AGRO-ECOLOGICAL INDICATORS OF FIELD-FARMING SYSTEMS SUSTAINABILITY. I. ENERGY, LANDSCAPE AND SOIL MANAGEMENT

INDICATORI AGRO-ECOLOGICI PER LA SOSTENIBILITÀ DEL SISTEMA APPEZZAMENTO-AZIENDA. I. ENERGIA, PAESAGGIO E GESTIONE DEL SUOLO

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Abstract
Evaluation of the sustainability of farming systems management can be carried out with direct measurements, simulation models or indicators; the latter have the advantages of requiring a small amount of inputs, being fast to calculate and easy to interpret, allowing comparisons in space and time, and representing a synthesis of processes in complex systems. In this paper we propose a list of indicators which synthesise the state of the farming system or the management effects on the environment related to fossil energy use, landscape and soil management. We selected indicators from the literature which can be applied at the field and farm scale, based on data obtainable from the farmer and / or from existing agricultural databases; we excluded indicators based on direct measurements. In a second paper we will introduce indicators related to nutrients and pesticides use.
The direct and indirect consumption of fossil energy can be calculated at different levels of detail and it is used to calculate the efficiencies of different systems (output/input ratios). Landscape indicators describe the presence and the density of various elements that compose the landscape (crops, linear elements, isolated shapes), allowing also, in one case, to compare landscape "demand" and "supply". The soil management indicators describe the relation between soil quality and crop management using: i) the crop sequence indicator that evaluates the goodness of each previous-successive crop combination in a rotation, assigning specific scores to the effects of one crop to another in terms of development of pathogens, pests and weeds, soil structure and nitrogen supply; ii) the organic matter indicator that evaluates if the management adopted by the farmer on a specific soil tends to accumulate or deplete soil organic matter; and iii) the soil cover index for evaluating soil protection by crops. Overall the indicators, based on a rather small data set, allow to conduct immediate syntheses of important agro-ecological aspects of farming systems.

Key words: agroecosystems, environmental impact, rotation, organic matter.

Riassunto
La valutazione della sostenibilità della gestione agricola può essere ottenuta attraverso misure dirette, modelli di simulazione o indicatori. Questi ultimi hanno il vantaggio di richiedere pochi dati in input, di essere velocemente calcolabili e facilmente interpretabili, consentendo confronti nello spazio e nel tempo, fornendo così una sintesi dei processi che avvengono in sistemi complessi. In questo articolo proponiamo una lista di indicatori di gestione aziendale relativi all'utilizzo di fonti di energia fossile, alla qualità del paesaggio ed alla gestione del suolo. Abbiamo selezionato dalla letteratura indicatori che possono essere applicati a scala di appezzamento e di azienda, basati su dati ottenibili dall'agricoltore o da banche dati agricole; abbiamo escluso indicatori basati su misure dirette. In un secondo articolo presenteremo indicatori relativi all'uso di nutrienti e fitofarmaci.
I consumi diretti ed indiretti di energia fossile possono essere calcolati a diversi livelli di dettaglio ed usati per calcolare le efficienze di diversi sistemi (rapporti output/input). Gli indicatori di paesaggio descrivono la presenza e l'intensità dei vari elementi che compongono il paesaggio (colture, elementi lineari e isolati), permettendo anche, in un caso, di confrontare la "domanda" e l'"offerta" di paesaggio. Gli indicatori di gestione del suolo descrivono la relazione fra qualità del suolo e gestione colturale utilizzando: i) l'indicatore di rotazione, che valuta l'adeguatezza di ogni combinazione coltura precedente-coltura successiva all'interno di una rotazione, assegnando punteggi specifici all'effetto che una coltura ha sull'altra per quanto riguarda lo sviluppo di patogeni, parassiti, malerbe, l'effetto sulla struttura del suolo e la disponibilità di azoto; ii) l'indicatore sostanza organica, che valuta se la gestione adottata dall'agricoltore per uno specifico suolo tende ad accumulare o depauperare la sostanza organica del suolo; e iii) l'indicatore di copertura del suolo per la valutazione della protezione di quest'ultimo da parte delle colture. In generale gli indicatori proposti, calcolabili con un ridotto data set, permettono di condurre una sintesi immediata di importanti aspetti agro-ecologici del sistema aziendale.

Parole chiave: *agroecosistema, impatto ambientale, rotazione, sostanza organica.*

Introduction

The Bruntland commission (World Commission on Environment and Development**,** 1987) defined the concept of sustainability as "(…) a form of sustainable development which meets the needs of the present without compromising the ability of future generations to meet their own needs." We can distinguish three aspects of sustainability: environmental sustainability, social sustainability and economic sustainability (Goodland, 1995). In this paper we deal with environmental sustainability, defined as the maintenance of the global ecosystem (or of the "natural capital"), both as a "source" of inputs and as a "sink" for wastes (Goodland, 1995). The agricultural system is involved in all these aspects and farmers are guardians of the countryside, of the ecosystem and of the rural landscape (European Commission, 2001). We recall the definition of agro-ecosystem: "an ecosystem constituted by several organism populations that interact one with each other, and with environmental and anthropic factors; man manages the equilibria of this system in order to increase the growth of a few economic-interesting vegetable and animal species." (Borin, 1999).

In order to analyse the environmental sustainability of agroecosystems it is possible to choose different methods, like direct measurements, simulation models, simple or composite indicators that have different levels of applicability and potential explanation of the system (Fig. 1).

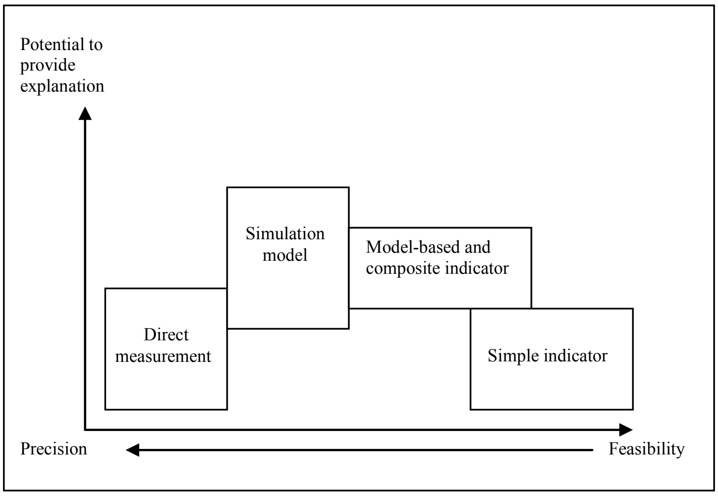

Fig. 1 – Potentials and weaknesses of different assessment methods (from Bockstaller and Girardin, 2002, modified).

Fig. 1 *– Potenzialità e debolezze di differenti metodi valutazione (da Bockstaller e Girardin, 2002, modificato).*

In many contexts, routine direct measurements are costly and often time consuming, especially if the studied area is large. Often, simulation models require many input data that can be difficult to obtain; moreover, sometimes models are not validated for a wide range of conditions (Bockstaller *et al*., 1997). Therefore, indicators are interesting to analyse agro-ecological systems when it is not possible to carry out direct measurements.

