., 1998).

2.6. Agro-environmental indicators (AEI)

The aim of AEI approaches is to characterise the environmental impact of a farming system from a set of indicators (AEI-1 and AEI-2, Table 1). The use of agro-environmental indicators does not of itself constitute the definition of an evaluation method. In fact, the five methods already described depend on the calculation of indicators. The characteristic of AEI methods is that they provide a conceptual framework to define and bring together a set of agro-environmental indicators. In the ELISA approach (environmental indicators for sustainable agriculture) (ECNC, 2000), about 100 indicators are defined according to the Driving force – State – Response concept. The Driving force indicators characterise the positive or negative effects on the environment of agricultural activity linked to land use and to farming practices. The State indicators characterise the ecological state of different environmental compartments affected by agricultural activity. Finally, Response indicators can assess the response of society in regulatory terms to the state of the environment. Methods for combining indicators have been proposed, to obtain assessment criteria from several evaluation modules, such as in the AGRO-ECO method (Girardin et al., 2000).

The AEI approach is not standardised like EIA and LCA. It is not based on optimisation models like the LP approach or on a representation of the behaviour of the agents, as the MAS approaches. Finally, AEI approaches do not simply seek to determine an environmental risk by spatial analysis like the ERM approaches. Some indicators used in these approaches, such as contamination by pesticides, losses of nutrients or soil losses, can be obtained and mapped using ERM (ECNC, 2000). Economic indicators such as the cost/benefit of a crop or social indicators like food security can complement environmental indicators (OECD, 2001a; Rasul and Thapa, 2004).

3. Comparison of approaches

3.1. Users-target groups

The variability in environmental impact assessment methods may be explained by the very different objectives of the various users (Table 2). Thus the ERM approaches developed by research workers are mostly intended for policy makers and local government to improve the management of the risk associated with new farming practices (ERM-1 and ERM-2, Table 2; Assimakopoulos et al., 2003).

Scientists studying sustainable production systems, operators of the production chain, farmer's advisors and politicians (LCA-1 and LCA-2, Table 2; Bare et al., 2003) are the main users of the LCA approach. EIA approaches are mostly used by policy-makers (EIA, Table 2). MAS approaches aim to facilitate the dialogue concerning the management of a resource among a group of stakeholders, which may include farmers, local institutions, policy makers and research workers (MAS-1 and MAS-2, Table 2; Berger, 2001; Janssen, 2001). LP approaches were developed by scientists to provide policy-makers and Non-governmental Organisations with options for managing a farming region (LP-1 and LP-2, Table 2; Bouman et al., 1998; Agrell et al., 2004). Lastly, AEI approaches are meant to provide diagnostic tools, especially to policy makers, local stakeholders and research workers (AEI-1 and AEI-2, Table 2; OECD, 2001a).

3.2. Definition of objectives

The assessment of the environmental impact, or more generally, of the sustainability of a farming region involves, firstly, the definition of the objectives which should be achieved in order to create a sustainable system in environmental, social and economic terms (Girardin et al., 2000). The environmental objectives can be grouped into three classes—input related, emission related and system state related (van der Werf and Petit, 2002). According to the pressure–state–response classification of OECD (2001a), both input related and emission related objectives aim at reducing the pressure on the environment. These objectives aim respectively at decreasing the inputs and at reducing the pollutant emissions (Table 3). For MAS, LP and AEI economic and social objectives (yields, income, self-sufficiency and equity) are included in the analysis (MAS-1, MAS-2, LP-1, LP-2, AEI-1 and AEI-2, Table 3). The system state related objectives aim to preserve or improve characteristics of the environment such as biodiversity, soil quantity and water and air quality. This type of objective can be related to the state part of the classification by OECD.

ERM approaches are mainly based on a small number of emission related (ERM-1 and ERM-2, Table 3) or system state related objectives, notably for erosion problems (Sahin and Kurum, 2002).

