



HAL
open science

Stockless organic farming: strengths and weaknesses evidenced by a multicriteria sustainability assessment model

Bruno Colomb, Matthieu Carof, Anne Aveline, Jacques-Eric Bergez

► To cite this version:

Bruno Colomb, Matthieu Carof, Anne Aveline, Jacques-Eric Bergez. Stockless organic farming: strengths and weaknesses evidenced by a multicriteria sustainability assessment model. *Agronomy for Sustainable Development*, 2013, 33 (3), pp.593-608. 10.1007/s13593-012-0126-5 . hal-01201369

HAL Id: hal-01201369

<https://hal.science/hal-01201369v1>

Submitted on 17 Sep 2015

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Stockless organic farming: strengths and weaknesses evidenced by a multicriteria sustainability assessment model

Bruno Colomb · Matthieu Carof · Anne Aveline · Jacques-Eric Bergez

Accepted: 23 November 2012 / Published online: 18 December 2012
© INRA and Springer-Verlag France 2012

Abstract Agronomists need methodologies to assess the sustainability of cropping systems. Few models such as MASC have been recently developed for evaluation. The effective use of those models is still a challenge, notably for low-input systems. Here a more specific model entitled MASC-OF was developed and applied to study stockless organic cropping systems. The MASC-OF model is original because it is based on agricultural advisers' needs and expertises. Two groups of advisers supported by agronomic scientists were involved in a nine-step methodology to progress from preliminary meetings to data analysis. The methodology allowed advisers to design a model including their own views on what is a sustainable organic cropping system. Soil fertility and weed and pest control were integrated as a new branch in

the original MASC model. We also developed evaluation criteria for each basic attribute, defining aggregation rules and weighting attributes. Tested case studies were based on 44 real cropping systems identified on 19 farms in the Midi-Pyrenees region of France and on 23 cropping system types developed by the advisers from the Centre, Ile-de-France, Pays de Loire, Poitou-Charentes and Rhône-Alpes regions of France. Our results show that a high score of economic sustainability is the most difficult to achieve. This finding is explained by low productivity of cereal crops and high variability of market prices for organic grain. Further, agronomic viability is also difficult to ensure, as a consequence of poor soil-fertility management practices. The ability to achieve social acceptability for the producer, including workload and health risk, is high. By contrast, acceptability for the society has a medium score due to reduced productivity and contribution to local employment. Environmental sustainability is the easiest dimension to achieve, despite nitrogen-loss risks in some situations and high water and energy consumption in irrigated systems. Overall our findings show that the potential for the development of more sustainable organic cropping systems in stockless farms is high.

B. Colomb · J.-E. Bergez
INRA, UMR 1248 AGIR, BP 52627,
31326 Castanet Tolosan Cedex, France

J.-E. Bergez
e-mail: jbergez@toulouse.inra.fr

B. Colomb (✉) · J.-E. Bergez
INP Toulouse, UMR 1248 AGIR, BP 52627,
31326 Castanet Tolosan Cedex, France
e-mail: colomb@toulouse.inra.fr

M. Carof
AGROCAMPUS OUEST, Sol Agro et Hydrosystème
Spatialisation, 35000 Rennes, France
e-mail: matthieu.carof@agrocampus-ouest.fr

M. Carof
INRA, UMR1069, Sol Agro et Hydrosystème Spatialisation,
35000 Rennes, France

M. Carof
Université Européenne de Bretagne, 5 Boulevard Laënnec,
35000 Rennes, France

A. Aveline
Groupe ESA, LEVA, BP 30748, 49007 Angers Cedex 01, France
e-mail: a.aveline@groupe-esa.com

Keywords Cropping systems · Sustainability assessment · Organic farming · Multicriteria · MASC · MASC-OF · DEXI

1 Introduction

Designing cropping systems to combine both productivity and general principles of sustainability is a complex decision problem (Bergez et al. 2010; Kropff et al. 2001; Meynard et al. 2001; Sadok et al. 2008). Formal approaches involve at least four steps: (a) analysing to encompass the diverse economic, social and environmental goals associated with cropping systems; (b) envisioning new scenarios; (c) assessing these scenarios and (d) testing promising ones in targeted

territorial contexts (Debaeke et al. 2009; Vereijken 1997). Such approaches require the integration of several scientific disciplines and involvement of stakeholders from the agricultural sector. The French government encouraged the emergence of specialised national agricultural networks (RMT SdCi 2011; RMT DévAB 2011) to facilitate multiple-stakeholder projects targeting the design, assessment and testing of cropping systems. Network members from agricultural advisory institutions highlighted the lack of accessible tools to assess the sustainability of existing or candidate cropping systems, which allow them to be fully involved in the evaluation process and to incorporate their own views on how to make the concept of sustainability operational.

Few models for the evaluation and design of agricultural systems at field or farm levels have been published during the last two decades (Bachinger and Zander 2007; Dogliotti et al. 2003; Mazzetto and Bonera 2003; Pacini et al. 2003; Strassert and Prato 2002; Zander et al. 1999). These models have different operational definitions of the agricultural sustainability of cropping systems. The diversity of their panels of indicators reflects that sustainability is far from a unique and straightforward assessment. Considering the experience gained from these and other works (Bockstaller et al. 2008; Sadok et al. 2008) and the requests of advisory institutions, a new family of models has been recently developed in France. Based on the same qualitative multi-attribute decision support system, these models have assessed the sustainability of cropping systems (Craheix et al. 2012; Pelzer et al. 2012; Sadok et al. 2009) and vineyard systems (Aouadi 2011). They have the following common features: (a) ability to qualitatively assess economic, social and environmental sustainability of production systems at a fine scale (e.g. field, vine); (b) a hierarchical breakdown of sustainability dimensions that allows for aggregation of basic indicators into a single sustainability indicator for ranking systems; (c) a flexible way for stakeholders to incorporate their own visions of the relative importance of sustainability issues (i.e. modify indicator weights), due to the underlying decision support system and (d) no pre-defined method to calculate the basic indicators, allowing stakeholders to choose appropriate methods from available knowledge, human skill-sets, financial support and scientific sources.

The first objective of our study was methodological. In France, these qualitative models have been used to test scenarios of innovative cropping systems (Craheix et al. 2012) and vineyard systems (Aouadi 2011) that minimise pesticide use, both systems being designed with the help of farmers or agricultural advisers. In this paper, we demonstrate that this qualitative multicriteria tool can be used to profile the sustainability of existing cropping systems at the regional level and in a way which takes advantage of advisers' expertise. Profiling existing systems consists of revealing strong points to be preserved and weak points to be improved, which would be useful in the first step of the

above-mentioned formal approach for designing more sustainable systems.

The second objective was practical, through the application of the model to evaluate the sustainability of stockless organic cropping systems. This type of cropping system has been developing in France since the launch of a government plan for organic farming (Riquois 1999). According to Agence Bio (2012), organic grain crops represented 130,000 ha in France in 2011, with more than 5,000 ha in nine French regions. Despite the lack of detailed statistics, we consider that 35–40 % of organic grain crops are currently grown within stockless cropping systems. David (2010) concluded that such "specialised" organic systems risked economic and agronomic problems (e.g. nutrient supply, weed management) over the long term, a risk subsequently observed by field advisers as early as 2005. Advisory institutions later decided to undertake a formal evaluation of organic farm sustainability, requesting our help with the design and use of an adequate assessment model, the subject of this paper.

2 Material and methods

2.1 Work organisation and steps of the assessment project

Two groups of advisers supported by agronomic scientists were involved in a nine-step methodology to progress from preliminary meetings to data analysis. The first group was engaged in the 3-year RotAB project launched in 2008 by the French Technical Institute for Organic Farming to survey stockless organic cropping systems in France (ITAB 2008). It included four organic farming advisers from the Chamber of Agriculture of four French regions, three scientists from agricultural engineering schools (Angers, Lyon and Rennes) and the managers of five ongoing French organic cropping system experimental sites. The second group was part of the 3-year CITODAB project launched in 2007 to support the development of organic farming in the Midi-Pyrénées region (Colomb and Gafsi 2011). This group consisted of organic farming advisers from five Chambers of Agriculture in the region, the manager of the long-term experimental site devoted to organic cropping systems located in the region and a coordinator from the regional Chamber of Agriculture in the Midi-Pyrenees region. The nine steps were the following:

Step 1: Both groups detailed the objectives of the project. First, the project should assess the economic, social and agro-environmental sustainability dimensions of a wide range of organic cropping systems, with management strategies ranging from least to most intensive (e.g. the lowest to highest levels of irrigation and fertilisation). Second, the process

should keep the design of the assessment model separate from the choice of the expert methods or tools used to assess the basic indicators. Third, methods and tools involved in the project should be simple to handle, incorporate advisers' expertise and avoid "black box" effects to increase confidence in the results.

Step 2: The choice of the MASC model as a starting point resulted from a comparative study of seven models published for the evaluation of cropping systems at the field or farm level (Carof et al. 2012). They were reviewed according to the following criteria: (a) assessment scale, (b) target audience, (c) relevance of the indicators used, (d) ability to capture the relative importance of indicators to users, (e) ability to aggregate indicators to rank organic cropping systems, (f) ability to perform sensitivity analyses and (g) availability of the software tool and relevant documentation. Considering these criteria, the MASC model (Sadok et al. 2009) was deemed the most appropriate for the goals of the project and so validated by the advisers groups.