The term indicator has been defined as a variable which supplies information on other variables which are difficult to access (Bockstaller *et al*., 1997). Indicators can provide in a relatively short time a synthesis on processes and impacts at different scales. They are valuable tools for evaluation and decision making as they synthesise information and can thus help to understand a complex system (Mitchell *et al*., 1995). The indicators can be calculated rapidly and are efficient tools to evaluate the real achievement of agronomic, economic and environmental targets (Silvestri *et al*., 2002). Since each agro-ecological indicator represents a different point of view on environmental sustainability, the indicators can be included in a multi-criteria evaluation of the sustainability of agricultural systems, which may also include socio-economic indicators of sustainability. In order to build a good indicator it is necessary to take into consideration some properties that influence its potential use: i) independence from the size of the study object; ii) robustness: not highly influenced by extreme or uncommon events; iii) accuracy; iv) precision; v) responsiveness: quick change in response to actions or alterations in the study objects, compared to direct measurements, requiring time for sampling and analysis, and to detect changes in the state of the study objects because of resilience and inertia; vi) measurability: based on planned or available data; vii) ease of interpretation: to communicate essential information in a way that is unambiguous and easy to understand; viii) pertinence: the capacity of identifying the behaviour of studied entity; ix) cost effectiveness: in proportion to the value of the information derived; x) policy relevance: to drive the key environmental issues (European Commission, 2001; Silvestri *et al*., 2002).

In the set proposed in this paper, not all indicators have all the properties mentioned before. Precision (defined as the variability between replicated measures) is not considered because of the lack of replicated values. The accuracy of indicator (closeness to the real value) is not valuable without a comparison whit other methods or direct measurements. For the measurability property, the planned data are not considered, because the aim of the selected indicators is to provide a judgement on a specific topic using existing and available data. Indicators do not provide an absolute but a relative evaluation of different entities.

Moreover, the errors resulting from lack or inaccuracy of input data are uniformly spread in all alternative study cases (Silvestri *et al*., 2002). Inputs for calculating indicators are often dissimilar and a semi-quantitative approach can be necessary to integrate all the variables in a unique value (expressed in physical units) or in a judgment (expressed with a qualitative scale). Further conversion to a unit scale (e.g. 0 – 10) is useful in order to compare the result of different indicators. Finally a good indicator should have a benchmark that permits, also for non experts, an easy evaluation.

In the last 10 years the interest for agro-ecological indicators (AEIs) has increased and several sets of AEIs have been proposed. The OECD's DSR (Drive – State – Response) framework (Organisation for Economic Cooperation and Development, 1999) and the European

Environmental Agency's DPSIR (Drive – Pressure – State – Impact – Response) framework (European Environmental Agency, 1999) provide the basis for an agro-environmental indicators framework named agricultural DPSIR (European Commission, 2000). The objective of agricultural DPSIR is to provide an harmonised structure of agro-environmental indicators in EU Member States in order to present a common basic level of information that can be aggregated and facilitate comparisons among regions. The agricultural DPSIR identifies a set of 35 agro-environmental indicators (European Commission, 2000) to help monitor and assess agro-environmental policies and programmes, to provide contextual information for rural development, to identify environmental issues, to help target programmes that address agro-environmental issues and to understand the linkages between agricultural practices and the environment (European Commission, 2001).

Within the Italian project "Agriculture for protected areas" (Agripark, 2006; Bisol, 2006) we are evaluating the environmental sustainability of different cropping and farming systems. Our objective in the project is to synthesise the effects of agricultural management using quantities which: i) allow to integrate different aspects of reality, doing a synthesis characterized by a good compromise between the description of the processes and their simplification into single numerical quantities; ii) can be derived from farm characteristics, easily obtainable from the farmer and/or from existing agricultural databases (e.g. Common Agricultural Policy declarations); iii) are easy to interpret and can be used to drive the improvement of environmental performances of agricultural systems. We therefore excluded the indicators constituted by direct measures on soils, waters or crops. We also excluded indicators like the ones used in the IRENA project (Organisation for Economic Co-operation and Development, 2002; European Environmental Agency, 2005) because they aggregate data at nation- or macro-region level, and do not represent the actual processes occurring in single farms. The indicators proposed by Agenzia Nazionale per la Protezione dell'Ambiente (2000) were excluded as well, because many of these require an analytical approach (e.g. state and impact indicators are based on measurements of heavy metals, organic matter, pesticides and nutrients in the soil and in the water), while others can be used only at regional scale and not at field-farm scale.

We propose a framework, derived from an extensive literature review, to evaluate the sustainability of agro-ecosystems management at field and farm level, using a set of agro-ecological indicators divided in five categories (energy, landscape, soil, nutrients and pesticides) that describe the environmental sustainability of farming and cropping systems from different points of view. The different categories of agro-ecological indicators are similar to those found in the literature for farm management analysis (Vereijken, 1995; Bockstaller and Girardin, 2000), and for policy analysis (Organisation for Economic Co-operation and Development, 2001; European Environmental Agency, 2005). We did not select categories describing social and economic sustainability. In this paper we report on the first set of indicators, related to fossil energy use, landscape and soil management. In a second paper we will focus on nutrients and pesticides management.

Energy indicators

Environmental problems due to the intensive use of energy are crucial, especially for CO_2 and NO_x emission due to fossil energy combustion (Pervanchon *et al.*, 2002) and to the limitation of energy sources available nowadays. CO_2 is one the major greenhouse gases; agriculture can contribute to CO_2 emissions with the use of fertilizers, lime and fuel (Robertson *et al.*, 2000). NO_x contributes to acidification and to the generation of ozone in the troposphere (Olivier *et al.*, 1998). Therefore the quantification of fossil energy use is important in order to improve the efficiency of agro-ecosystems and to reduce the emissions and the consumption of limited resources. Different ways are proposed to quantify fossil energy flows in agricultural systems. Dalgaard *et al.* (2000) use a synthetic approach based on simple description of farm operations carried out for crop and livestock management. Similar approaches are used by many other Authors (e.g. Biondi *et al.*, 1989; Volpi, 1992). Others, like Pervanchon *et al.* (2002), use a more analytical methodology to estimate energy flows in cropping systems. Once the flows are calculated with one of these methods, they can be interpreted by calculating output/input ratios; Tellarini and Caporali (1999) provide a rich set of possible ratios.

We describe in detail the simple method of Dalgaard *et al.*(2000), as a recent and complete example of the approaches of the first type. This procedure assesses fossil energy use in different types of farms. The energy balance is divided into two modules: crop module and animal module, each divided in two sub-modules. The energy use (EU) at farm level is calculated as: $EU_{farm} = EU_{crop} + EU_{animal}$ (MJ). The crop module is divided in the sub-module for the direct (EU_{direct}) and for the indirect energy use ($EU_{indirect}$). The sub module EU_{direct} is divided in two components: the first for the diesel fuel (EU_{diesel}), the second for other energy use (EU_{other}):

$EU_{crop} = EU_{direct} + EU_{indirect}$

$EU_{crop} =(EU_{diesel} + EU_{other}) + EU_{indirect}$.

EU_{diesel} represents the diesel use for crop management operations:

$$EU_{diesel} = \sum_{i=1}^{N_{oper}} C_i \cdot D_i \cdot k \text{ (MJ)},$$

where N_{oper} is the total number of operations to grow a specific crop, C_i is the area treated (ha) or the amount input factor applied (t) or the weight of crop harvested (t) or the distance to the field (km) on which the i-th operation is carried out, D_i is the norm of diesel use for that operation (L ha^{-1} for field operations, L km^{-1} for transport, L t^{-1} for product removed), k is a specific energetic coefficient (35.9 MJ L^{-1} diesel). For the soil preparation, D_i is corrected for soil type by a factor of 1.1 for a loamy soil, a factor of 1.0 for a sandy-loam soil and a factor of 0.9 for a sandy soil. EU_{other} represents other energy forms directly consumed in the farm activity, such as lubrication, drying and irrigation:

$$EU_{other} = \sum_{i=1}^{N_{oper}} C_i \cdot D_i \cdot L + \sum_{j=1}^{N_{dry}} (AD_j \cdot PD_j \cdot R) + \sum_{k=1}^{N_{irr}} (AI_k \cdot I)$$

(MJ), where L is the energy consumed for lubrication per unit of fuel used (3.6 MJ L^{-1} diesel), N_{dry} is the total number of drying operations, AD_j is the mass of crops dried (t, wet basis), PD_j is the percentage of drying (t water removed t^{-1} wet crop), R is the energy required for drying (5 000 MJ t^{-1} water removed), N_{irr} is the total number of irrigations, AI_k is the amount of water used in the k-th irrigation event (mm), I is the energy consumed for a unit volume of water applied (52 MJ mm^{-1}).