Table 3
Environmental, economic and social objectives taken in account in 11 case studies of regional environmental impact assessment

Objectives	Case studies											
	ERM-1[a]	ERM-2	LCA-1	LCA-2	EIA	MAS-1	MAS-2	LP-1	LP-2	AEI-1	AEI-2	Total
Environmental												
Input related												
Use of non-renewable energy ↓[b]			X	X	X			X				4
Use of other non-renewable resources ↓			X									1
Soil erosion ↓	X[c]		X		X			X	X	X		6
Land use ↓			X	X	X			X		X	X	6
Water use ↓			X		X	X	X			X		5
Nitrogen fertiliser use ∩	X				X				X	X	X	5
Pesticide use ↓					X				X	X	X	4
Emission related												
Emission of greenhouse gases ↓			X	X	X					X		4
Emission of ozone depleting gases ↓			X									1
Emissions of acidifying gases ↓			X	X	X							3
Emissions of nutrifying substances ↓	X	X	X	X	X			X	X	X		8
Emissions of pesticides ↓		X	X	X	X					X		5
Terrestrial ecotoxicity ↓of emissions				X	X					X		3
Aquatic ecotoxicity ↓of emissions		X		X	X					X		4
Human ecotoxicity ↓of emissions		X		X								2
Waste production ↓ and utilisation ↑	X		X									2
Noise↓					X							1
System state related												
Landscape quality			X	X	X		X			X		5
Natural biodiversity			X	X	X			X		X		5
Agricultural biodiversity											X	1
Air quality										X		1
Water quality		X			X					X		3
Soil quality	X				X			X	X	X	X	6
Water quantity						X	X			X		3
Economic												
Income ↑						X	X	X			X	4
Employment ↑			X			X		X	X			4
Costs ↓						X	X		X			3
Yields ↑							X		X	X	X	4
Social												
Input self-sufficiency ↑							X				X	2
Equity ↑											X	1
Risk and uncertainties in crop cultivation ↓											X	1
Total	5	5	14	11	17	5	7	8	8	17	10	

[a] See Table 1.
[b] ↓: objective to be minimised; ∩: objective to be optimised; ↑: objective to be maximised.
[c] An "X" indicates that the objective is taken into account.

The assessment of environmental impacts in the EIA and LCA approaches is based essentially on emission related objectives (Geier and Köpke, 1998). Input related indicators to assess the use of non-renewable energy or land are also defined (LCA-1 and LCA-2, Table 3). Environmental objectives may be associated with a socio-economic type objective, such as the number of workers for a type of crop (Biewinga and van der Bijl, 1996). The EIA and LCA approaches may be based on more than 10 distinct objectives (Table 3).

The environmental objectives of the MAS and LP approaches are generally input related, linked to the resource utilised, such as water supply, and system state related (e.g. available surface water or groundwater), to determine the state of the system subjected to agent pressure (Zander and Kächele, 1999; Petit et al., 2001; Becu et al., 2004). The viability of the use of the resource is also analysed by means of economic (MAS-2, MAS-1, LP-1 and LP-2, Table 3) and social objectives (MAS-2, Table 3).

AEI approaches may include the three types of environmental objective (AEI-1, Table 3), just the input related and state related types (AEI-2, Table 3) or just the input related and emission related types (CORPEN, 1988; Lanquetuit and Sebillotte, 1997). These approaches can also include economic objectives such as yield, or social ones, like the willingness of the farming profession to respect the environment (Lanquetuit and Sebillotte, 1997).

3.3. Indicators used to quantify the objectives

Indicators are the basis of the different methods for environmental impact assessment. They are used to diagnose the impact of a farming system on the environment in relation to the objectives chosen (IISD, 1997). The use of indicators avoids the difficulty of obtaining direct measurements due to methodological problems, practical reasons, or the cost or time needed to acquire them (Bockstaller and Girardin, 2003). "An indicator is a variable which supplies information on other variables which are difficult to access (. . .) and which can be used as a benchmark to take a decision" (Gras et al., 1989). Indicators are also "alternative measures (. . .) that enable us to gain an understanding of the complex system around us (. . .) so that effective management decisions can be taken" (Mitchell et al., 1995).

Indicators can be classified in different ways. As specified previously, the OECD classification distinguishes pressure, state and response indicators (2001a). For example, to quantify the environmental objective "reduction of the emissions of nutrifying substances", pressure and state indicators have been developed. Indicators can also be classified by considering their position in the cause-effect chain linking farmer practices to environmental impacts (Fig. 1).