The MASC model, developed with the DEXi software, evaluates the sustainability of existing or innovative cropping systems. The DEXi software (Bohanec 2011) allows development of qualitative multi-attribute models (Znidarsic et al. 2008). A model is created by defining (a) attributes (qualitative variables that represent decision sub-problems), (b) scales (ordered or unordered sets of symbolic values assigned to attributes, such as "low" or "excellent"), (c) an attribute tree (a hierarchical structure breaking down the decision problem) and (d) IF-THEN decision rules that define attribute aggregation throughout the attribute tree. The structure of the MASC model is presented in detail in Sadok et al. (2009). It is composed of 65 attributes (Fig. 1a) split between 39 basic attributes (input data) and 26 aggregated attributes. The root attribute is Contribution to sustainable development, which results from aggregation of three attributes: Economic sustainability, Social sustainability and Environmental sustainability. Based on the scores of basic attributes, the model calculates the scores of all aggregated attributes and the root attribute.

Step 3: Involved meetings required for (a) detailed analysis of critical issues in organic cropping systems which were considered not sufficiently addressed by MASC; (b) incorporation and scaling of new attributes and (c) hierarchisation of the new panel of attributes to obtain the MASC-OF model.

Step 4: Dealt with the choice or design of the calculation methods for each basic attribute of the MASC-OF

model. When methods recommended by Sadok et al. (2009) for the MASC model could not be applied (due to lack of data or time), or for new attributes inserted in the model, simple methods were chosen consistently with available information resources, in particular advisers' expertise.

Step 5: Parameterisation of the model (definition of aggregation rules and attribute weighting) was not straightforward. A few weighting patterns were tested, along with changes to some attribute scales.

Step 6: The sensitivity of model predictions was assessed by the scientists with the methodology of Carpani et al. (2012) for sensitivity analysis of hierarchical qualitative decision models. A Monte Carlo sensitivity analysis approach was used, which consists of a random selection of input values according to their probabilities of occurrence. Distribution of the root attribute score provides information about model structure and behaviour. Three iterations were necessary between steps 6 and 5 to verify that the weighting pattern gave the MASC-OF model the ability to distinguish among degrees of sustainability of cropping systems.

Step 7: Conducted independently by each advisers group, aimed at the definition of two case studies to be assessed with the MASC-OF model and its associated databases.

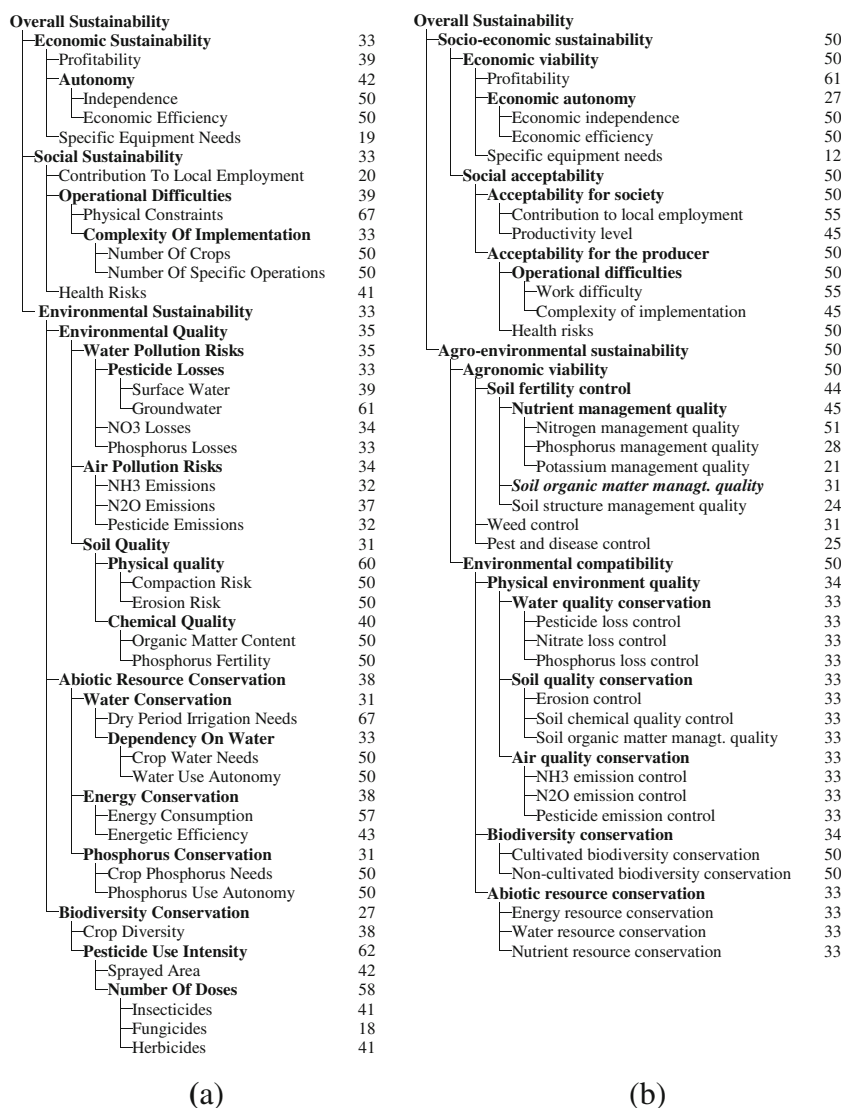
Step 8: Assessment of the two case studies with the MASC-OF model and creation of output databases were performed by the scientists alone.

Step 9: Through intensive discussions within and between groups, advisers analysed the results to identify the sustainability profiles of the two case studies and the main factors (e.g. cropping system features, crop management practices) influencing the scores of sustainability attributes.

2.2 Case studies

The first case study (CS1), developed by the CITODAB group, consisted of 44 cropping systems identified on 19 farms in the Midi-Pyrenees region which were converted to organic farming from 1995 to 2001 (Table 1). The farms were previously selected as representative of organic cropping systems that developed over the last two decades in the region for a detailed energy analysis (Colomb et al. 2009). On each farm, two or three crop sequences managed from 2003 to 2007 were chosen to represent the entire cropping system. The main crops within the 44 systems were winter wheat (29 %), soybean (23 %), sunflower (11 %), lentil (9 %) and faba bean (9 %). No intercropping occurred, and catch crops occurred before less than 2 % of the main

Fig. 1 Comparison of the MASC 1.0 (a, left) and MASC-OF (b, right) models. The latter incorporates a branch dealing with agronomic viability issues, located at the same level as for economic viability, social acceptability and environmental compatibility dimensions. Numbers refer to the weights of the attributes, relative to the closest parental attribute. In the MASC-OF model, apart for the agronomic viability branch, attributes located at the same level within the same branch were given equal weights



crops. Fifty percent of cereals were fertilised with off-farm organic fertilisers. Amounts of applied nitrogen (N) generally ranged between 40 and 80 kg N/ha. Forty percent of summer crops were irrigated. Small amounts of manure and rock phosphate were applied. Fields were typically ploughed yearly, and two to four additional mechanical operations were performed for weed control. More details on CS1 (soil types, data sources) are provided in a project report (Colomb et al. 2011).

The second case study (CS2) was developed by the RotAB group as a result of a survey of organic cropping systems in the Centre, Ile-de-France, Pays de Loire, Poitou-Charentes and Rhône-Alpes regions of France. The advisers identified 11 cropping system types as representative of the most common organic cropping systems within these diverse regions. Several of these typical organic cropping systems are implemented in two or three different soil and climate contexts; therefore, CS2 consisted of 23 contextualised cropping systems (Table 1). Rotation length ranged

from 3 to 10 years; 12 cropping systems involved a 2- or 3-year lucerne crop, and nine systems were irrigated. More details are provided in a RotAB project report (ITAB 2011).

3 Results and discussion

3.1 The MASC-OF model

The resulting MASC-OF model consists of 30 basic input attributes and 19 aggregated attributes (Fig. 1b). The overall sustainability attribute is divided into socioeconomic sustainability and agro-environmental sustainability attributes. The former is then divided into economic viability and social acceptability attributes, while the latter (agro-environmental sustainability) is divided into agronomic viability and environmental compatibility attributes. All seven main attributes are based on the same seven-value qualitative scale (very low, low, rather low, mean, rather high, high,