$EU_{indirect}$ represents the energy used in the production of inputs, such as machinery, fertilisers and pesticides.

$$EU_{indirect} = \sum_{n=1}^{N_m} CD_n \cdot M + \sum_{i=1}^{5} AE_i \cdot E_i \quad \text{(MJ)},$$

where N_m is the number of machines used in the farm, CD_n is therefore the diesel fuel consumed (L), M is the energy incorporated in the machinery (the energy necessary for the construction, averaged per unit of fuel consumed, 12 MJ L^{-1} diesel); and AE_i E_i represents the indirect energy used derived from five types of external inputs: nitrogen (i = 1), phosphorus (i = 2), potassium (i = 3), lime (i = 4), pesticides (i = 5); AE_i is the total amount of input product used (kg for NPK or pesticides, t for lime), and E_i is the energy needed for the production of the input (50 – 12 – 7 – 40 MJ kg^{-1} for N, P, K and formulated spraying agent of herbicides, insecticides and fungicides respectly, and 30 MJ t^{-1} for lime).

The animal module, developed for pig and cattle production, is divided in two sub-modules. The first module (EU_{direct}) describes the direct energy use for cattle or pig breeding; it is divided in two components: livestock housing (S), and heating of the livestock housing (H). The second sub-module ($EU_{indirect}$) describes the indirect energy requirement for the cattle/pig breeding, and is divided in three components: farm building (B), imported fodder (F) and self-produced fodder (O).

$$EU_{animal} = EU_{direct} + EU_{indirect}$$

$$EU_{animal} = (S + H) \cdot LSU + (B \cdot LSU + F \cdot SFU + O \cdot SFU),$$

where S represents the energy required for operation in livestock housing (light, ventilation, milking, milk cooling, fodder milling and pumping), equivalent to 8 – 1.7 – 6.1 – 3.2 – 0.9 – 0.5 GJ LSU^{-1} (Livestock Unit, corresponding to 1 large-breed dairy cow, or 30 slaughter pigs) for dairy cows, other cattle, conventional sows, organic sows, conventional slaughter pigs, organic slaughter pigs, respectively; H is the energy required for heating the cattle or pig housing (3.1 – 0.6 GJ LSU^{-1} for conventional sows and conventional slaughter pigs, respectively); B is the energy required for the maintenance of farm buildings and the store (2.5 GJ LSU^{-1}), F is the energy for the imported fodder (5.7 MJ SFU^{-1}, Scandinavian Feed Unit, corresponding to 12 MJ of metabolizable energy, equivalent to the fodder value of 1 kg of barley), O is energy consumption for self-produced fodder (EU_{crop}/harvested yield, MJ SFU^{-1}). Overall, the coefficients proposed by Dalgaard *et al.* (2000) for converting mass fluxes into energy fluxes are in good agreement with the ones found in other similar works (e.g. Biondi *et al.*, 1989; Jarach, 1985); more specific parameters (e.g. energy content of single active ingredients or pesticide groups) can be found in Volpi (1992). The use of older parameters, however, needs to be carefully evaluated because, as stated by Pervanchon *et al.* (2002), the efficiency of production of fertilisers and pesticides has increased in the last decades.

An alternative methodology is proposed by Pervanchon *et al.* (2002) and by Bockstaller and Girardin (2000); they suggest the use of an energy indicator (I_{En}) to evaluate the energy consumption of field crop production calculated with an analytical approach. The indicator provides a value from 0 (worst value) to 10 (best value). A value of 7 represents the achievement of a minimum level.

The energy indicator (I_{En}) is defined as:

$$\begin{cases} I_{En} = 10 & \text{if } 0 < E_t < 3500\ MJ \cdot ha^{-1} \\ I_{En} = a \cdot E_t^2 + b \cdot E_t + c & \text{if } 3500\ MJ \cdot ha^{-1} < E_t < 34\ 900\ MJ \cdot ha^{-1} \\ I_{En} = 0 & \text{if } E_t > 34\ 900\ MJ \cdot ha^{-1} \end{cases}$$

where E_t is the total amount of energy consumed (MJ ha^{-1}) and a, b, c are coefficients (a = 8.75544 10^{-9}; b = -6.5492 10^{-4}; c = 12.184).

E_t is composed by four modules ($E_t = E_m + E_{irr} + E_{fert} + E_{phyto}$), E_m for the fuel consumption, E_{irr} for the irrigation, E_{fert} for fertiliser utilisation, and E_{phyto} for pesticide utilisation. E_m (MJ ha^{-1}) quantifies the direct energy consumed by machinery for each crop management operation, without considering the energy incorporated in the machines during construction.

$E_m = [(36\ P_a / \eta) / (VLC)] + D / S$, where 36 is a conversion factor, P_a is the tractor power required (kW), η is motor yield (estimated equal to 35%), V is tractor speed (km h^{-1}), L is machine width (m), C is a correction coefficient taking into account the over consumption factor (dimensionless), depending on machine characteristics that increase the energy consumption, D is a correction factor taking into account the distance between the farm and the field (MJ), S is the field area (ha). P_a can be obtained from a database developed by the French Institute for Cereal Crop (ITCF), or can be estimated by a linear correlation: $P_a = \alpha VL + \beta V + \alpha' L + \beta'$, where V and L are given by the farmer, and α, β, α', β' are coefficients calculated by means of a linear regressions for each machine. The over consumption factor is calculated as $C = C_1\ C_2\ C_3\ C_4\ C_5\ F$, where C_1 is 1.00 if the tractor has a driving help systems (e.g. computer) and 0.93 if not, C_2 is 1.00 if the difference between the real tractor power and the power required for the machine used is lower than 15%, 0.85 if the difference is comprised between 15 and 30%, and 0.70 if the difference is greater than 30%, C_3 is 1.00 if the maintenance of the field machines is good, and 0.92 in other cases, C_4 ranges from 0.65 to 1.00 on the basis of the maintenance of the tractor (air filter change, injector and fuel pomp adjustment, tyre's pressure), C_5 ranges from 0.50 to 1.00 according to the soil wetness during work and the pneumatics characteristics (width and age), F depends on the type of machine

Tab. 1 – Energy (GJ) and monetary (€) inputs and outputs (from Tellarini and Caporali, 1999).

***Tab. 1** – Input e output energetici (GJ) e monetari (€) (da Tellarini e Caporali, 1999).*

i1	Total re-use of current year farm production (internal transfers)
i1a	Obligatory re-use of current year farm production
i1b	Voluntary re-use of current year farm production
i2	Total re-use of previous year's farm production
i2a	Obligatory re-use of previous year's farm production
i2b	Voluntary re-use of previous year's farm production
i3	External input produced by agriculture
i4	External input produced by other sectors (non-renewable)
i5	Input produced on the farm (i1+i2)
i6	Input external to the farm (i3+i4)
i7	Input produced by agriculture (i1+i2+i3)
i8	Total input (i1+i2+i3+i4)
o1	Output destined for re-use on the farm in the current year
o1a	Output obligatorily destined for re-use on the farm in the current year
o1b	Output voluntarily destined for re-use on the farm in the current year
o2	Output destined for the subsequent cycle
o2a	Output obligatorily destined for the subsequent cycle
o2b	Output voluntarily destined for the subsequent cycle
o3	Output destined for final consumption
o4	Net output (o2+o3)
o5	Gross output (o1+o2+o3)