Means-based indicators estimate the technical means and inputs introduced in a farming system, such as the amount of fertiliser (ERM-1, EIA, LP-2, AEI-1 and AEI-2, Table 3). The data required for this type of indicator are usually of relatively easy access. This type of indicator is developed to evaluate the input related objectives described in Section 3.2.

Secondly, emission indicators evaluate the contribution of farming in terms of polluting emissions as nitrates, N_2O or CO_2 fluxes (LCA-1, LCA-2, EIA and AEI-1, Table 3).

Finally, impact indicators supply information directly on the effect of the pollutant emissions. Impact indicators may be of the midpoint or endpoint type, depending on the point in the cause-effect chain at which they are defined (Udo de Haes et al., 1999). Midpoint indicators are defined close to the emissions. For example, the different greenhouse gases are expressed in terms of CO_2 equivalents to obtain a climate change indicator. For the endpoint type, the emissions are aggregated at the level of category endpoints, which are variables of direct societal concern, such as damage to human health or damage to ecosystem quality. For instance, the effects of the emissions of different toxic substances could be modelled and expressed as a decrease of life expectancy. The volume of data needed to calculate endpoint indicators and the complexity of the models required to implement these indicators explains the success of midpoint indicators.

Emission and impact indicators can be grouped under the term of effect-based indicators as opposed to means-based indicators (Fig. 1). The diagnosis of environmental impact is thus more direct with effect-based indicators than with means-based indicators. However, effect-based indicators may require data which are less readily available, e.g. levels of post-cropping mineral nitrogen in the soil.

The risk maps resulting from ERM approaches represent the spatial variability of an impact indicator, qualitatively expressed in the form of a score such as for toxicity or eutrophication (Giupponi, 1998; Finizio and Villa, 2002). Quantitative emission indicators can also be developed to characterise pollutants exported from a catchment area, expressed in kg/ha/yr of nitrogen (de Koning et al., 1997) or phosphorus (Bouchardy, 1992).

In LCA approaches, both pressure and state indicators are used. Each type of impact is quantitatively expressed through an equivalent unit, i.e. kg