Table 1 Main features of the cropping systems assessed with the MASC-OF model

Case studies	#	Region/sub-region	Soil	Crop sequence	Irrigation
Case studies 1 (CITODAB project). Midi-Pyrenees Region	1	Vallees-Terrasses garonnaises	Loam	RC-WW-SOY-WW	Yes
	2	Vallees-Terrasses garonnaises	Loam	WW-SOY-WW-SOY	Yes
	3	Vallees-Terrasses garonnaises	Clay loam	LEN-WW-SOY-SOY	Yes
	4	Lauragais	Loam	MAI-SUN-WW-SOY	Yes
	5	Lauragais	Loam	SOY-WW-LEN-PEA	Yes
	6	Lauragais	Loam	FABA-LEN-SOY-WW	Yes
	7	Lauragais	Clay calcareous	WW-SOY-SUN-FABA	No
	8	Lauragais	Clay calcareous	LEN-WW-SUN-FAB	No
	9	Gaillacois	Clay calcareous	WW-SUN-WW-SUN	No
	10	Gaillacois	Clay calcareous	SUN-WW-FAB-WW	No
	11	Coteaux du Gers	Clay calcareous	WDW-WR-FAB-PEA	No
	12	Coteaux du Gers	Clay calcareous	FAB-WR-PEA-CE	No
	13	Coteaux du Gers	Clay calcareous	FAB-WW-LUC-WW	no
	14	Coteaux de Gascogne	Loam	SOY-RC-SOY-SOY	Yes
	15	Coteaux de Gascogne	Clay calcareous	FAB-WW-SOY-SOY	Yes
	16	Coteaux de Gascogne	Loam	WW-FAB-SOY-SOY	Yes
	17	Coteaux de Gascogne	Loam	PEA-WW-SOY-SOY	Yes
	18	Vallees-Terrasses garonnaises	Heavy clay	SUN-WR-LEN-WW	No
	19	Vallees-Terrasses garonnaises	Clay calcareous	MAI-LEN-WW-SOR	No
	20	Lauragais	Clay calcareous	SOY-LEN-SOY-SOY	Yes
	21	Lauragais	Clay calcareous	SOY-SOY-SOY-SUN	Yes
	22	Lauragais	Clay calcareous	SOY-WW-SOY-WW	Yes
	23	Lauragais	Clay calcareous	SOY-WW-LEN-WW	No
	24	Lauragais	Clay calcareous	WW-SOY-SOY-WW	Yes
	25	Vallees-Terrasses garonnaises	Heavy clay	FAB-WW-SOY-WW	Yes
	26	Vallees-Terrasses garonnaises	Heavy clay	SOY-FAB-WW-WDW	Yes
	27	Lauragais	Clay loam	LEN-WDW-SUN-SOY	Yes
	28	Lauragais	Heavy clay	WDW-LENWW-FABA	No
	29	Lauragais	Clay calcareous	SOY-SOY-LEN-WW	Yes
	30	Lauragais	Clay calcareous	PEA-WDW-CP-SUN	No
	31	Plaine albigeoise	Loam	LEN-SUN-WW-LEN	No
	32	Plaine albigeoise	Loam	LEN-WW-SUN-WW	No
	33	Vallees-Terrasses garonnaises	Clay calcareous	WW-SUN-WW-WW	No
	34	Razes	Clay calcareous	WW-PEA-WW-SUN	No
	35	Razes	Clay calcareous	WW-SUN-WW-FABA	No
	36	Razes	Clay calcareous	SUN-WW-LEN-WW	No
	37	Coteaux du Gers	Clay calcareous	WW-LEN-WW-SOY	Yes
	38	Coteaux du Gers	Clay calcareous	SUN-FABA-WW-SUN	No
	39	Coteaux du Gers	Clay calcareous	WW-SOY-WW-SOY	Yes
	40	Coteaux du Gers	Clay calcareous	WW-SOY-WW-SOY	Yes
	41	Coteaux du Gers	Clay calcareous	LU-SUN-EPP-TOU	No
	42	Coteaux du Gers	Clay calcareous	FAB-SR-FAB-WW	No
	43	Coteaux du Gers	Clay calcareous	CP-WW-LEN-WR	No
	44	Coteaux du Gers	Clay calcareous	WW-LEN-WW-HEM	No

Table 1 (continued)

Case studies	#	Region/sub-region	Soil	Crop sequence	Irrigation
Case studies 2 (RotAB project). Five regions	1	Centre 1	Silty clay calcareous	LU(3y)-WW-TRI- WW-FAB-WW-WB	No
	2	Centre 2	Sandy loam	LU(2y)-WW-RB- WW-MAI-FAB-WW	Yes
	3	Ile-de-France 1a	Clay loam	LU(2y)-WW-TRI-WO-FAB-WW-SB-WC-WW	No
	4	Ile-de-France 1b	Loam	LU(2y)-WW-TRI-WO-FAB-WW-SB-WC-WW	No
	5	Ile-de-France 2a	Loam	LU(3y)-WW-OR-WW-FB-WW-SB	No
	6	Ile-de-France 2b	Clay loam	LU(3y)-WW-OR-WW-FB-WW-SB	No
	7	Ile-de-France 3a	Clay loam	FB-WW-MAI-(TRI+PEA)-WW-TRI	No
	8	Ile-de-France 3b	Loam	FB-WW-MAI-(TRI+PEA)-WW-TRI	No
	9	Pays de Loire 1a	Loam	FAB-WW-MAI	Yes
	10	Pays de Loire 1b	Clay	FAB-WW-MAI	Yes
	11	Pays de Loire 2	Sandy loam	FAB-WW-SUN-WB-(TRI+PEA)	No
	12	Poitou-Charentes 1a	Silty clay	LU(3y)-WW-MAI-FAB-TRI-SUN-WB	Yes
	13	Poitou-Charentes 1b	Loam	LU(3y)-WW-MAI-FAB-TRI-SUN-WB	Yes
	14	Poitou-Charentes 1	Silty clay	LU(3y)-WW-MAI-FAB-TRI-SUN-WB	Yes
	15	Poitou-Charentes 2a	Calcareous clay loam	FAB-WW-WB-SUN-WW	No
	16	Poitou-Charentes 2b	Clay loam	FAB-WW-WB-SUN-WW	No
	17	Poitou-Charentes 2c	Loam	FAB-WW-WB-SUN-WW	No
	18	Rhône-Alpes 1a	Loam	LU(3y)-WW-WW-MAI	No
	19	Rhône-Alpes 1b	Silty clay / Sand	LU(3y)-WW-WW-MAI	No
	20	Rhône-Alpes 1c	Silty clay / Sand	LU(3y)-WW-WW-MAI	No
	21	Rhône-Alpes 2a	Clay loam	SOY-WW-MAI	Yes
	22	Rhône-Alpes 2b	Sandy	SOY-WW-MAI	Yes
	23	Rhône-Alpes 2c	Loam	SOY-WW-MAI	Yes

CE cultivated eikorn, *CP* chick pea, *FAB* faba bean, *LEN* lentil, *LU(2y)* 2-year lucerne, *LU(3y)* 3-year lucerne, *MAI* grain maize, *OR* oilseed rape, *PEA* peas, *RC* red clover, *RB* red beet, *SB* spring barley, *SUN* sunflower, *SOR* sorghum, *SOY* soybean, *SR* spring rye, *TRI* triticale, *TRI+PEA* triticale + peas intercropped, *WB* winter barley, *WC* white clover, *WDW* winter durum wheat, *WO* winter oat, *WR* winter rye, *WW* winter wheat

very high) to reflect goal-achievement levels assigned to the cropping systems.

Economic viability is a function of three sub-attributes, inherited from the MASC model. Cropping system profitability represents the annual gross margin. Economic autonomy combines economic independence (i.e. viability without subsidies) and economic efficiency (revenue as a function of operational costs). Specific equipment needs refer to machinery required to cultivate organic fields, such as light spiked harrows for post-emergence weed control, which are not usually used for conventional production.

The social acceptability attribute is separated into acceptability for society and acceptability for the producer. The former encompasses a cropping system's potential contribution to local employment and its productivity level, used for comparison with other cropping systems in the study area. Productivity level is part of the social acceptability attribute, since the ability of organic farming to feed the world or to provide enough goods to society is debated. Acceptability for the producer combines farmer evaluation of health risks and operational difficulties associated with cropping system

management, considering the relative difficulty and complexity of managing cropping systems.

The agronomic viability attribute, not present in the MASC model, refers to an important issue for organically managed fields: the extent to which crop successions maintain soil fertility and control weeds, pests and diseases. The soil fertility control attribute aggregates three sub-attributes. The nutrient management quality attribute was created by advisers. Nitrogen limits productivity in most organically managed fields (Watson et al. 2002), particularly of non-leguminous crops, as shown for French organic wheat (David et al. 2005). A decline in plant-available phosphorus (P) has been observed from surveys of organic fields with different times since conversion and is related to lack of P input, which might affect long-term crop productivity (Goulding et al. 2008). Most soils in France contain large amounts of potassium (K), which can sustain crop requirements for many years. Nevertheless, K deficiencies are likely to occur in light sandy soils for grain crops after growing fodder crops with high K removal, as observed in other European countries (Goulding et al. 2008). The second

(soil organic matter management quality) and third (soil structure management quality) sub-attributes of soil fertility control are inherited from the original MASC model.

Organic cropping systems are designed to reduce perennial and annual weed populations (Mohler 2009; Vereijken 1994). The goal of the weed control attribute is to ascertain whether crop rotation will result in mid- or long-term establishment of a more or less damaging weed flora compared to the initial weed flora. Cropping systems can control damage caused by pest and disease populations, particularly those that are non-mobile and crop-specific (Wijnands 1999). The goal of the pest and disease control attribute is to assess the level of pest and disease pressure on crops within a cropping system in a given environment.

The environmental compatibility attribute is based on three sub-attributes: physical environment quality, biodiversity conservation and abiotic resource conservation. For physical environment quality, the two underlying attributes water quality conservation and air quality conservation refer to the same basic attributes as in the MASC model (i.e. NO_3 , NH_3 , N_2O , pesticides and P emissions). Due to the introduction of agronomic viability in the model, the soil quality conservation attribute differs from that in the MASC model. It combines three attributes: erosion control, soil chemical quality control and soil organic matter management quality. The latter is the only duplicated attribute in MASC-OF. This reflects the importance of soil organic status in organic cropping systems from both environmental and agronomic perspectives. Soil chemical quality control refers to the presence or absence of heavy metals, organic pollutants or soil acidification due to cropping systems. The biodiversity conservation attribute encompasses both non-cultivated and cultivated biodiversity conservation issues. Similar to the MASC model, the abiotic resource conservation attribute considers the conservation (parsimonious use) of fossil energy, water and P resources.