and on field size. $D = (35.8\ t_c / 8)\ d$ (MJ), where 35.8 is the energy constant of 1 litre of diesel fuel (MJ L^{-1}), t_c is the specific tractor consumption (L h^{-1}), 8 is a reference tractor speed (km h^{-1}) and d is the farm-field distance (km). E_{irr} (MJ ha^{-1}) accounts for energy consumption used in irrigation: $E_{irr} = [36\ P_u\ I / (Q\ G)] + A/ S$ (MJ ha^{-1}), where 36 is a conversion factor, P_u is the power absorbed by the pump (kW), I is the irrigation volume (mm), Q is the water flow ($m^3\ h^{-1}$), G (dimensionless) is a correction coefficient for the over consumption factors (related to the type of irrigation, the water transport efficiency, the maintenance and accessories of the irrigation systems), A (MJ) is a correction coefficient taking into account the energetic cost of the implementation of the irrigation system (reservoir or well), S is the area of the irrigated field (ha). The correction coefficient $G = G_1\ G_2\ G_3$ (dimensionless), where G_1 is a correction coefficient for the application efficiency (0.6 for flooding on a sandy soil, 0.7 for flooding on other soil types, 0.9 for localized irrigation and 0.8 for sprinkler irrigation), G_2 is a coefficient considering the water transport efficiency (0.8 for flooding and 1.0 for localized and sprinkling), G_3 is a coefficient for the maintenance and accessories of the irrigation system (it varies from 0.8 to 1.0 depending on the presence of a sprinkler automatism system and the periodical check of irrigation system state), $A = [h_d\ (4000 + 120 + 130)] / 30$ (MJ m^{-1}), where h_d is drilling height expressed in metres, 4000, 120 and 130 (MJ) are the energy consumptions for drilling, cement and steel, respectively, used for 1 m depth. The values of A assume a life of 30 years for the well. In case of a reservoir, A represents 40% of the corresponding drilling cost. For irrigation with surface water (e.g. rivers, lakes), A = 0 (Pervanchon, personal communication) because the water does not need work to be extracted. The indirect energy costs for fertilisers $E_{fert} = D_{fert}\ k_{fert} + FPT$ (MJ ha^{-1}) is obtained by multiplying the total amount of the product applied, D_{fert} (kg ha^{-1}), by a specific energetic coefficient, k_{fert} (MJ kg^{-1}), which includes the energetic costs for fertiliser production. In order to estimate the energy costs for formulation, packaging and transport of input product used, it is necessary to add the Formulation Packaging Transport Coefficient (FPT) of the specific nutrient in the fertilisers. FPT cost is 1.5 – 9.8 – 7.3 and 5.7 MJ kg^{-1} respectively for N fertilisers, P fertilisers, K fertilisers and NP fertilisers. For other types of fertilisers (S, etc.) the mean FTP cost is 6 MJ kg^{-1}. The indirect energy costs for pesticides (E_{phyto}) is obtained by multiplying the total amount of active ingredient (D_{phyto}) by a specific energetic cost coefficient k_{phyto}. For example k_{phyto} is 310, 272 and 214 MJ kg^{-1} for generic insecticides, herbicides and fungicides, respectively. Specific k_{phyto} for several active ingredients are also indicated by Volpi (1992).

After fossil energy inputs have been quantified, the energy content of crop and animal products can be calculates, using coefficients available in the literature (e.g. Biondi *et al*., 1989; Jarach, 1985; Volpi, 1992). In order to describe the sustainability of crops and farming systems, it is then possible to highlight the relation between inputs and outputs. Based on the classical calculation of output/input ratios, Tellarini and Caporali (1999) have proposed an input/output methodology, providing several indicators to describe and to analyse farming systems in terms of energy and monetary values. The indicators are based on the quantification of input (i) and output (o) flows of energy and money. These flows can be directed from inside to outside the farm (or viceversa), or can be completely internal (recycling). Internal transfers can be classified as "obligatory" (crop roots and part of crop residues left in the soil which, not being removed from the system, are reused) or "voluntary" (all farm products that the farmer chooses to recycle into the production process rather than destine for final consumption). In particular (Tab. 1), internal transfers can derive from current year (i1) or previous year farm production (i2); inputs from outside derive from agriculture (i3), or from other production sectors (i4). Similarly, output flows can recycle production in current year (o1) or for subsequent cycle (o2), or can be destined for final consumption (o3). A set of agro-ecosystem performance indicators (Tab. 2) is then defined to compare homogeneous output/input flows (monetary or energetic: "direct" indicators), or heterogeneous output/input flows (monetary versus energetic: "crossed" indicators). Direct indicators can be structural (describing the most relevant characteristics of agricultural systems) or functional (measuring the efficiency of different systems and the dependence from non-renewable or external inputs).

Landscape indicators

The agro-ecological network, made of the patch of cultivated fields and interconnected linear elements (such as hedgerows), has a double function: to build the landscape

Tab. 2 – Sructural, functional and crossed indicators (from Tellarini and Caporali, 1999).
Tab. 2 *– Indicatori strutturali, funzionali ed incrociati (da Tellarini e Caporali, 1999).*

Structural indicators	
1	Indicator of dependence on non-renewable energy sources (i4/i8)
2	Indicator of obligatory re-use [(i1a+i2a)/i8]
3	Indicator of immediate voluntary re-use (i1b/i8)
4	Indicator of deferred voluntary re-use (i2b/i8)
5	Global indicator of voluntary re-use [(i1b+i2b)/i8]
6	Indicator of farm autonomy (i5/i8)
7	Indicator of overall sustainability (i7/i8)
8	Indicator of immediate removal (o3/o5)
9	Indicator of total removal (o4/o5)
10	Indicator of obligatory internal destination [(o1a+o2a)/o5]
11	Indicator of immediate voluntary internal destination (o1b/o5)
12	Global indicator of immediate internal destination (o1/o5)
Functional indicators (GJ/GJ or €/€)	
13	Indicator of gross output from total input (o5/i8)
14	Indicator of gross output from total farm input (o5/i5)
15	Indicator of gross output from annual farm input (o5/i1)
16	Indicator of gross output from external non-renewable input (o5/i4)
17	Indicator of gross output from total external input (o5/i6)
13	Indicator of net output from total input (o4/i8)
14	Indicator of net output from total farm input (o4/i5)
15	Indicator of net output from annual farm input (o4/i1)
16	Indicator of net output from external non-renewable input (o4/i4)
17	Indicator of net output from total external input (o4/i6)
Crossed indicators (€/GJ or GJ/€)	
18	Gross economic productivity of total energy input (o5/i8)
19	Gross economic productivity of energy input from outside the farm (o5/i6)
20	Gross economic productivity of non-renewable energy input (o5/i4)
21	Gross economic productivity of energy input produced by agriculture (o5/i7)
22	Net economic productivity of total energy input (o4/i8)
23	Net economic productivity of energy input from outside the farm (o4/i6)
24	Net economic productivity of non-renewable energy input (o4/i4)
25	Net economic productivity of energy input produced by agriculture (o4/i7)