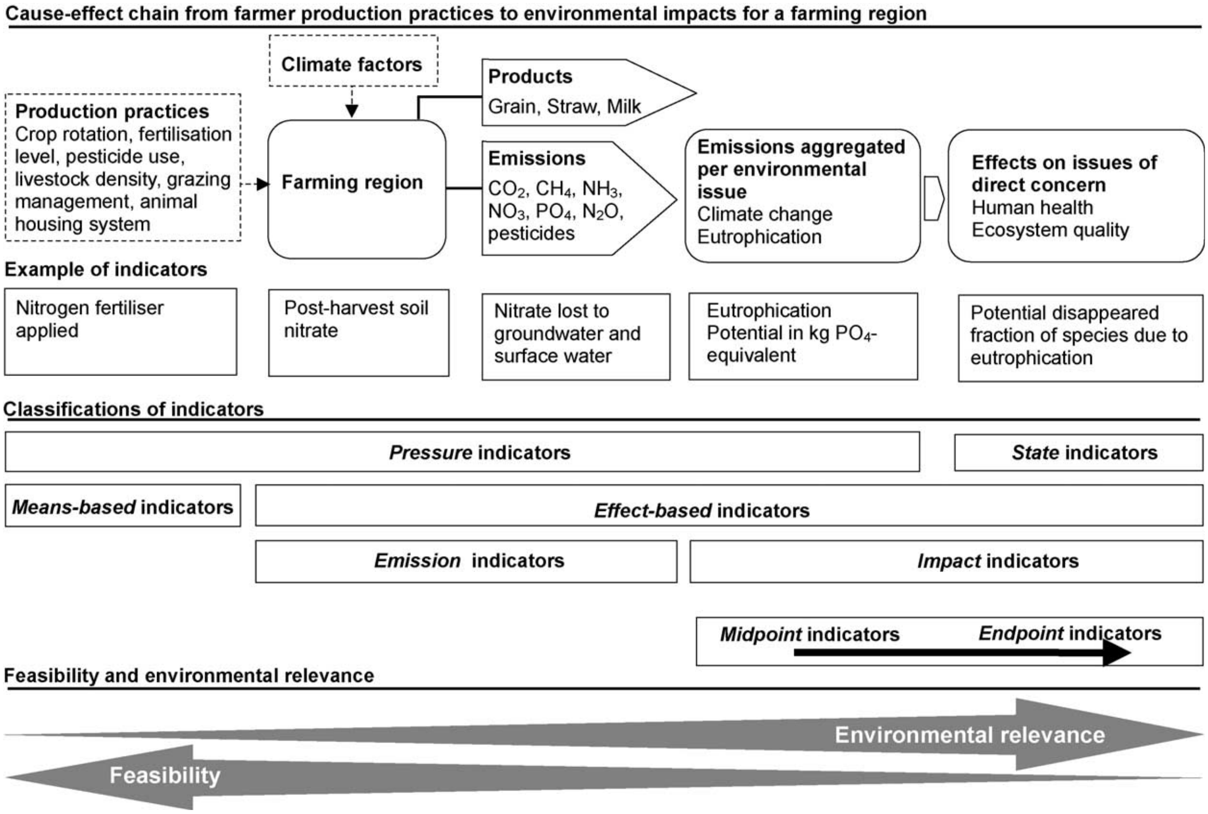

Fig. 1. Representation of a farming region and its environmental impacts, example of indicators and classifications according to their position in the cause-effect chain linking the production practices to environmental impacts, trade-off between feasibility and environmental relevance.

CO_2 for the greenhouse effect, per kg of agricultural product or per unit area of agricultural land (Brentrup et al., 2004). As in LCA, the indicators used in the EIA approaches are of the pressure and state type.

MAS approaches use both means-based and effect-based indicators, expressed in the form of values that characterise a farming region. The means-based indicator ‘‘m^3 of water extracted’’ from a water table or an irrigation channel has thus been developed (Petit et al., 2001; Becu et al., 2004). Effect-based indicators used are usually of the emission type, such as tonnes of phosphorus exported from a catchment area into a lake (Janssen, 2001).

The indicators used in LP approaches may be means-based, such as the quantity of nitrogen fertiliser used, of the emission type, such as emission of eutrophying substances, or of the state type, such as soil quality (Zander and Kächele, 1999; Hengsdijk and van Ittersum, 2003). AEI approaches may be based either on means-based indicators such as the quantity of pesticides used or on effect-based indicators like the amount of soil eroded (ECNC, 2000).

3.4. Temporal variation

The assessment of the environmental impacts of agricultural production involves a calculation of pollutant emissions. These emissions vary both in space and time. The methods reviewed here take account of these two kinds of variability to different degrees, according to their objectives (Table 4).

With respect to time, most approaches to environmental impact assessment have an annual basis (Table 4). Longer time scales can take account of year-to-year weather variation (ERM-1, ERM-2, MAS-1, MAS-2 and LP-2, Table 4). Dry, normal or wet scenarios can treat this variability qualitatively (Petit et al., 2001; Agrell et al., 2004). Indicators can

Table 4
Spatial scale, spatial unit, number of farms considered, spatial information used and temporal scale of 11 case studies of regional environmental impact assessment

Case studies	Characteristics of the case studies				
	Spatial scale	Spatial unit	Number of farms considered	Spatial information	Temporal scale
ERM-1[a]	National	Cells (9.25 km × 9.25 km)	65415 farms	Soil map of Ecuador (1:1 million); climate zones; land use map; crops and animals statistics map	Year (inter-annual variability taken into account)
ERM-2	1840 km^2	Pixel: 200 m × 200 m (4 ha)	Census information at the commune level	Soil map, climate map, administrative boundaries map, drainage networks, geological map, landscape variability map	Year with daily time step (30 years tested)
LCA-1	Four European regions from 7770 to 45300 km^2	Region	Census information	Land use	Year
LCA-2	70 km^2	Farm	15 farms	Land use	Year
EIA	–	Field–farm	–	–	Year
MAS-1	6000 km^2	Farm	6000 farms	Climate, soil type	10 years
MAS-2	43.5 km^2	Grid cells corresponding to typical field size (0.32 ha)	327 farms	Soil map, land use, irrigation scheme	Year with daily time step (10 years tested)
LP-1	Three scales: (1) 20 km^2; (2) 200 km^2; (3) 52000 km^2	Field–farm	(1) 40 farms; (2) 32 farms; (3) census information	Land use, soil resources, hydrology, relief	Year without inter-annual variability
LP-2	460000 km^2	Stratification of 21 units according to climate and soil type	Census information from handbook	Climate, soil type	Year with daily step (31 years tested)
AEI-1	Europe	Depends on indicator	Depends on indicator	Soil map, land use map (CORINE land cover)	Depends on indicator
AEI-2	Two micro-regions	Household	110 households	Land use	Year