The calculation or evaluation methods associated with the 30 basic attributes are detailed in Table 2. For 19 attributes based on one quantitative criterion or calculated, the criteria, formula or reference methods are provided. For seven attributes based on direct expertise, the main factors considered during discussions are reported. Four attributes referring to complex agronomic issues (P- and K-management quality, soil structure management quality, weed control) were evaluated through a formal process involving both quantitative data and expert evaluation. The formal reasoning processes were framed as hierarchical decision trees using the DEXi methodology and so-called satellite trees compared to the main MASC-OF tree assessment model (Fig. 2a–c). A satellite tree has as a root attribute one of the basic attributes of the main MASC-OF model. Internally, it links this root attribute to attributes referring to influential management practices, soil properties or cropping system features

Within the hierarchy of the MASC-OF model, attributes were given the same weights when located within the same branch at the same level (Fig. 1b). For example, economic viability and social acceptability both have weights of 50%. These equal weights reflect the choice of the working groups not to give one component a larger importance than the other when assessing socioeconomic sustainability. The only exception was for the agronomic viability dimension, in which advisers wished to incorporate their perceptions of the relative importance of attributes. For example, soil fertility, weed control and pest management control were given weights of 44, 31 and 25 %, respectively, for the assessment of agronomic viability.

3.2 Assessment of the case studies

3.2.1 Analysis of the main sustainability indicator scores

Frequencies of the qualitative scores for all attributes are presented in Table 3. The most frequent score for overall sustainability is mean for CS1 and rather high for CS2. Rather low occurs only for CS1 with limited frequency (0.07). There are few very high scores for both cases. The distribution of overall sustainability results from a more favourable distribution of agro-environmental sustainability than for socioeconomic sustainability.

For socioeconomic sustainability the most frequent score is mean for CS1 and rather high for CS2. One fifth of CS1 cropping systems have a rather low score. The distribution of socioeconomic sustainability results from a more favourable distribution of social acceptability than of economic viability in both case studies. Economic viability shows the highest variability among the main sustainability attributes, all scores being present (Fig. 3). The most frequent score is rather low for CS1 and mean for CS2. For social acceptability, the most frequent score is rather high for both case studies.

For agro-environmental sustainability, the most frequent score is rather high for both case studies. The frequency of a mean score is 0.27 for CS1 and zero for CS2. For the agronomic viability sub-attribute, the most frequent score is mean. There is a noticeable proportion of rather low scores for CS1 and CS2, with frequencies of 0.20 and 0.13, respectively. For environmental acceptability, the most frequent score is very high in both cases. Mean scores occur only for CS1 (frequency 0.11). It has the least variability among the main sustainability attributes.

In the DEXi software, an ordinal scale is associated with each qualitative scale (e.g. very low=1, low=2, ..., very high=7), meaning that mean and standard deviation of ordinal scores can be calculated for each attribute in each case study (Table 3, columns M and SD). According to the standard deviation, all top seven sustainability attributes

Table 2 Evaluation methods of the 30 basic attributes of the MASCOF model: C—attributes based on one quantitative criterion or calculated; E—attributes based on direct expertise; S—attributes evaluated through a qualitative approach involving both quantitative data and expert evaluation (see Fig. 2)

Sustainability sub-dimensions	Evaluation mode	Basic attributes	Methods (calculation or expertise)	Criteria, reference methods or main factors considered
Economic viability	C	Profitability	$GM=GP-OC$ (€ha ⁻¹ year ⁻¹)	GM = gross margin; GP = gross product (€ha ⁻¹ year ⁻¹)
	C	Economic independence	$EI=(1-DS/GM)\times 100$ (%)	OC = operational costs; DS = direct subsidies (€ha ⁻¹ year ⁻¹)
	C	Economic efficiency	$EE=(1-OC/GP)\times 100$ (%)	Identification of new machinery required for organic system
	C	Specific equipment needs	Increase (%) in depreciation rate of machinery (€ha ⁻¹ year ⁻¹)	Evaluation of depreciation rate for each machine
Acceptability for society	C	Contribution to local employment	Mean annual labour time (h ha ⁻¹ year ⁻¹)	Labour time required for each crop (h ha ⁻¹ year ⁻¹)
	C	Productivity level	Score from regional yield variability of crops (either organic or conventional)	Observed yields of crops (study case 1) or average expected yields (study case 2)
Acceptability for the producer	E	Work difficulty	Expertise based on presence/absence of risk factors	Vibration frequency; heavy load frequency; duration and repetitiveness of awkward positions; noise levels
	E	Complexity of implementation	Expertise, considering for each crop	Number of field operations Risks of failure associated with each operation (considering soil and climate conditions)
	E	Health risks	Expertise, considering for each crop	TFI=Treatment Frequency Index for each crop considering all hazardous products (Pingault 2007); risks of dust inhalation
Agronomic viability	C	Nitrogen management quality	Mean ratio between crop N demands and N availabilities for non-leguminous crop	Crop N demands N availabilities from soil, fertilisers and crop residues (COMIFER 2011)
	S	Phosphorus management quality	Expertise (formal qualitative scheme)	See Fig. 2a
	S	Potassium management quality	Expertise (formal qualitative scheme)	Similar to Fig. 2a with K instead of P
	C	Soil organic matter management quality	I_{MO}	Indigo method. Bockstaller et al. 1997
	S	Soil structure management quality	Expertise (formal qualitative scheme)	See Fig. 2c
	S	Weed control	Expertise (formal qualitative scheme)	See Fig. 2b
	E	Pest and disease control	Expertise, considering for each crop	Sensitivity to diseases/pests within the regional context Position of the crop in the crop sequence Availability of allowed pesticides
Physical environment quality	C	Pesticide loss control	$I-PhysW$	Indigo method. Bockstaller et al. 1997
	C	Nitrate loss control	I_{NO3}	Indigo method. Bockstaller et al. 1997
	C	Phosphorus loss control	I_P	Indigo method. Bockstaller et al. 1997
	S	Erosion control	Expertise considering the risks factors	Field slope; soil texture; crop sequence; management techniques; soil sensitivity critical periods
	E	Soil chemical quality control	Expertise based on presence/absence of	Acidification risks; heavy metal or organic pollution
	C	Soil organic matter management quality	I_{MO}	Indigo method. Bockstaller et al. 1997
	C	NH3 emission control	I_{NH3}	Indigo method. Bockstaller et al. 1997

Table 2 (continued)

Sustainability sub-dimensions	Evaluation mode	Basic attributes	Methods (calculation or expertise)	Criteria, reference methods or main factors considered
Biodiversity conservation	C	N2O emission control	I_{N2O}	Indigo method. Bockstaller et al. 1997
	C	Pesticide emission control	$I-Phy_{air}$	Indigo method. Bockstaller et al. 1997
	C	Cultivated biodiversity conservation	I_{Div}	Indigo method. Bockstaller et al. 1997
	E	Non-cultivated biodiversity conservation	Expertise, considering for each crop	TFI=Treatment Frequency Index for all pesticides Presence / absence of ploughing Cultivated biodiversity attribute
Abiotic resource conservation	C	Energy resource conservation	Scored from mean energy consumption and mean energy efficiency	Energy consumption ($MJ\ ha^{-1}\ year^{-1}$) for each crop Energy efficiency ($MJ\ MJ^{-1}$) for each crop
	C	Water resource conservation	Water consumption for irrigation during critical periods ($m^3\ ha^{-1}\ year^{-1}$)	Irrigation plan (amounts, date) Beginning and end of the critical period for water demand at the regional level
	C	Phosphorus resource conservation	Mean rock phosphate consumption of the cropping system ($P_2O_5\ kg\ ha^{-1}\ year^{-1}$)	Rock phosphate consumption for each crop

(a)

Attribute	Scale
Phosphorus management quality	very unfavourable; unfavourable; favourable; very favourable
—Average matching level of crop demand for P	very unfavourable; unfavourable; favourable; very favourable
Phosphorus fertility trend	very unfavourable; unfavourable; favourable; very favourable
— P balance and P organic recycling	very unfavourable; unfavourable; favourable; very favourable
—Average P mineral balance	very negative; negative; balanced; positive; very positive
—Average P organic return from crop residues	low; mean; high
—Initial Phosphorus fertility level	low; mean; high
—P buffer capacity	low; mean; high
—Autonomy for P to meet crop demand and maintain P soil fertility	very unfavourable; unfavourable; favourable; very favourable

(b)

Attribute	Scale
Weed control	very low; low; medium; high
— Initial weed flora	very unfavourable; unfavourable; favorable; very favorable
—Initial perennial weed flora	high; medium; low
—Initial annual weed flora	high; medium; low
— Whole competitiveness of the rotation	very low; low; medium; high
—Effect of alternating winter-sown and spring-sown crops	low; medium; high
— Competitiveness of crop with weed	very low; low; medium; high
—Direct competitiveness of crops	very low; low; medium; high
—Mechanical control performed within the main crop cycles	very low; low; medium; high
— Competitiveness with weed outside the main crop cycles	low; medium; high
—Direct competitiveness of catch crop and green manure	low; medium; high
—Mechanical weed control performed outside the main crops cycles	low; medium; high

(c)

Attribute	Scale
Soil structure management quality	very unfavourable; unfavourable; favourable; very favourable
—Soil resistance to compaction	very low; low; mean; high
— Effect of mechanical operation on soil structure	very unfavourable; unfavourable; favourable; very favourable
—Number of cultivations during unfavourable critical periods	high; mean; low
—Effect of wheel-tracks on soil compaction	unfavourable; mean favourable; favourable
— Improving effect of soil cultivation	very unfavourable; unfavourable; favourable; very favourable
—Improving effect of primary cultivation	unfavourable; mean favourable; favourable
—Improving effect of secondary cultivation	unfavourable; mean favourable; favourable
— Whole effect of crops on the soil structure	very unfavourable; unfavourable; favourable; very favourable
—Effect of ley crops or perennial crops	mean favourable; favourable; very favourable
—Effect of annual crops	very unfavourable; unfavourable; favourable; very favourable