and to maintain the biological diversity, important for air, water and soil quality. Farm management influences the quality of landscape and consequently the biodiversity and this concept is highlighted by several approaches aimed at studying the importance of agriculture in the evolution of the landscape (Weinstoerffer and Girardin, 2000). Here we focus on indicators describing the relation between farm management and landscape.
In particular, many indicators were developed for application at regional scale, where the action of agriculture takes place on landscape. However, indicators can be useful also to identify the contribution of single farms to landscape quality and biodiversity. We will therefore comment the indicators which can be applied at single farming systems, like the crop diversity indicator proposed by Bockstaller and Girardin (2000), the hedge-row indicator used by Bocchi *et al.* (2004), applied at regional scale, but applicable also for single farms, and the landscape indicator by Weinstoerffer and Girardin (2000). Other approaches like the Mosaic indicators (Hoffmann and Greef, 2003; Hoffman *et al.*, 2003) consider the presence and abundance of specific indicator species, chosen as representative of the location and the region. This indicator requires several input data, some of which require specific measurements; for this reason, and despite their interest, we will not consider these indicators in our review.
At the farm scale, Bockstaller and Girardin (2000) have proposed a crop diversity indicator (I_{cd}) that evaluates the impact of crop partitioning and field size on landscape and biodiversity. It provides a value from 0 (worst case) to 10 (best case). A value of 7 represents the achievement of a minimum level. The indicator is calculated as: I_{cd} = K NC D T, where K is a calibration factor depending on the number of crops (K is equal to 2.00, 1.83, 1.70, 1.59, 1.50, 1.42, 1.36, 1.30, 1.25 if NC is $\leq$ 4, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0 respectively), NC is the number of crops (from 1 to 8; the intercrop in double-crop systems has a weight of 0.5), D is the crop partitioning factor and T is the field size factor. The crop partitioning factor (D) measures the diversity of crop partitioning; its maximum value is 1, and corresponds to the situation when the areas cultivated with each crop are equal; low values indicate that one or few crops dominate, i.e. occupy most of farm area. The factor D is calculated by dividing the Shannon diversity index (calculated using crop areas instead of species abundances) by the maximum value of the Shannon index which would be obtained in the case of homogeneous partitioning:

D = IS / IS_h, where $IS = \sum_{i=1}^{NC} (p_i \ln p_i)$,

with $p_i = S_i / S_{tot}$ (ratio of S_i the area of the i-th species, to S_{tot}, the total farm area), and IS_h = ln (1 / NC). The field size factor (T) considers the fragmentation of the field:
$T = 1 - SA_{big} / S_{tot}$,
where SA_{big} is the area of the fields considered "big" (ha):

$$SA_{big} = \sum_{i=1}^{FN} (c_i F_i),$$

where FN is the number of the fields, F_i is the area of the i-th field (ha), c_i is a factor depending on field size:

$c_i = 0$ if $F_i < L_{low}$,
$c_i = 1$ if $F_i > L_{high}$,

$$c_i = \left(\frac{1}{(L_{high} - L_{low})}\right) \cdot \left[F_i - \left(\frac{L_{low}}{L_{high} - L_{low}}\right)\right]$$

if $L_{low} \leq F_i \leq L_{high}$,

where L_{high} is the threshold over which the field is considered "big" (proposed value: 15 ha), L_{low} is the threshold under which the field is considered "small" (proposed value: 5 ha). The hedge-row indicator (Bocchi *et al.*, 2004) describes the evolution and the quality of the landscape, considering the hedges and the rows as impor-

Tab. 3 – Scores of spatial (S_k) and linear (H_k) shapes contributing to landscape openness, used in the calculation of the landscape indicator (from Weinstoerffer and Girardin**,** 2000).

Tab. 3 – *Punteggi degli strati spaziali (S_k) e lineari (H_k) che contribuiscono all'apertura visiva, usati nel calcolo dell'indicatore di paesaggio (da Weinstoerffer e Girardin, 2000).*

Contribution of the spatial shapes to the openness supply			
Forest	0	Wooded orchard	3
Intensive orchard hops	1	"Open" crops[b]	4
"Closed" crops[a]	2		
Contribution of the linear shapes to the openness supply			
Linear wooded margin	0	New hedge[c], line of trees	3
Windbreak hedge	1	Grassland field margin	4
Hedge fence	2		

a "Closed" crops: maize, sorghum, sunflower, which close the landscape because of the height of the plants.
b "Open" crops, which have no influence on the openness of landscape.
c Less than 2 years.

tant structural elements. $I_{hr} = L / A$ (m ha^{-1}), where L is the hedge-row length (m) and A is the total area analysed (ha). This indicator has been created and applied for the regional scale, but it is possible to apply it also at the farm scale.

The landscape indicator **(**Weinstoerffer and Girardin**,** 2000) evaluates the correspondence between landscape supply by farmer and landscape demand by social groups. The four main evaluation criteria proposed to calculate demand and supply are: openness (the ease with which an observer can obtain an exhaustive view over the surrounding country), upkeep (the fact that land forms are as uniform and well organised as possible), heritage (the presence of evidence of numerous traces of ancient practices), diversity (the differences in nature, quality and aspect). To calculate the indicator (Fig. 2), supply and demand are separately calculated, and then compared, for each evaluation criterion; landscape supply is calculated for each field and averaged for the farm. In the calculation of the supply, the landscape is described with three different types of shapes that compose the landscape: spatial shapes (crop, permanent grassland, farm yard, woodland, etc.), linear shapes (hedge, row of trees, grassland margin, wall, trench, bank, etc.) and isolated shapes (single tree, agricultural equipment, building, etc.). For every evaluation criterion (openness, upkeep, heritage, diversity) all shapes pertaining to a field are evaluated with a score; the scores are then linearly aggregated:

$$I_S(i) = \frac{\sum_{k=1}^{j} S_k}{j}, \quad I_L(i) = \frac{\sum_{k=1}^{m} \left[L_k \cdot (H_k) \right]}{\sum_{k=1}^{m} L_k}, \quad I_P(i) = \frac{\sum_{k=1}^{n} P_k}{n},$$

where $I_S(i)$ is the spatial shape index, $I_L(i)$ is the linear shape index and $I_P(i)$ is the punctual shape index for the i-th field; S_k is the score that characterizes the state of k-th spatial shape (not weighted based on shape area), j is the number of spatial shapes in the i-th field; H_k is the score that characterizes the state of the k-th linear shape,

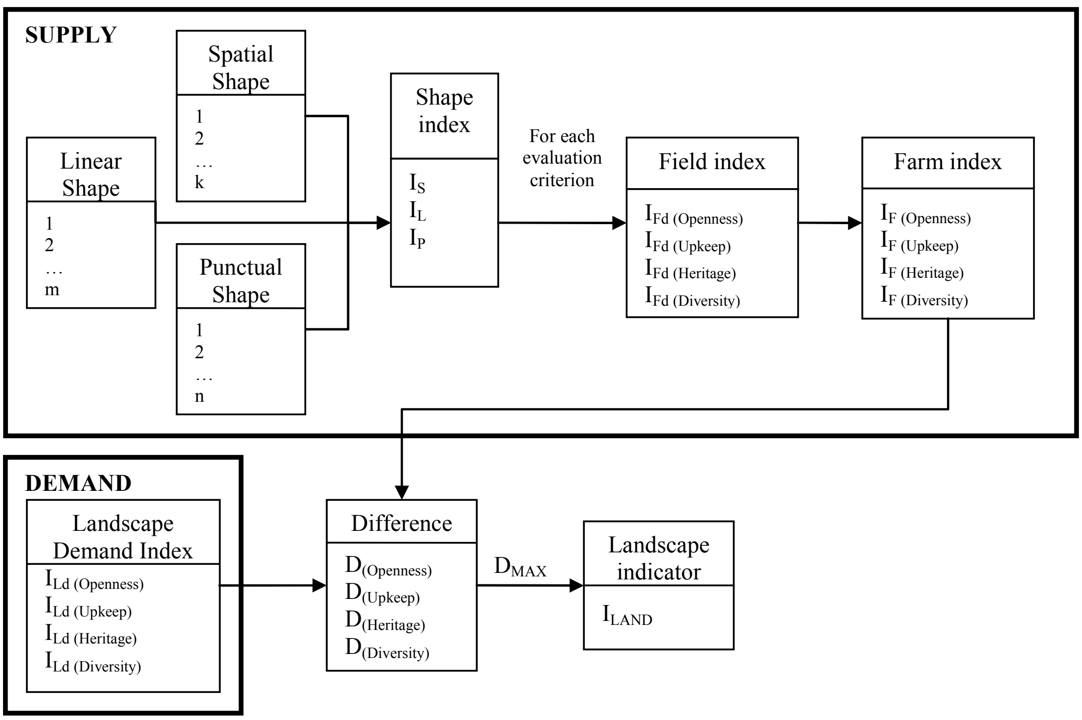

Fig. 2 – Calculation of the landscape indicator (I_{LAND}) (from Weinstoerffer and Girardin, 2000).