[a] See Table 1.

be calculated over less than a year; for example on a daily basis, notably when using simulation models for water quality or agronomic models, in the case of the AEI, MAS and LP approaches. Indicators can also include the potential transfer of a pollutant during a rainfall event as in the potability index, which is based on the annual frequency with which a critical potability concentration is exceeded (ERM-2, Table 4).

By definition, in the LCA approach, the time period considered to calculate emissions is a function of the lifetime of the product considered. Hence, as far as environmental assessment of a plant product is concerned, the period considered can be reduced to the lifespan of the crop (Biewinga and van der Bijl, 1996). A yearly basis is often used in LCA, considering all the emissions produced over the year of study for one or more farms (LCA-1 and LCA-2, Table 4). In LCA, long-term effects of pollutant emissions are taken into account. These often exceed the annual time period used for the emissions. The duration of an effect depends on the type of impact and may exceed 100 years, as for greenhouse gases. Qualitative approaches for mapping risk (ERM) often ignore time (Finizio and Villa, 2002; Assimakopoulos et al., 2003), the indicators used indicate a degree of relative risk. A quantitative estimate of the masses of pollutants exported from a geographical zone can however be obtained on a yearly scale, such as for phosphorus (ERM-1, Table 4; Bouchardy, 1992).

3.5. Spatial variability

ERM approaches normally consider spatial variability in terms of pollution pressure and vulnerability. This spatial representation may be based on a grid (ERM-2, Table 4) or on a vector approach (Sahin and Kurum, 2002). The potential environmental risk is thus calculated on each basic object after combining different geographical "layers". In these approaches GISs are therefore frequently used to combine layers.

The spatial variability of pollutant emissions and the vulnerability of the affected environment are rarely considered in LCA approaches. There is work, however, which attempts to specify the geographical location of each stage of production (Bengtsson et al., 1998). Likewise, a better consideration of the spatial variability, both with respect to the fate of pollutants as well as concerning the vulnerability of the environment, can be included in the LCA approach, notably for regional phenomena like acidification (Potting, 2000). However, taking account of this spatial variability requires a lot of extra information in an approach already overburdened in terms of data input.

EIA approaches require a synthesis of pollutant emission maps and vulnerability maps as developed in the ERM approaches. GISs in particular can produce small-scale maps to illustrate local impacts and larger-scale maps to assess the regional impact of pollutant emissions (Antunes et al., 2001).

The localisation of resources, farmers, fields, centres of exchange such as markets, and manure treatment plants is indispensable for modelling the relationships between agents in MAS approaches. The minimum consideration of localisation consists of simply including the distances between these objects. This distance will affect the quantity and quality of the exchanges. For a better representation of the system of agents, two-dimensional simulation platforms have been developed, such as CORMAS (Bousquet et al., 1998). This platform was used in a study of the sustainability of irrigation within a catchment area in Thailand by considering units of 0.32 ha, a typical field size (MAS-2, Table 4). Several spatially linked objects may be used simultaneously, such as the farm, a group of farms with uniform practices, or different systems of aquifers (Petit et al., 2001).

LP approaches involve a classification of the agronomic properties of the study zone as a function of soil type, land use, rainfall, etc. (LP-1 and LP-2, Table 4). The presumed homogenous units may vary from the field to regions of more than 21,000 km^2 (Hengsdijk and van Ittersum, 2003). GISs are routinely used to delineate these homogeneous units.