Fig. 2 Qualitative decision trees defined by the advisers to assess three basic agronomic attributes of the MASC-OF model: **a** phosphorus management quality (a similar tree was used for potassium management quality); **b** weed control management quality; **c** soil structure

management quality. The trees were implemented with the DEXi tool to form a set of satellite trees associated with the MASC-OF model. In contrast to the MASC-OF model, the satellite trees may include management practices, crop properties or rotation features as attributes

Table 3 Frequency distribution (range 0–1) of the scores of all basic and aggregated sustainability attributes from the assessment of two cropping systems case studies with the MASCOF model

Attribute names	Scale (3 to 7 scores)				Case study 1 CITODAB				Case study 2 RotAB									
					Frequency/score				Frequency/score									
	M	SD	M	SD	Frequency/score	Frequency/score	Frequency/score	Frequency/score	M	SD	M	SD						
Overall sustainability	VL; L; RL; M; RH; H; VH		0.00	0.07	0.48	0.32	0.09	0.05	0.05	0.93	0.00	0.00	0.17	0.43	0.30	0.09	5.3	0.88
Socioeconomic sustainability	VL; L; RL; M; RH; H; VH		0.00	0.20	0.32	0.27	0.18	0.00	0.00	1.08	0.00	0.00	0.13	0.43	0.39	0.00	5.2	0.83
Economic viability	VL; L; RL; M; RH; H; VH		0.05	0.36	0.30	0.23	0.02	0.02	0.00	1.17	0.00	0.00	0.57	0.13	0.17	0.09	4.7	1.11
Profitability	VL; L; M; H		0.05	0.66	0.27	0.02				0.59	0.00	0.04	0.70	0.26			3.2	0.52
Economic autonomy	VL; L; M; H		0.11	0.34	0.50	0.05				0.76	0.00	0.78	0.22	0.00			2.2	0.42
Economic independence	L; M; H		0.27	0.41	0.32					0.78	0.00	0.39	0.61				2.6	0.50
Economic efficiency	L; M; H		0.30	0.66	0.05					0.53	0.78	0.22	0.00				1.2	0.42
Specific equipment	VH; H; M; L		0.00	0.05	0.11	0.84				0.51	0.00	0.00	1.00				4.0	0.00
Social acceptability	VL; L; RL; M; RH; H; VH		0.00	0.00	0.05	0.32	0.39	0.25	0.00	0.86	0.00	0.00	0.17	0.70	0.13	0.00	5.0	0.56
Acceptability for society	VL; L; M; H; VH		0.00	0.45	0.50	0.05	0.00			0.58	0.00	0.00	0.48	0.52	0.00		3.5	0.51
Contribution to local employment	VL; L; M; H		0.77	0.23	0.00	0.00				0.42	0.96	0.04	0.00				1.0	0.21
Productivity level	VL; L; M; H; VH		0.00	0.55	0.41	0.05	0.00			0.59	0.00	0.00	0.48	0.52	0.00		3.5	0.51
Acceptability for the producer	VL; L; M; H; VH		0.00	0.07	0.09	0.36	0.48			0.89	0.00	0.00	0.57	0.30	0.13		3.6	0.73
Operational difficulties	VL; L; M; H		0.00	0.16	0.02	0.82				0.75	0.00	0.57	0.30	0.13			2.6	0.73
Work difficulty	H; M; L		0.00	0.18	0.82					0.39	0.13	0.61	0.26				2.1	0.63
Complexity of implementation	H; M; L		0.00	0.73	0.27					0.45	0.09	0.61	0.30				2.2	0.60
Health risks	H; M; L; N		0.00	0.41	0.14	0.45				0.94	0.00	0.00	0.39	0.61			3.6	0.50
Agro-environmental sustainability	VL; L; RL; M; RH; H; VH		0.00	0.00	0.02	0.27	0.39	0.20	0.11	1.02	0.00	0.00	0.00	0.52	0.39	0.09	5.6	0.66
Agro-nomic viability	VL; L; RL; M; RH; H; VH		0.00	0.00	0.20	0.41	0.25	0.09	0.05	1.06	0.00	0.13	0.39	0.35	0.09	0.04	4.5	0.99
Soil fertility	VL; L; M; H		0.00	0.36	0.64	0.00				0.49	0.00	0.74	0.26	0.00			2.3	0.45
Nutrient	VL; L; M; H		0.00	0.50	0.41	0.09				0.66	0.00	0.13	0.87	0.00			2.9	0.34
Nitrogen	VL; L; M; H		0.02	0.55	0.27	0.16				0.79	0.00	0.00	0.91	0.09			3.1	0.29
Phosphorus	VL; L; M; H		0.16	0.61	0.09	0.14				0.88	0.30	0.09	0.61	0.00			2.3	0.93
Potassium	VL; L; M; H		0.00	0.00	0.25	0.75				0.44	0.00	0.13	0.39	0.48			3.4	0.71
Soil organic matter	VL; L; M; H		0.07	0.66	0.27	0.00				0.55	0.35	0.57	0.09	0.00			1.7	0.62
Soil structure	VL; L; M; H		0.09	0.23	0.43	0.25				0.91	0.13	0.70	0.09	0.09			2.1	0.76
Weed	VL; L; M; H		0.05	0.50	0.36	0.09				0.73	0.00	0.13	0.61	0.26			3.1	0.63
Pest and disease	VL; L; M; H		0.00	0.14	0.66	0.20				0.59	0.00	0.52	0.22	0.26			2.7	0.86
Environmental compatibility	VL; L; RL; M; RH; H; VH		0.00	0.00	0.00	0.11	0.18	0.11	0.59	1.11	0.00	0.00	0.00	0.00	0.39	0.61	6.6	0.50
Physical environment quality	VL; L; M; H		0.00	0.00	0.59	0.41				0.50	0.00	0.00	1.00	0.00			3.0	0.00
Water quality	VL; L; M; H		0.00	0.02	0.43	0.55				0.55	0.00	0.00	0.96	0.04			3.0	0.21
Pesticide loss	VL; L; M; H		0.00	0.00	0.00	1.00				0.00	0.00	0.00	1.00				4.0	0.00
Nitrate loss	VL; L; M; H		0.18	0.25	0.30	0.27				1.08	0.00	0.87	0.13	0.00			2.1	0.34
Phosphorus loss	VL; L; M; H		0.00	0.02	0.23	0.75				0.50	0.00	0.00	0.65	0.35			3.4	0.49

Table 3 (continued)

Attribute names	Scale (3 to 7 scores)	Case study 1 CITODAB			Case study 2 RotAB									
		Frequency/score	M	SD	Frequency/score	M	SD							
Soil quality	VL; L; M; H	0.00	0.00	0.95	0.05	0.00	0.04	0.96	0.00	3.1	0.21	3.0	0.21	
Erosion	VL; L; M; H	0.00	0.14	0.18	0.68	0.00	0.00	0.00	1.00	0.00	3.6	0.73	3.0	0.00
Soil chemical quality	VL; L; M; H	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.39	0.61	4.0	0.00	3.6	0.50
Soil organic matter quality	VL; L; M; H	0.07	0.66	0.27	0.00	0.00	0.35	0.57	0.09	0.00	2.2	0.55	1.7	0.62
Air quality	VL; L; M; H	0.00	0.00	0.43	0.57	0.00	0.00	0.00	0.09	0.91	3.6	0.50	3.9	0.29
NH ₃ emission	VL; L; M; H	0.00	0.14	0.41	0.45	0.00	0.00	0.00	0.09	0.91	3.3	0.71	3.9	0.29
N ₂ O emission	VL; L; M; H	0.00	0.41	0.18	0.41	0.00	0.00	0.00	0.96	0.04	3.0	0.91	3.0	0.21
Pesticides emission	VL; L; M; H	0.00	0.00	0.00	1.00	0.00	0.00	0.00	1.00	0.00	4.0	0.00	4.0	0.00
Biodiversity conservation	VL; L; M; H	0.07	0.20	0.70	0.02	0.00	0.00	0.00	1.00	0.00	2.7	0.64	3.0	0.00
Cultivated biodiversity	VL; L; M; H	0.02	0.48	0.41	0.09	0.00	0.00	0.00	1.00	0.00	2.6	0.70	3.0	0.00
Non-cultivated biodiversity	VL; L; M; H	0.07	0.34	0.39	0.20	0.00	0.00	0.00	1.00	0.00	2.7	0.87	3.0	0.00
Abiotic resources	VL; L; M; H	0.00	0.14	0.32	0.55	0.00	0.00	0.00	0.39	0.61	3.4	0.73	3.6	0.50
Energy resources	VL; L; M; H	0.00	0.32	0.11	0.57	0.00	0.00	0.00	0.43	0.57	3.3	0.92	3.6	0.51
Water resources	VL; L; M; H	0.16	0.23	0.09	0.52	0.00	0.13	0.26	0.61	0.00	3.0	1.19	3.5	0.73
Nutrient resources	VL; L; M; H	0.00	0.00	0.00	1.00	0.00	0.00	0.00	1.00	0.00	4.0	0.00	4.0	0.00

An ordinal scale is associated to each qualitative scale (very low=1, ..., very high=7). Differences between mean score values of all main sustainability attributes (bold names) are not significant among the two case studies