Fig. 2 *– Calcolo dell'indicatore paesaggio (I_{LAND}) (da Weinstoerffer e Girardin, 2000).*

Tab. 4 – Scores of spatial (S_k), linear (H_k) and punctual (P_k) shapes contributing to landscape heritage, used in the calculation of the landscape indicator (from Weinstoerffer and Girardin, 2000).

Tab 4 *– Punteggi degli strati spaziali (S_k), lineari (H_k) e puntuali (P_k) che contribuiscono all'eredità nel del paesaggio, usati nel calcolo dell'indicatore di paesaggio (da Weinstoerffer e Girardin, 2000).*

Contribution of the spatial shapes to the heritage supply					
The crops					
Species	Usual 4	New 0			
Area	Stable 4	Transformed 2	Changed 0		
Shape	Stable 4	Transformed 2	New 0		
The Farm					
Site	Identical 4	New 2			
Arrange ment	Identical 4	Transformed 2	New 0		
Farm yard	Identical 4	Transformed 2	New 0		
Contribution of the linear shapes to the heritage supply					
Linear shapes	Stable 4		Transformed 0		
Contribution of the punctual shapes to the heritage supply					
Building	Maintained customs	Died out customs	Rebuilt according to the traditional style	Deeply reshaped	Newly built or destroyed
	4	3	2	1	0
Vegetation	Identical		New		
	4		0		

L_k is the length of the k-th linear shape, m is the number of linear shapes in the i-th field; P_k is the score that characterizes the state of k-th punctual shape, n is the number of punctual shapes in the i-th field. The score is limited between 0 to 4 (0 is given to the shape contributing the least to the criterion), and the authors suggest an expert judgement score for the openness criterion (Tab. 3), the landscape upkeep criterion (Tab. 5), and the heritage criterion (Tab. 4). For the landscape diversity criterion, the supply of diversity of a farm is integrated into the calculation of the crop diversity indicator, described previously (I_{cs}, Bockstaller and Girardin, 2000). The field index (I_{Fd}) is obtained by combining the three shape indices:

$$I_{Fd(i)} = \frac{I_{S(i)} + I_{L(i)} + I_{P(i)}}{3}$$

assuming that each shape group, at this level, has an equal influence in the contribution to the landscape supply. The farm index is obtained by combining the field indices for the total number of fields in the farm. The score for every field is weighted accordingly to its area and it is separately calculated for every evaluation criterion:

Tab. 5 – Scores of spatial (S_k), linear (H_k) and punctual (P_k) shapes contributing to landscape upkeep, used in the calculation of the landscape indicator (from Weinstoerffer and Girardin**,** 2000).

Tab. 5- Punteggi degli strati spaziali (S_k), lineari (H_k) e puntuali (P_k) che contribuiscono al mantenimento del paesaggio, usati nel calcolo dell'indicatore di paesaggio (da Weinstoerffer e Girardin, 2000).

Contribution of the spatial shapes to the upkeep supply					
Crops	Tillage and weeding				
	No intervention	Mechanical weeding		Chemical weeding	
		No tillage	Tillage	No tillage	Tillage
Winter cereals, rape seed	0.0	1.0	2.0	3.0	4.0
Spring cereals, peas	0.0	1.0	2.0	4.0	
Other spring crops	0.0	0.5	1.5	3.5	
Green manure	2.0	3.0	2.0	3.0	

Set aside	Spontaneous set aside		Cultivated set aside
	After sunflower, maize, soybean, sugar beet or potatoes	After cereals, rape seed or peas	
	0	1	2
Fallow land	0		
Permanent crops			
Meadow	Cutting frequency (year^{-1})		
	≥3	2	1
	4	2	0
Cut grazed pasture	Cutting or grazing frequency (year^{-1})		
	≥3	2	1
	4	2	0
Grazed pasture	Intensive pasture		Extensive pasture
	With refusals cutting	Without refusals cutting	
	4	2	0
Arboriculture — forest	Woody plant pruning		
	Regular upkeep	Occasional upkeep	Without upkeep
	4	2	0
Farm yard	Aspect		
	Kept up	Occasional	Untidy
	4	2	0
Contribution of the linear shapes to the upkeep supply			
Upkeep of each linear shape	Regular 4	Occasional 2	Without upkeep 0
Contribution of the punctual shapes to the upkeep supply			
Upkeep of each punctual shape	Regular 4	Occasional 2	Without upkeep 0

$$I_F = \frac{\sum_{i=1}^{n} \left[A_{(i)} \cdot I_{Fd(i)} \right]}{\sum_{i=1}^{n} A_{(i)}},$$

where I_F is the farm index for a specific criterion, $A_{(i)}$ is the area of i-th field.

The evaluation of the landscape demand is qualitative and it is done using the judgement of several stakeholders. In a questionnaire all the terms are listed that can be used to describe agricultural landscape in a qualitative way. The stakeholders have to choose the element which they wish to see in the farm area (Tab.). The median score is assumed as the indifference evaluation on the part of the observers. For each criterion the absolute value of the difference between the supply and the demand is calculated. It is assumed that one of the criteria cannot compensate for another in the final result; therefore for the evaluation of landscape indicator the least favourable difference between supply and demand (D_{MAX}) is used. The maximum difference is scaled to a maximum of 10 using a coefficient (2.5) to obtain the landscape indicator: I_{LAND}= 10 - (D_{MAX} 2.5). The landscape indicator can also be used for an assessment at the regional level.

Tab. 6 – Scores of desired landscape elements used for landscape demand calculation (I_{ld}) (modified from Weinstoerffer and Girardin, 2000).

Tab. *– Punteggi degli elementi di paesaggio desiderabili utilizzati per il calcolo della domanda di paesaggio (I_{ld}) (modificato da Weinstoerffer e Girardin, 2000).*

Evaluation criteria							
Openness		Heritage		Upkeep		Diversity	
Bared	4	Preserved	4	Meticulous	4	Varied	4
Stripped	3	Protected	3	Well kept	3	Heterogeneous	3
Indifferent	2	Indifferent	2	Indifferent	2	Indifferent	2
Obstructed	1	Modified	1	Badly kept	1	Homogeneous	1
Blocked	0	Transformed	0	Disused	0	Uniform	0

Soil management indicators

These indicators describe how tillage, incorporation of organic materials into the soil, soil cover with crops and residues, and consequently crop rotations influence soil fertility.

Crop rotation is one of the most important factors that influence soil fertility, helping to break the cycle of harmful organisms, improving soil structure, enhancing soil quality and making soil less vulnerable to erosion (Leteinturier *et al.*, 2006). The crop sequence indicator (I_{sc}) was developed by Bockstaller and Girardin (1996, 2000); it provides a value from 0 (worst value) to 10 (best value); a value of 7 represents the achievement of a minimum level. It is a method of global diagnosis applicable at field level; for a single crop it is defined as: I_{sc} = K_p K_r K_d, where K_p is the coefficient describing the effects of the preceding crop on the current crop, K_r depends on the frequency of crop cultivation and K_d is an index of crop diversity.