4. Discussion

The aim of this discussion is not to classify the methods, but to extract the key elements which enable one to choose or develop a method of environmental impact assessment for a given farming region.

4.1. A holistic view of agriculture

Agriculture is increasingly viewed as a multifunctional activity and notably represents both a tool for plant and animal production and a way of managing the countryside (OECD, 2001b). This complexity of farming activity should lead to the adoption of a holistic approach to environmental assessment (Smith et al., 2000). Methods which combine several environmental objectives are better suited to evaluate the environmental impact of farming activity than single-criterion approaches. To be suitable for analysing the sustainability of a farming system, the assessment method should integrate not only environmental objectives but also social equity and economic viability. All assessment methods reviewed here set out to make a more or less complete environmental diagnosis and can identify to varying degrees the farming practices contributing most to emissions of pollutants or to use of resources. Only certain methods (LP, MAS) also allow an optimisation at the level of the farming region. However, these methods consider a restricted number of objectives, between 5 and 8, which may be environmental, economic or social (MAS-1, MAS-2, LP-1 and LP-2, Table 3).

The boundaries of the system analysed must be sufficiently large in terms of space and time (IISD, 1997). In terms of space, the assessment method should include not only local and regional impacts but also global impacts, such as climate change. Thus, cases of "problem shifting" (e.g. reducing a local impact at the cost of an increased global impact) can be identified. Only methods considering a sufficient number of environmental objectives, such as EIA or LCA, are able to spot such problem shifting (EIA, LCA-1 and LCA-2, Table 3). Moreover, from the spatial point of view, the effects of the physical characteristics of the study area, both on the fate of the polluting emissions and on the vulnerability of the environment, should be taken into account as far as possible. In this respect the ERM approach does best.

The time period over which emissions are considered should be sufficient to cover the cycle of farming practices. A yearly time step is therefore usually chosen. Depending on the dynamics of the pollutants, it may be necessary to adjust the time step for analysis, for example to the scale of a flooding episode, e.g. when quantifying the impacts of pesticides which are mainly exported during flooding (Giupponi et al., 1999). On the other hand, the duration for which the fate of pollutants and their effects are considered must be sufficiently long. In the case of LCA, this duration may exceed a hundred years for certain impact categories. The volume of data needed and the complexity of the simulation models required increase as the time step for analysis diminishes. A compromise has to be sought between the environmental relevance of the method and its feasibility (Fig. 1).

The assessment of a multifunctional activity like agriculture also poses the question of the reference unit for the impacts. Regional approaches usually express impacts per ha of land (Geier and Köpke, 1998). LCA introduces the concept of the functional unit, the reference unit by which the impacts are expressed according to the function of the system studied. From this point of view, the impacts will be expressed per kg of product when the function of the system is the production of commodities, and by hectare for a non-market function (e.g. environmental services). In the case of a regional assessment there is a multitude of products of different kinds. In this case the expression of the impacts per kg of product requires the definition of a common unit, such as the protein or energy content of the products or their market value. The choice of a common unit involves favouring one of the functions of agriculture (economic activity, land use or food production) at the expense of others. Therefore, methods which allow the expression of impacts according to several reference units are preferable (Biewinga and van der Bijl, 1996).

The principle of a holistic view implies favouring a systems approach, notably one such as LCA or MAS. The environmental impact should be assessed both overall, at the farming region scale, as well as for each farm in the region. The systems approach can, among other things, be used to assess the effect of interactions between farms on the overall environmental impact of the farming region.

To facilitate its acceptance by end users, the evaluation method should be as transparent as possible (IISD, 1997). Simplifying hypotheses, uncertainty associated with the data and with the results, and the interpretation technique must be explained. Assessment approaches based on a more thorough formalisation in terms of impact and interpretation, such as LCA and EIA, can facilitate this acceptance. Methods for the evaluation of a farming region have to be sufficiently simple to be practical and sufficiently complete so as not to lead to errors in diagnosis. The search for this balance is a crucial aspect of the choice of a method or when developing a new method.