VL very low, L low, RL rather low, M mean, RH rather high, H high, VH very high, M mean values of the ordinal scores for each attribute, SD standard deviation values of the ordinal scores for each attribute

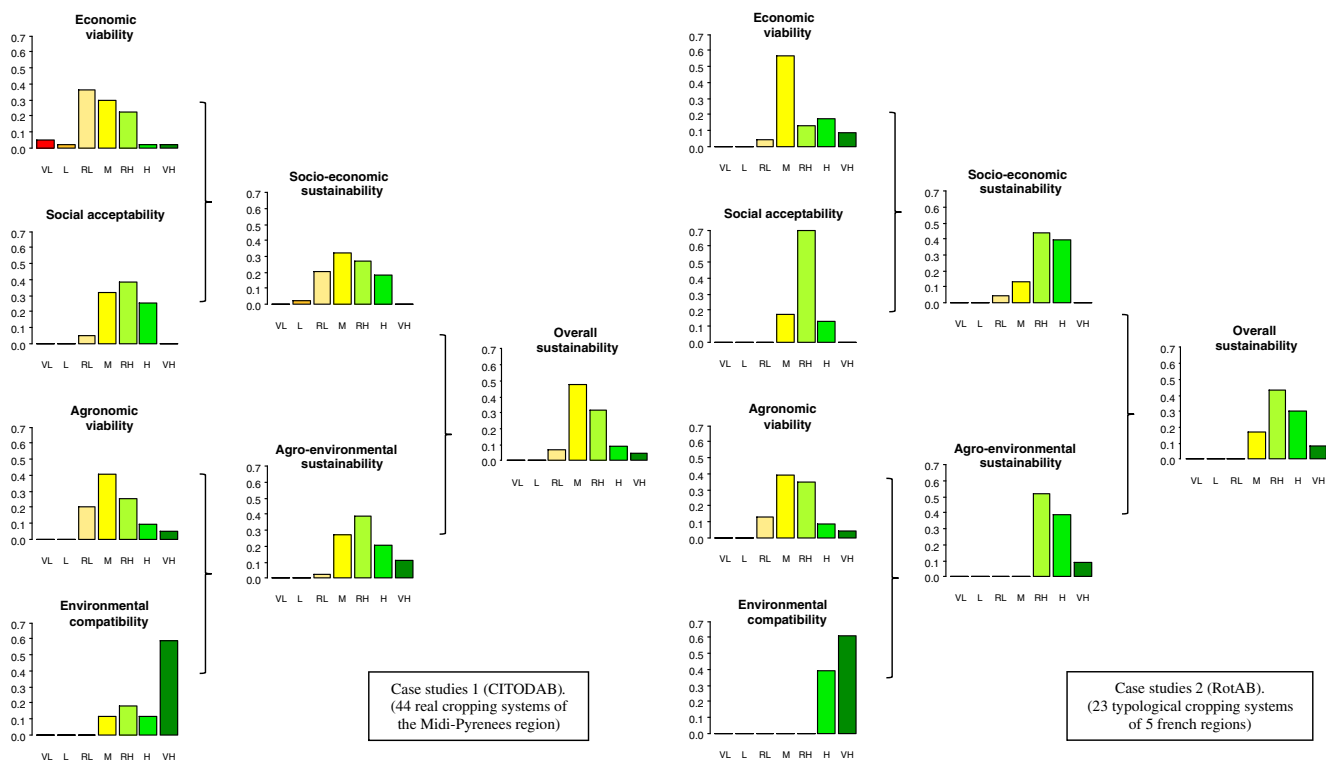


Fig. 3 Frequency distributions of the main sustainability scores obtained using the MASC-OF model for two organic cropping system case studies. The scale used for scoring is the following: *VL* very low, *L* low, *RL* rather low, *M* mean, *RH* rather high, *H* high, *VH* very high. For all attributes, score variability is higher for case studies 1 than for case

studies 2. Among the seven attributes, economic viability is the most variable and environmental compatibility is the least variable for both case studies. There is no low or very low scores for the overall sustainability attribute

have greater variability in CS1 than CS2. This could be explained mainly by differences in their size and composition (i.e. 44 real cropping systems for CS1, 23 cropping system types for CS2). CS2 has higher mean ordinal scores and lower standard deviations for all seven attributes. Differences in mean scores between the two case studies are not significant due to their high variability. Nevertheless, comparing the results is worth considering. For both sets of case studies, the rank of scores of the main sustainability dimensions was similar (Table 3). Economic viability and agronomic viability were the most difficult to achieve. This result is consistent with findings of David (2010). In contrast, environmental compatibility was the easiest to achieve, followed by social acceptability. Thus, ability to achieve the four sustainability aspects was ranked as follows (in increasing order):

$$\text{economic} \sim \text{agronomic} < \text{social} \ll \text{environmental}$$

3.2.2 Analysis of determining factors of attribute scores

We emphasise that the links between the attribute scores and certain factors were established via direct discussion among

advisers and scientists. The different natures and small sample sizes of the two case studies, as well as the multiple factors and potential interactions among them, did not allow statistical analysis of results, consistent with the qualitative feature of the study.

The economic viability attribute is assessed considering profitability, economic autonomy and specific equipment need. Profitability is highly variable, with the most frequent score low for CS1 and mean for CS2. The higher profitability for CS2 is due to higher productivity level and higher organic grain prices. In CS1, profitability is higher for irrigated cropping systems (mean) than for non-irrigated systems (low). The most frequent scores for the economic independence are mean for CS1 and high for CS2. Again the higher productivity level for profitable crops (e.g. wheat, maize) for CS2 help explains the difference. The other reason is that most of CS1 cropping systems received subsidies for mechanical equipment from the Midi-Pyrenees region. For economic efficiency, the most frequent score is mean for CS1. The low score for CS2 is due on average to greater amounts of inputs. The specific equipment need resulting from conversion to organic farming remains low in both cases. This attribute does not influence the economic viability of organic cropping systems much.

The most frequent scores for the acceptability for society are mean for CS1 and high for CS2. For both cases, contribution to local employment scores very low. The difference for acceptability for society is due to productivity level, with most frequent scores being low for CS1 and high for CS2 (i.e. higher and more regular yields due to climate). The most frequent scores for acceptability for producers are very high for CS1 and mean for CS2. The difference is explained by the two sub-attributes. For operational difficulties, the most frequent score is low for CS1 and high for CS2, for which the average duration of the rotations is higher, with more diverse crops managed by the farmer. For health risks encountered by the farmer, the most frequent score is low for both cases.

Agronomic viability aggregates soil fertility, weed control and pest and disease control. The most frequent scores for soil fertility are mean for CS1 and low for CS2. The difference comes from the sub-attributes. Nutrient quality management considers simultaneously N, P and K; its most frequent scores are low for CS1 and mean for CS2. For N- and P-management quality attributes taken individually, the most frequent scores are low for CS1 and mean for CS2. The amount of N available to meet non-leguminous crop demands is generally insufficient in CS1 cropping systems, apart from crops directly following faba bean. Efficient use of organic fertilisers spread during the spring generally remains low, due to climatic conditions which do not favour mineralisation of organic N when crop demand is high. For CS2, more organic fertiliser is spread, and climatic conditions are more favourable for N mineralisation. Further, the presence of lucerne in the rotation ensures high N availabilities for the two following crops in the rotation. For P, only ten cropping systems out of 44 received at least one P input over the 4-year period in CS1. The soil P balance depends on the productivity level, which determines the amount of P removal. In CS2, all systems except one received P fertiliser, with frequencies varying from every third year to 5 years out of 6. For the K-management quality attribute, the most frequent score is high for both case studies. Both mean (frequency 0.39) and low scores (frequency 0.13) for K occur for CS2 cropping systems, in line with the K removals associated with the presence of lucerne in the rotations. The most frequent score for soil organic matter management quality is low for both case studies. Very low scores occur with a frequency of 0.07 in CS1 and 0.35 in CS2. The proportion of loamy soils, which demand more organic matter for acceptable soil fertility, is higher in CS2 than in CS1. The most frequent scores for soil structure management quality are mean for CS2 and low for CS1. As with the soil organic matter attribute, the difference in score is due to higher proportion of loamy soils in CS2, which are more sensitive to compaction. Another reason lies in the frequent critical soil water content which favours soil degradation in

CS2 cropping systems. The most frequent score for weed control is low for CS1 and mean for CS2. The difference is explained well by the presence of 2- or 3-year lucerne in CS2 rotations. Very low scores occur only for CS1 (frequency 0.05), for short rotations with irrigated soybean. The most frequent score for pest and disease management quality are mean for CS1 and low for CS2. Since tolerant varieties are planted in both cases when available, advisers attribute the difference mainly to climatic conditions that favour more pests or diseases under CS2 cropping conditions. Low scores are due in part to the development of diseases for which there are no highly tolerant varieties (e.g. against *Uromyces viciae-fabae*, faba bean rust) or where cultivation techniques are unable to control some pests efficiently (e.g. *Sitonia lineatus* L., pea weevil).