K_p is derived from the sum of five effect scores (development of pathogens, pests, weeds, soil structure and nitrogen), representing the effect of the previous crop on the current crop. These effects are estimated by an expert group on a semiquantitive scale, from –1 to +1 for soil structure and nitrogen supply, from –3 to +1 for pathogens, from –2 to +1 for weeds and pests. A transformation is then made to convert the sum of scores (S) into the K_p coefficient, obtaining a value on a scale from 1 to 6 (K_p = S + 5 with a minimum and maximum value of 1 and 6 respectively). Examples of K_p values for many previous/actual crop combinations are given in the literature for French and Belgian pedo-climatic and agronomic conditions (Bockstaller and Girardin, 1996, 2000; Leteinturier *et al.*, 2006). K_r is obtained by transforming the difference of the actual return time of crop on a field (t) minus the recommended return time (t_r) which is known to limit the risks of diseases or pests (K_r is equal to 0.3, 0.5, 0.8, 1.0 and 1.2 if t-t_r is -3, -2, -1, 0 and $\geq$ 1 respectively). The quantity K_d is calculated by transforming the number of different crops (NC) cultivated in the last four years (K_d = 0.2 NC + 0.6 with a minimum and maximum value of 1.0 and 1.4 respectively). The indicator I_{sc} can be calculated for every crop in the rotation; the I_{sc} for the entire rotation is calculated as the average of the I_{sc} of single crops.

One of the most important attributes of soil quality is the organic matter (SOM) content; Bockstaller *et al.* (1997) and Bockstaller and Girardin (2000) have proposed the organic matter indicator in order to detect the negative and the positive effects of different crop management practices on SOM content. The aim of this indicator is to identify and promote the practices that maintain SOM at a satisfactory level. It is an impact indicator applicable at field level and it provides a value from 0 (worst value) to 10 (best value); a value of 7 represents the achievement of a minimum level. The indicator is defined as: I_{OM} = 7 (A_x / A_r), where A_x (kg ha^{-1} y^{-1}) is the mean of OM inputs (residues, manure, green manure, etc.) in the four preceding cropping years, A_r (kg ha^{-1} y^{-1}) is the recommended level of OM inputs needed to maintain a satisfying level of SOM in the long term.

The organic supply (A_x) is defined as (Boffin *et al.*, 1986):

$$A_x = \sum_{i=1}^{N}(k_{root(i)} \cdot m_{root(i)} \cdot f_{root(i)} + k_{residue(i)} \cdot m_{residue(i)} \cdot f_{residue(i)}) + ,$$

$$+ \sum_{i=1}^{N}(k_{manure(i)} \cdot m_{manure(i)} \cdot f_{manure(i)}) \qquad ,$$

where k_{root}, $k_{residue}$, k_{manure} are humification coefficients of roots, residues and manures, respectively (dimensionless), m_{root}, $m_{residue}$, m_{manure}, are the mass applied of roots, residues and manures respectively (kg ha^{-1} y^{-1}), and f_{root}, $f_{residue}$, f_{manure} are the frequencies of application in the four years. Example of k coefficients are available in Boffin *et al.* (1986).

The Hénin and Dupuis model (1945) is used to derive the relationship between the equilibrium level of SOM and OM inputs to a specific soil: $A_r = \tau_{es}$ k_2 M P, where τ_{es} is the SOM concentration (g SOM g soil^{-1}) recommended for a specific textural class, k_2 is the annual mineralization coefficient (y^{-1}), M is the soil mass at tilled depth (kg soil ha^{-1}), P is a modifier of the mineralization coefficient (dimensionless). The annual mineralization coefficient is estimated on the basis of soil texture, limestone content and air temperature:

$$k_2 = \frac{1200 \cdot f_\theta}{(200 + A) \cdot (200 + 0.3 \cdot C)}$$

(Boiffin *et al*., 1986), where f_θ is a temperature factor: $f_\theta = 0.2(T-5)$, where T is the average annual air temperature (°C), A is clay content (g kg^{-1}), C is limestone content (g kg^{-1}). If no soil analyses are available for every field, soil maps or geostatistical techniques (e.g. Guimaraes Couto *et al*., 1997; Schloeder *et al*., 2001; De Ferrari *et al*., 2002) can be used to estimate clay and limestone contents. The modifier of mineralization coefficient is calculated as:

$P = f_r I T_s$,

where f_r is a coefficient considering crop management (Tab.), I is a mineralization weight factor (suggested value: 1.25), T_s is a tillage factor (1.0 if the soil is tilled at least once in four years; 0.5 if only no tillage practices were used in the last four years; 0.8 in intermediate cases, with at least one year of minimum tillage).

Other risks related to soil management are structure degradation, erosion, nutrient and pesticide losses and reduction of biodiversity. Vereijken (1995) has proposed the Soil Cover Index (SCI) for evaluation of soil protection by crops. This indicator calculates the percentage of soil cover by crops or residues in a short period (month), in one year or in a critical period (e.g. autumn):

$SCI_{month} = (SCI_{start} + SCI_{end}) / 2$,

where SCI_{start} is the percentage of soil surface cover by crops or residues on the first day of the month and SCI_{end} is the percentage on the last day. To avoid direct measurements of soil cover by the crop, the well know crop coefficients (Allen *et al*., 1998) can be used. SCI is 1 if the soil is completely covered by crops or residues and is 0 if the soil is bare. It is possible to choose intermediate values in proportion to the percentage of cover. For a period longer than a month (e.g. year),

$$SCI_{period} = \left(\sum_{i=1}^{n} SCI_{month} \right) / n,$$

where n is the number of months considered. SCI_{month} provides a value between 0 and 1, and SCI_{period} is in the range 0 – 12, if the chosen period is one year. Once SCI is calculated at field scale, it can be averaged for the farm, recalling that it is necessary to calculate the SCI also for the fallow, for the woodland and for the row-hedges. Similar calculations can be done also at regional scale. The Organisation for Economic Co-operation and Development (2001) suggested the use of a similar indicator, calculated from agricultural census data, and representing the number of days in a year that agricultural soils are covered with crops. The Organisation for Economic Co-operation and Development (2001) proposed also another indicator at national scale, but applicable also at farm scale, in order to represent the winter soil cover; its values are calculated according to the type of cover, and are maximum (100) for fallow land planted before September, intermediate for rapeseed and winter wheat (80 and 40 respectively) and lowest for bare soil (0). The individual values are then aggregated into a single indicator. The risk for soil erosion and nutrient leaching is considered acceptable when the aggregate index is above 50.

For the determination of the risk of soil erosion by water, the Organisation for Economic Co-operation and Development (2001) proposed to use the well-known Universal Soil Loss Equation (USLE): $E_{water} = R\ K\ LS\ C\ P / T$, where E_{water} is an indicator of the potential long term average annual soil loss (unitless), R is the rainfall and runoff erosivity (MJ mm ha^{-1} h^{-1} y^{-1}) considering the intensity, the duration and the frequency of rain storms, K is the soil erodibility factor (t h MJ^{-1} mm^{-1}), LS is the slope length-gradient factor (dimensionless), C is the crop/vegetation and management factor (dimensionless), P is the conservation management factor (dimensionless), T is the tolerable soil loss rate (t ha^{-1} y^{-1}), which can be evaluated according to the levels (Tab.) of soil erosion risk proposed by the Organisation for Economic Co-operation and Development (2001).

We did not find in the literature a simple indicator of the effects of soil management on soil structure and its stability. We believe that this would be a very important indicator, also considering the increasing importance of no tillage and minimum tillage practices. Works as the ones of Défossez and Richard (2002) or of Roger-Estrade *et al*. (2000) may constitute a good starting point for the development of such an indicator.

Tab. 7 – Crop management coefficient (fr) used to consider crop management in the calculation of the modifier of mineralization coefficient (P) in the organic matter indicator (from Bockstaller and Girardin, 2000).

Tab. *– Coefficiente di gestione colturale (fr) utilizzato per considerare la gestione delle colture nel calcolo del coefficiente di modificazione della mineralizzazione (P) per l'indicatore di sostanza organica (da Bockstaller e Girardin, 2000).*

Crop residue management	**Organic input frequency (manure, compost, etc.)**			
	> 10 years	Between 5 and 10 years	Between 3 and 5 years	< 3 year
Removed or burned	0.8	0.9	1.0	1.1
Incorporated once in two years	0.9	1.0	1.1	1.2
Incorporated every year	1.0	1.1	1.2	1.3

Tab. 8 – Definition of soil water erosion risk based on the total amount of soil loss (from Organisation for Economic Co-operation and Development, 2001).