4.2. Types of indicators

The indicators chosen must allow the evaluation of a farming region in relation to environmental objectives. Effect-based indicators are preferred, as they allow a more direct assessment of an environmental impact than mean-based indicators. Two complementary strategies have been proposed to define indicators at the scale of the farming region (OECD, 2001a).

The first approach consists of combining the values of the indicators established at the farm level. Existing methods for this scale are in fact very numerous (von Wiren-Lehr, 2001; van der Werf and Petit, 2002). However, as the surface of the area studied increases, it will no longer be feasible to make an environmental diagnosis for every farm. The recourse to farm classification is therefore quite routine in all six methods, once the study zone exceeds 20 or 30 km^2 (Table 4). The classic approach is to define the environmental impacts associated with each type of farm and then to summate them, after weighting them in proportion to the areas of the different types in the study zone. This form of aggregation does not take into account the positive or negative effects of interactions between farms on the overall impact for the zone of study. New indicators are needed therefore to take into account these interactions (Zander and Kächele, 1999; Courdier et al., 2002; Becu et al., 2004). The use, at the scale of the farming region, of indicators developed for the farm scale may necessitate methods of extrapolation or linear or non-linear scaling procedures, depending on the nature of the interactions considered (Dalgaard et al., 2003). The consideration of exchanges of products, by-products or waste material between farms could prove to be important for a correct evaluation at the level of a region. It is therefore important to integrate the origin, the fate and the internal recycling of different material flows, when evaluating environmental impact on a regional scale.

The second approach consists of breaking down the indicators calculated at a higher level, in order to reveal regional or indeed local variability. Such a breakdown assumes decision rules to separate the information into different subunits (de Koning et al., 1999). This kind of approach was used for pig production to determine the periods and locations for manure spreading by using local statistical data (Tissot et al., 2001). The distribution of this kind of information presumes the existence of (i) time filters such as periods of manure production, permitted periods for manure spreading, rainfall periods, etc. and (ii) spatial filters to allocate the manure onto the various fields. This type of breakdown may, however, lead to errors if the spatial unit for the farming statistics (often the municipality) does not correspond with the boundaries of the farms. Furthermore, the spatial and temporal distribution of local information requires detailed knowledge of spatial features, such as land use, slope or hydrology.

4.3. Including uncertainty

The interpretation of the results of an environmental impact assessment requires knowledge of the uncertainty associated with these results. This stage of the analysis is rarely discussed and even less put into practice during the application of the evaluation methods. For the highly formalised LCA and EIA approaches, the analysis of uncertainty should be an integral part of the approach (De Jongh, 1988; Steen, 1997). In reality, the inclusion of uncertainty is far from routine (Geneletti, 2002). In the six evaluation approaches reviewed, uncertainty depends on both the input data and the models used. In the case of input data derived from experiments, uncertainty is a function of the spatial and temporal variability of the variable considered, of the analytical protocol and of measurement errors (Dubus et al., 2003). The uncertainty of the model parameters used may also lead to uncertainty in the results (Huijbregts et al., 2000). This uncertainty depends very much on the origin of the parameters: expert knowledge, a database, or derived from empirical functions (Dubus et al., 2003).

A synthesis of tools for analysing the propagation of uncertainty was published as part of the LCA approach (Björklund, 2002). The first level in the analysis can be based on a partial analysis of the propagation of uncertainty by concentrating on a limited set of key parameters for which uncertainty intervals are defined and which allow the construction of ''favourable'' and ''unfavourable'' variant scenarios (Biewinga and van der Bijl, 1996). The higher level involves the application of a systematic or random Monte Carlo-type analysis on all parameters used (Huijbregts et al., 2000). These techniques assume knowledge of the uncertainty associated with each parameter and the characterisation of the distribution of this uncertainty. The use of fuzzy logic also allows a degree of uncertainty to be included both at the time of crossing geographical layers in ERM approaches (Assimakopoulos et al., 2003) as well as during the calculations in the LCA and EIA approaches (Geneletti et al., 2000). A better way of dealing with uncertainty is a major challenge for the improvement of existing methods of environmental impact assessment (Dubus et al., 2003).