Environmental compatibility refers to the conservation of the physical environment, biodiversity and abiotic resources. For brevity, we do not detail scores of all attributes aggregated by physical environment quality. As expected, air and water quality are not threatened by case study pesticide emissions. For water quality, there is some risk from case study nitrate emissions. For CS1, the reason lies mainly in the near-total absence of catch crops in the rotation and the low N use efficiency of organic fertilisers. For CS2, large amounts of N released by lucerne after destruction may also contribute to nitrate emissions. As already mentioned for agronomic viability, the most frequent score for soil organic matter management is low for both case studies. For biodiversity conservation, the most frequent score is mean for both case studies. Low (frequency 0.20) and very low scores (frequency 0.07) occur for CS1. For the cultivated biodiversity attribute, the most frequent score is low for CS1 and mean CS2. The difference results from the longer duration of crop rotations in CS2, with more crop species planted over time. For non-cultivated biodiversity, the most frequent score is mean for both case studies. The ploughing practice prevents the occurrence of high scores for all cropping systems. The variability of this attribute is higher for CS1, since the number of cultivation practices was also considered in the evaluation by the second group of advisors. This leads to very low (frequency 0.07) or low scores (frequency 0.34) for CS1 cropping systems having short rotation duration, ploughing every year and more than five cultivation techniques. The abiotic resource attribute refers to water, energy and nutrient resources considered simultaneously. The most frequent score is high for both case studies, while mean scores occur with frequency of 0.32 for CS1 and 0.39 for CS2. The scores for the water resource attribute reflect the proportion of irrigated systems in both case studies. The most frequent score is high, with frequencies of 0.51 and 0.62, respectively, for CS1 and CS2. Very low scores occur only for CS1 (frequency 0.16), when two out of three crops of the rotation are irrigated. For the

energy resource attribute, the most frequent score is high for both case studies, due mainly to not using synthetic N fertilisers. Nevertheless, low scores are observed with frequency of 0.32 in CS1, which could be attributed to cropping systems that combine irrigation, ploughing and more than two cultivation practices for weed control. The nutrient resource conservation attribute has a high score for both case studies, since the average amount of rock phosphate applied per year is small or zero for most of the cropping systems.

3.2.3 Summary of sustainability strengths and weaknesses of stockless organic cropping systems

During final discussions of the study, advisers summarised each sustainability sub-dimension.

Economic viability In increasing order, profitability depends on input costs, yield level and market prices of organic grains. Productivity fluctuations over years are harmful for the economic viability, particularly where the mean productivity of the rotation is low, as for non-irrigated systems in the Midi-Pyrenees region. If economic and climate hazards occur at the same time, the economic viability of organic cropping systems depends highly on subsidies. The higher the intensification of the cropping system, the higher its economic autonomy and viability.

Social acceptability Organic cropping systems do not contribute notably to local employment in rural areas, in contrast to other forms of organic farming (i.e. vegetable or vineyard systems). The acceptability of organic cropping systems for farmers is high considering the associated work load and health risks. This finding is consistent with the near absence of “reverse” transition (from organic to conventional farming) during the past decade. How well organic cropping systems may feed the world varies highly by region, farm and year. In this study, the ability to provide grain for human or animal consumption could be high for irrigated systems or for systems with a high proportion of leguminous grain crops, provided there are no severe limiting factors. These situations are consistent with the conclusion of Badgley et al. (2007), according to organic systems can contribute significantly to feed the world. In some cases, productivity of stockless organic cropping systems can be low (e.g. non-irrigated systems of the Midi-Pyrenees region), as noted by Kirchmann et al. (2008), who doubted the ability of organic farming to feed the world.

Agronomic viability The weakest component of the agronomic viability of stockless organic cropping systems is the maintenance of soil fertility over the long term, mainly due to difficulties in managing N and P resources adequately.

The ability to meet the N demand of non-leguminous grain crops ranges from poor to acceptable. Severe failure of weed control is rare; nevertheless, it remains the second greatest concern for organic systems. These remarks agree with numerous long-term experiments conducted in the Northern Hemisphere and reviews (e.g. Gosling and Shepherd 2005; Raup et al. 2006; Seremesic et al. 2008; Watson et al. 2008).

Environmental compatibility Although the physical environment is preserved well, some risks of nitrate emissions for water quality and poor management of soil organic matter remain two matters of concern. Biodiversity is mainly impacted by too-short rotations, as well as by ploughing practice. Considering its role for weed control, it is unlikely that ploughing can be decreased to improve soil biodiversity. These remarks agree with conclusions of a study of environmental impacts of organic farming conducted in the UK with a similar panel of indicators (DEFRA 2003). Efficient use of P resources is achieved due to organic regulations, low P availability and costs of organic fertilisers, but it is not for energy or water, particularly in irrigated systems, as stated by others (Bertilsson et al. 2008; Pimentel et al. 2005).

3.3 Lessons learned from designing and using the MASC-OF model

One objective of this research was to provide agricultural advisers with a tool to analyse the sustainability of stockless organic systems that developed in France over the last decade. The method used allowed the advisers to be deeply involved in tool development, starting from a model already designed for cropping system assessment. During adaptation of the MASC model, advisers and scientists encountered significant procedural challenges that were identified in previous studies (Andreoli et al. 1999; Bockstaller et al. 1997, 2008; Pacini et al. 2003). Initially, advisers involved in the study regarded the process of designing and handling an assessment model as professionally risky, time-consuming and intimidating. Due to the simplicity of use of the DEXi software, advisers rapidly acquired confidence in their ability to design an assessment model deeply rooted in their empirical knowledge. This knowledge, derived from extensive on-farm observations and long-term involvement in institutional surveys of farm performances, is usually ignored or undervalued by scientists performing academic assessment of agricultural systems. Advisers appreciated the ability of the DEXi software to capture their preferences concerning the weighting of indicators, which is a key step of the process. Further, the “satellite” trees included with DEXi methodology emerged as a useful way to build the required qualitative plan for assessing complex agronomic

issues, thereby taking advantage of other aspects of advisers' expert knowledge. The complementarity of the main MASC-OF tree and satellite trees respected one essential requirement of the assessment process: to keep the assessment model separate from the choice of the expert methods or tools used to assess the basic attributes. Then, in assessment projects performed with the MASC-OF model in a purely scientific context, evaluation could be achieved via mechanistic or statistical modelling. In evaluation projects driven by advisers, however, assessment can be based on extensive use of expertise, as performed in this study.

4 Conclusions

Designing more sustainable cropping systems first requires obtaining a reliable diagnosis on the extent to which existing cropping systems are sustainable. The diagnosis should be done at field and farm scales (and beyond) with appropriate methodologies (academic and/or empirical). Empirical assessment surveys benefiting from experienced advisers' knowledge at the field level could contribute to efficient approaches for the design of sustainable cropping systems as described in the introductory section.

At the field scale and for crop sequences over the mid and long term, the MASC-OF model, derived from the MASC model, helped to reveal the main strengths and weaknesses of organic cropping systems in different French regional contexts. The flexibility of the qualitative hierarchical approach allowed group members to improve the model to address critical points of organic systems that were previously under-considered in the MASC model. The ability to adapt the panel of indicators (i.e. attributes) was highly appreciated by the advisers, as was the ability to fine-tune the weighting of indicators within the assessment tree. These abilities ensured that advisers' views on what could constitute a more sustainable cropping system was considered and incorporated in the MASC-OF assessment model.

The study delivered a sound assessment of stockless organic cropping systems that developed in France over the last decade, according to advisers in the project. The added value of the study also lies in the confirmation and deepening of the analysis of specialised organic systems in France performed by David (2010). Nevertheless, more in-depth approaches should be undertaken in the four sustainability domains investigated to strengthen the conclusions, detail relations between determining factors and sustainability performances and identify mechanisms to improve performances. Concerning agronomic viability, identification of factors that may hamper soil fertility maintenance and reduce weed, pest and disease control, thus limiting crop production in organic systems, should be continued using appropriate methods. Along with the application of such

approaches, further improvements in the assessment model and application to additional case studies would lead to more reliable and operational sustainability assessments of cropping systems.

Acknowledgments This work was supported by grants from the French Midi-Pyrenees region and INRA via the PSDR 3 "CITODAB" project and by the French Ministry of Agriculture, Food, Fishing and Rural Affairs (MAAPRAT) via the CASDAR "RotAB" project. We warmly thank INRA and AgroParisTech for authorisation to use and modify the MASC model. We thank Michael Corson for correcting the manuscript. We are very grateful to the editorial team and the anonymous reviewers for their helpful comments on improving the paper.