Tab. *– Definizione del rischio di erosione da acqua in base alla quantità di suolo perso (da Organisation for Economic Co-operation and Development, 2001).*

Definition	**t ha^{-1} y^{-1}**
Tolerable erosion	< 6.0
Low erosion	6.0 - 10.9
Moderate erosion	11.0 - 21.9
High erosion	22.0 - 32.9
Severe erosion	> 33.0

Discussion and conclusions

The proposed agro-ecological indicators can be calculated at field and farm scale on a relatively small data set describing management, based on farmer's declarations, public databases, or remote-sensed information, without the need of direct measurements. Their calculation is relatively rapid, and interpretation is simple. As such, they represent an excellent tool to rank and classify cropping and farming systems according to their level of sustainability, by exploring a wide range of aspects (fossil energy use, landscape and soil management). After the application of the indicators, additional analyses for particular fields or farms can be carried out, by applying simulation models, or by taking direct measures of the variables of interest for understanding specific processes. Several critical aspects, however, should be considered, namely indicator complexity, input data uncertainty, parameterisation and benchmarks.

Simple vs. complex indicators

First of all, agro-ecological indicators vary widely in the range of complexity and in the associated range of detail of system representation. As shown in this review, indicators range from simple ratios (e.g. the hedge-row indicator) to complex calculations involving detailed aspects of crop management (e.g. the energy indicator proposed by Pervanchon *et al*., 2002). The question then arises whether one should use a simple or a complex indicator. In general, simple indicators require less input data and are easier to calculate, but the representation of the system they can provide may be poor.

The quantification of fossil energy use with the method of Dalgaard *et al*. (2000) is based on crop management data at field and animal housing level which can be obtained by interviewing the farmer. Therefore this indicator represents a good compromise between detail and ease of application. On the other hand, the approach proposed by Pervanchon *et al*. (2002) is relatively more complex (being based on numerous variables about agricultural machineries) and can be used to better calculate and understand energy flows at the cropping system level. Also, their method is more process-based compared to Dalgaard *et al*. (2000) and is therefore more promising to evaluate alternative management scenarios; a limitation is that it does not consider animal breeding. If one would like to calculate fossil energy use at farm level only, the approach would be much easier: aggregated consumptions of fuel, fertilisers and pesticides (derived for example from documents of purchase) could be multiplied by energy conversion coefficients.

The three landscape indicators are of different level of detail; the one proposed by Bocchi *et al*. (2004) is the simplest, but does not consider several important factors, as the size and the degree of connection of different vegetated elements; it is therefore adequate for a first screening over large areas, but the results need to be further developed using other approaches. The crop diversity indicator of Bockstaller and Girardin (2000) makes an original synthesis of various important aspects of crop allocation to farm land (number of crops and area occupied, area of single fields), and represents a useful tool to investigate the effects of the crop partitioning scheme on landscape quality. A limitation of this indicator is that the temporal variation of crop appearance and its effects on landscape are not taken into account, i.e. the crops are considered as static entities showing no variation over time. The crop diversity indicator is further developed in the framework of the landscape indicator of Weinstoerffer and Girardin (2000), which also considers non-crop elements of farming systems; it is therefore the most complete landscape indicator revised here, with the additional advantage of considering the point of view of interested stakeholders in the concept of landscape demand.

Soil management indicators represent the effects of various processes on soil fertility. The simplest indicator is the Soil Cover Index, which can be easily calculated based on sowing and harvest dates and literature data on crop cover. A simple but reductionist (Kinnell, 2005) approach is also used to calculate the risk of soil erosion. In spite of their simplicity, these two indicators can rank different cropping systems (e.g. for erosion: Boellstorff and Benito, 2005) and allow further studies with models or direct measurements on soil, water and nutrient dynamics for specific cultivation systems. The organic matter indicator makes a synthesis of different aspects of crop management related to humus formation and mineralisation. This complex issue is approached with the simplified annual mineralisation and humification coefficients, corrected for climatic, soil and management effects. Again, it is an approach which can be used to integrate existing information about cropping systems management, to estimate trends and to compare cultivation systems. If more insights are needed, the application of a dedicated simulation model, integrated with relevant experimental data, would represent a good way forward. Finally, the crop sequence indicator attempts to compare cropping systems based on the goodness of crop combinations in the rotation. This is a complex issue, involving many different aspects of soil fertility. In this case, an indicator is probably the best approach when a quantitative solution is needed: simulation models do not fully consider the wide range of processes involved (e.g. pests, weeds) and direct measurements would be too expensive, due to the large number of variables to be considered.

Therefore, we believe that in most cases the indicators can be used as a first warning system before other more complex solutions are introduced in the study. And even when the indicators are relatively complex, we think that they still represent a simpler solution compared to the application of simulation models or measurements for the same domain. Also, beyond the definition of simple and complex, the main issue is that the level of complexity and the potential to describe the system of the indicators should be chosen together with the stakeholders, according to the aim of the study, and considering the relevant agronomic and pedo-climatic context. Therefore there are no predefined categories of simple or complex indicators, but a range of possibilities that can be selected according to the study carried out and to the people participating in it. From the research side, an effort should be undertaken to develop indicators with different compromises between the level of system description (processes represented, wide bibliographic support) and simplification (data requirement, ease of interpretation).

Input data uncertainty

Another issue is that input data used in the calculation of indicators are uncertain; this statement applies to parameters and variables used to describe agricultural management. Public administrations can give a strong contribution to the application of indicators by ensuring the availability of good-quality digital databases at farm and field level, including alpha-numerical information and maps. On the other hand, researchers can contribute by developing indicators whose parameters can be clearly and simply calculated, or retrieved from literature. Also, they should quantify the uncertainty in the calculated values of indicators (and the corresponding variations in the ranking of the studied systems) arising from the uncertainty in input data.

Parameterisation

The application of indicators requires in several cases the use of site-specific parameters. Examples taken from the indicators presented in this review include: the thresholds defining "small" and "big" fields for the crop diversity indicator (Bockstaller and Girardin, 2000); the coefficients used to calculate the energy consumed for crop and animal management, and the indirect energy used in the production of inputs; the scores defining the contribution of three types of shapes to the landscape supply (Weinstoerffer and Girardin, 2000); the parameters describing the effect of each previous-successive crop combination in a rotation (Bockstaller and Girardin, 1996, 2000). It is likely that these parameters vary in different study areas; therefore new values need to be defined when the indicators are applied to new situations. Even if this can be seen as a limitation, we believe that in most cases it is a necessary step in the calculation of agro-ecological indicators, as a mean of adapting a general rule (algorithm) to a specific situation. It also should be noted that only the use of very simple indicators, constituted by the direct use of available data (e.g. amount of fuel consumed per kg of output obtained) could avoid this problem, while simulation models and other assessment tools would still require parameterisation. The degree of subjectivity can also be narrowed by selecting parameter values together with the stakeholders, to represent the system using information from all interested groups. Also, the uncertainty analysis should provide indications on the variation of the ranking of different systems generated by the variation of parameter values. If, as in the case of the crop diversity indicator (Bechini, data not published), the ranking of farms does not vary much with the variation of parameter values, parameterisation becomes of smaller importance.

Benchmarks

Finally, one of the most critical aspects of the application of indicators is the level chosen for the threshold benchmark. The value of the benchmarks changes of course depending on the stakeholders involved (e.g. educators, advisors, researchers, farmers, policy makers, food industry, certifying organisations, consumers, supermarkets), and on agro-pedo-climatic conditions. Existing laws or bio-physical considerations can provide useful indications for the development of benchmarks. The development of specific benchmarks for the indicators represent an important field of interaction between researchers and stakeholders.

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