4.4. Validation of approaches

The validation of assessment methods is indispensable for a scientific diagnosis. Just as for the estimation of uncertainty, the validation stage has received little attention in studies conducted at the regional scale. A similar situation has been observed for evaluation studies at the farm level (van der Werf and Petit, 2002). Bockstaller and Girardin (2003) proposed a method of validation based on (i) the validity of the basis of the method and its indicators, (ii) the consistency of the indicator values in relation to observations, and lastly (iii) on the take-up of the method by the end users. Depending on the nature of the method, only one of these validation stages may be realised. Thus, if its indicators cannot be compared directly with observations, acceptance by a panel of experts may constitute the only stage of validation. This type of validation was used to validate a method for the assessment of environmental risk from pesticides (van der Werf and Zimmer, 1998).

In the MAS and LP approaches, the authors make major efforts to compare simulation results with observations. The proportions of land area of each crop type simulated can thus be compared with remote sensing data (de Koning et al., 1999; Becu et al., 2004). However, given the volume of data needed to validate these approaches (environmental, economic and social) often only validation by experts is feasible (Berger, 2001; Janssen, 2001).

The indicators used in the ERM and EIA approaches can be validated by statistical tools of the rank correlation type. Spearman or Kendall coefficients (Siegel, 1956) may be used to study the relationship between the indicator and the variable which one tries to explain. This type of tool was used at the catchment area scale to validate the use of the indicator maize area close to the drainage network to explain atrazine fluxes (Colin et al., 2000). It can also be used to validate indicators expressed in the form of scores (Reus et al., 2002).

For the indicators used in the LCA approaches validation by comparison with observations is more difficult, because of the potential character of the impacts. These potential impacts in fact only very rarely include the specific features of the receiving environment where the observations can be made (Potting et al., 1998). The acceptance of the indicators used in LCA is rather decided by a consensus of experts on the intensity of polluting emissions, their fate and effects.

The final stage of validation, known as end user validation, is crucial for judging the practical feasibility of the method. This stage should determine the balance between the robustness of the method, which must not lead to a wrong diagnosis, and the volume of data and time required for its implementation. The adoption of the assessment method by the end users is a key stage for its success, particularly for the MAS approaches (Petit et al., 2001).

5. Conclusions

The analysis of six approaches for environmental impact assessment reviewed here reveals the diversity of objectives, users, and concepts involved. Several key points have been identified in the implementation of the different methods at the regional scale. These key points can provide guidance for judging an existing method or for devising a new method for the regional assessment of the environmental impact of agriculture.

Some of these key points do not depend on the scale of implementation and apply both at the farm scale as well as the scale of the farming region:

- The inclusion of economic and social objectives can balance the environmental value of new farming practices against their social and economic viability.
- The time step used to analyse the different environmental impacts has to be a compromise between precision of the analysis and practicability of the method.
- From the spatial point of view, the description of the study zone must be sufficiently precise to allow a weighting of the effects in accordance with the vulnerability of the environment.
- Inclusion of the three levels of impact – local, regional and global – offers the possibility of identifying possible shifts from one type of impact to another.
- Methods using effect-based indicators are preferable to those which are means-based, since they enable the environmental risk to be characterised more directly. They are also easier to validate.
- An evaluation of uncertainty should be an integral part of the assessment method if the results are to be correctly interpreted.
- The method should be validated with respect to (i) the conception of the method and its indicators, (ii) the consistency of the values of the indicators in relation to observed values, and lastly (iii) the adoption of the indicators and more generally of the assessment method by the end users.

Some key points apply specifically for the regional assessment of the environmental impacts of agriculture:

- Methods which allow the expression of impacts according to several reference units are preferable, as they allow the different functions of agriculture at the regional scale, e.g. production of commodities versus non-market functions, to be evaluated.
- Methods of extrapolation or scaling procedures have to be defined to apply indicators developed at the farm level to the regional level in terms of classification of farms, vulnerability of the environment, or fate of pollutants, according to the available data at the regional scale.
- Finally, a systems approach to the environmental evaluation of a farming region should integrate into the assessment both inputs and outputs at the regional level as well as the possible effects of interactions between farms. Consideration of these interactions is absent in many existing methods and thus constitutes a challenge for new methods of regional evaluation.

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