References

- Agence bio (2012) L'agriculture biologique française: les chiffres clés —Edition 2012. La Documentation française
- Andreoli M, Rossi R, Tellarini V (1999) Farm sustainability assessment: some procedural issues. *Landsc Urban Plan* 46:41–50. doi:10.1016/S0169-2046(99)00045-6
- Aouadi N (2011) DEXiPM-vigne: un outil d'évaluation multicritère de stratégies phytosanitaires en viticulture. Master of Science n 115, CIHEAM-IAMM Publications
- Bachinger J, Zander P (2007) ROTOR, a tool for generating and evaluating crop rotations for organic farming systems. *Eur J Agron* 26:130–143. doi:10.1016/j.eja.2006.09.002
- Badgley C, Moghtader J, Quintero E, Zakem E, Chappell MJ, Avilés-Vázquez K, Samulon A, Perfecto I (2007) Organic agriculture and the global food supply. *Renew Agric Food Syst* 22:86–108
- Bergez J-E, Colbach N, Crespo O et al (2010) Designing crop management systems by simulation. *Eur J Agron* 32:3–9. doi:10.1016/j.eja.2009.06.001
- Bertilsson G, Kirchmann H, Bergström L (2008) Energy analysis of organic and conventional agricultural systems? In: Kirchmann H, Bergström L (eds) *Organic crop production—ambitions and limitations*. Springer, Berlin, pp 173–188
- Bockstaller C, Girardin P, van der Werf HMG (1997) Use of agro-ecological indicators for the evaluation of farming systems. *Eur J Agron* 7:261–270. doi:10.1016/S1161-0301(97)00041-5
- Bockstaller C, Guichard L, Makowski D (2008) Agri-environmental indicators to assess cropping and farming systems. A review. *Agron Sustain Dev* 28:139–149. doi:10.1051/agro:2007052
- Bohanec M (2011) DEXi: program for multi-attribute decision making. User's manual. Institut Joseph Stefan, Ljubljana
- Carof M, Colomb B, Aveline A (2012) A guide for choosing the most appropriate method for multi-criteria assessment of agricultural systems according to decision-makers' expectations. *Agric Syst*. doi:10.1016/j.agsy.2012.09.011
- Carpani M, Bergez J-E, Monod H (2012) Sensitivity analysis of a hierarchical qualitative model for sustainability assessment of cropping systems. *Environ Model Softw* 27–28:15–22. doi:10.1016/j.envsoft.2011.10.002
- Colomb B, Gafsi M (2011) CITODAB—Contribution des innovations techniques et organisationnelles à la durabilité de l'agriculture biologique. In: PSDR3 Midi-Pyrénées. <http://www4.inra.fr/psdr-midi-pyrenees/Projets-de-recherche/CITODAB>. Accessed 20 Mar 2012
- Colomb B, Glandières A, Carpy-Goulard F et al (2009) Analyse énergétique des systèmes de grandes cultures biologiques. Impact du niveau d'intensification. *Innov Agron* 4:176–181
- Colomb B, Aveline A, Carof M (2011) Une évaluation multicritère qualitative de la durabilité de systèmes de grandes cultures

- biologiques. Quels enseignements? Restitution des programmes RotAB et CITODAB. INRA. <http://www.itab.asso.fr/downloads/jtgc2011/rapport-citodab.pdf>. Accessed 20 Mar 2012
- COMIFER (2011) Calcul de la fertilisation azotée. Guide méthodologique pour l'établissement des prescriptions locales. Éditions COMIFER, Paris
- Craheix D, Angevin F, Bergez J-E, Bockstaller C, Colomb B, Guichard L, Reau R, Doré T (2012) MASC 2.0, un outil d'évaluation multicritère pour estimer la contribution des systèmes de culture au développement durable. *Innovations Agronomiques* 20, 35–48. http://www.inra.fr/ciag/revue/volume_20_juillet_2012. Accessed 15 Oct 2012
- David C (2010) Grandes cultures: des systèmes en équilibre instable. In: Lamine C, Bellon S (eds) *Transitions vers l'agriculture biologique. Pratiques et accompagnements pour des systèmes innovants*. Educagri éditions/Éditions Quae, Versailles, pp 129–141
- David C, Jeuffroy M-H, Henning J, Meynard J-M (2005) Yield variation in organic winter wheat: a diagnostic study in the Southeast of France. *Agron Sustain Dev* 25:213–223. doi:10.1051/agro:2005016
- Debaeke P, Munier-Jolain N, Bertrand M et al (2009) Iterative design and evaluation of rule-based cropping systems: methodology and case studies. A review. *Agron Sustain Dev* 29:73–86. doi:10.1051/agro:2008050
- DEFRA (2003) Final report. Organic farming: technology transfer. DEFRA project code OF0405
- Dogliotti S, Rossing WAH, van Ittersum MK (2003) ROTAT, a tool for systematically generating crop rotations. *Eur J Agron* 19:239–250. doi:10.1016/S1161-0301(02)00047-3
- Gosling P, Shepherd M (2005) Long-term changes in soil fertility in organic arable farming systems in England, with particular reference to phosphorus and potassium. *Agric Ecosyst Environ* 105:425–432. doi:10.1016/j.agee.2004.03.007
- Goulding K, Stockdale E, Watson C (2008) Plant nutrients in organic farming. In: Kirchmann H, Bergström L (eds) *Organic crop production—ambitions and limitations*. Springer, Dordrecht, pp 73–88. doi:10.1007/978-1-4020-9316-6_4
- ITAB (2008) RotAB. In: ITAB—Institut Technique de l'Agriculture Biologique. <http://www.itab.asso.fr/programmes/rotation.php>. Accessed 20 Mar 2012
- ITAB (2011) Rotations en grandes cultures biologiques sans élevage. 8 fermes-types, 11 rotations. Repères agronomiques, économiques, techniques et environnementaux. p 132
- Kirchmann H, Bergström L, Katterer T, Andrén O, Andersson R (2008) Can organic crop production feed the world? In: Kirchmann H, Bergström L (eds) *Organic crop production—ambitions and limitations*. Springer, Berlin, pp 39–72
- Kropff MJ, Bouma J, Jones JW (2001) Systems approaches for the design of sustainable agro-ecosystems. *Agric Syst* 70:369–393. doi:10.1016/S0308-521X(01)00052-X
- Mazzetto F, Bonera R (2003) MEACROS: a tool for multi-criteria evaluation of alternative cropping systems. *Eur J Agron* 18:379–387. doi:10.1016/S1161-0301(02)00127-2
- Meynard J-M, Doré T, Habib R (2001) L'évaluation et la conception de systèmes de culture pour une agriculture durable. *C R Acad Agric France* 87:223–236
- Mohler CL (2009) The role of crop rotation in weed management. In: Mohler CL, Johnson SE (eds) *Crop rotation on organic farms: a planning manual*. NRAES, Ithaca, pp 44–46
- Pacini C, Wossink A, Giesen G et al (2003) Evaluation of sustainability of organic, integrated and conventional farming systems: a farm and field-scale analysis. *Agric Ecosyst Environ* 95:273–288. doi:10.1016/S0167-8809(02)00091-9
- Pelzer E, Fortino G, Bockstaller C, Angevin F, Lamine C, Moonen C, Vasileiadis V, Guérin D, Guichard L, Reau R, Messéan A (2012) Assessing innovative cropping systems with DEXiPM, a qualitative multi-criteria assessment tool derived from DEXi. *Ecol Indic* 18:171–182. doi:10.1016/j.ecolind.2011.11.019
- Pimentel D, Hepperly P, Hanson J, Doude D, Seidel R (2005) Environmental, energetic, and economic comparisons of organic and conventional farming systems. *BioScience* 55:573–582
- Pingault N (2007) Améliorer la qualité de l'eau: Un indicateur pour favoriser une utilisation durable des produits phytosanitaires. Atelier OCDE, 19–21 mars 2007, Washington. Available at http://agriculture.gouv.fr/IMG/pdf/IFT_fr2.pdf. Accessed 12 Oct 2012
- Raup J, Pekrun C, Oltmanns M, Köpke U (2006) Long term field experiments in organic farming. ISOFAR Scientific Series. Verlag Dr. Köster, Berlin
- Riquois A (1999) L'agriculture biologique: un prototype au service de l'agriculture conventionnelle pour un développement durable. *Aménagement Nat* 132:49–61
- RMT DévAB (2011) RMT Développement de l'Agriculture Biologique; <http://www.devab.org/moodle/>. Accessed 20 Mar 2012
- RMT SdCi (2011) RMT Systèmes de culture innovants. <http://78.155.145.122/rmtsci/moodle>. Accessed 20 Mar 2012
- Sadok W, Angevin F, Bergez J-E et al (2008) Ex ante assessment of the sustainability of alternative cropping systems: implications for using multi-criteria decision-aid methods. A review. *Agron Sustain Dev* 28:163–174. doi:10.1051/agro:2007043
- Sadok W, Angevin F, Bergez J-E et al (2009) MASC, a qualitative multi-attribute decision model for ex ante assessment of the sustainability of cropping systems. *Agron Sustain Dev* 29:447–461. doi:10.1051/agro/2009006
- Seremesic S, Milosev D, Manojlovic M (2008) Evaluation of crop rotation on organic farms in northern Serbia. 16th IFOAM Organic World Congress. Modena Italy
- Strassert G, Prato T (2002) Selecting farming systems using a new multiple criteria decision model: the balancing and ranking method. *Ecol Econ* 40:269–277. doi:10.1016/S0921-8009(02)00002-2
- Vereijken P (1994) Designing prototypes. Progress report 1 of the research network on Integrated and Ecological Arable Farming Systems for EU and associated countries. AB-DLO, Wageningen
- Vereijken P (1997) A methodical way of prototyping integrated and ecological arable farming systems (IEAFS) in interaction with pilot farms. *Eur J Agron* 7:235–250. doi:10.1016/S1161-0301(97)00039-7
- Watson CA, Atkinson D, Gosling P et al (2002) Managing soil fertility in organic farming systems. *Soil Use Manag* 18:239–247. doi:10.1111/j.1475-2743.2002.tb00265.x
- Watson CA, Stockdale EA, Rees RM (2008) Assessment and maintenance of soil fertility in temperate organic agriculture. *CAB Rev Perspect Agric Vet Sci Nutr Nat Res* 3:1–11
- Wijnands FWT (1999) Crop rotations in organic farming: theory and practice. In: Olesen JE, Eltun R, Gooding MJ et al (eds) *Designing and testing crop rotations for organic farming*. DARCOF, Foulum, pp 21–36
- Zander P, Kächele H, Meyer-Aurich A (1999) Development and application of a multi-objective decision support tool for agroecosystem management (MODAM). *Q Bull Int Assoc Agric Inf Spec* 44:66–72
- Znidarsic M, Bohanec M, Zupan B (2008) Modelling impacts of cropping systems: demands and solutions for DEX methodology. *Eur J Oper Res* 189:594–608. doi:10.1016/j.ejor.2006.09.093