Using a multicriteria assessment model to evaluate the sustainability of conservation agriculture at the cropping system level in France

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Highlights

- Sustainability of French cropping systems was assessed with a multicriteria model.
- Systems implemented various levels of conservation agriculture principles.
- Diversified rotations achieved good sustainability scores regardless tillage type.
- Combining reduced tillage and diversified rotation improves environmental impacts.
- Conservation agriculture is not panacea, but it remains a promising strategy.

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Abstract

Several international research and development organisations are promoting conservation agriculture in a wide range of contexts. Conservation agriculture is based on a combination of three main principles: (i) minimal or no mechanical soil disturbance; (ii) diversified crop rotations and (iii) permanent soil cover (consisting of a growing crop or a dead mulch of crop residues). However, in the face of the diversity of practices that can be associated with conservation agriculture, of goals assigned to agricultural systems, and pedoclimatic contexts, there is still no empirical evidence about the overall performance of conservation agriculture in France. Global assessments of conservation agriculture, with the full or partial application of its principles and in different contexts, are required to provide a more comprehensive picture of the performance of such systems. We tackled these objectives simultaneously, by evaluating 31 cropping systems with the MASC® model (for Multicriteria Assessment of the Sustainability of Cropping Systems). These systems were selected to represent a wide diversity of practices, from ploughed conventional systems to crop sequences based on the full application of conservation agriculture principles. Positive interactions were observed between the key elements of conservation agriculture, resulting in better sustainability performances (particularly in terms of environmental criteria). Nevertheless, the systems most closely respecting the principles of conservation agriculture displayed several weakness, principally of a social or technical nature, in this study. Careful attention should be paid to attenuating these weaknesses. A more detailed analysis of the results also suggested that decreasing soil tillage tends to decrease the overall performance of the system unless associated with a diversification of the crop rotation.

1. Introduction

After the Second World War, increasing yields was a key priority, influencing a shift in European policy towards the promotion of more intensive practices based on mechanisation and high levels of inputs such as energy, fertilisers, and pesticides (Tilman *et al*., 2002). These policies rapidly lead to increases in yield, but they were counterbalanced by negative environmental impacts, such as groundwater pollution, decreases in soil organic matter content, soil erosion and biodiversity losses. Agriculture is now facing an increasing number of new challenges (*e.g.* coping with market volatility, resource scarcity and rising demand for raw materials) placing the future of agricultural production systems, ecosystems and the services they provide to society in jeopardy (Tilman *et al*. 2002)

In response to these challenges, farmers and agronomists have been trying to develop alternative cropping systems. Conservation agriculture (CA) is one of the innovations proposed and is among the most extensively studied new systems developed in recent decades (Scopel *et al.*, 2012). CA systems are based on the following three principles: (i) minimal or no mechanical soil disturbance; (2) diversified crop rotations and (3) permanent soil cover (consisting of a growing crop or a dead mulch of crop residues) (FAO, 2008). Conservation agriculture has been actively promoted by several international research and development organisations, in a wide range of contexts, on the basis of specific field observations and literature reviews (Dumanski *et al.*, 1998; Hobbs *et al.*, 2008; Holland, 2004; Lapar and Pandley, 1999; Lestrelin *et al.,* 2012). CA has already been massively adopted on large-scale mechanised farms, particularly in Australia and Americas but its adoption remains limited in other parts of the world such as Africa and Western Europe (Derpsch *et al.*, 2003; Lahmar, 2010). With the low level of dissemination of CA systems in these regions and the diversity of practices associated with these systems, the effective and global performances of this set of innovations remain unclear and the benefits of CA are increasingly being questioned in the scientific community (Giller *et al.,* 2011; Peigné *et al.*, 2009; Serpantié *et al.,* 2009). Western European farmers adopting CA approaches often do so without completely respecting all of the principles of CA. This makes it possible for them to broaden the range of options open and to adapt the principles of CA to local conditions. However, it also greatly affects the efficiency and impact of CA systems in the short and long term (Scopel *et al.*, 2012). In the face of the diversity of (i) practices associated with CA, (ii) goals assigned to agricultural systems, and (iii) pedoclimatic contexts, there is still no empirical evidence about the overall performance of CA in the French context (Lhamar, 2010). There is therefore a crucial need to determine the reliability of this innovation with respect to conventional practices (generally involving more intensive soil tillage and less diversified crop rotations), and to clarify the benefits and drawbacks of the full or partial application of conservation agriculture in this context.

To this end, CA systems should be assessed, like other innovations in agriculture, by considering economic, social and environmental aspects, including the expectations of farmers and society at large. Classical approaches based on the optimisation of economic functions, such as cost-benefit analysis, have several drawbacks in this context. These methods are based on quantitative, often monetary variables and are not entirely adequate for the realistic representation of various performances, particularly those relating to social and environmental performances (*e.g.* difficulty, complexity of implementation, pressure on biodiversity). As already pointed out by other authors, multicriteria evaluation methods suitable for the analysis of qualitative data may be more relevant for the sorting and classification of technical solutions when considering a broad diversity of performances (Figueira *et al.*, 2005, Sadok *et al.*, 2008). Multicriteria decision aid methods, such as the MASC® model (Sadok *et al.*, 2009) should therefore be used for such assessments. In this study, using this assessment framework and performed in the context of medium-sized mechanised farms in France, we aimed to determine the extent to which the partial or complete implementation of CA principles affected the overall sustainability of cropping systems. More detailed analyses of the consequences of CA implementation, such as this one, should make it clearer which of the principles of CA contribute most (or not at all) to the desired effects in France, and should make it possible to identify ways of improving these cropping systems as well.

2. Materials and methods

2.1 Presentation of the MASC model

We chose to use the MASC 2.0 (for Multicriteria Assessment of the Sustainability of Cropping Systems) model (Craheix *et al.,* 2012a; Sadok *et al.,* 2009) in this study, for three reasons. Firstly, MASC operates at the level of the cropping system, defined as "a set of management procedures applied to a given, uniformly treated area, which may be a field or a group of fields" (Sebillotte, 1990). The cropping system includes the sequence of crops (rotation) and the various aspects of their management (soil tillage, sowing rate and date, cultivar choice, rates and dates of fertiliser application, crop protection strategy). This small scale is particularly relevant for precise assessments of the negative and positive impacts of the principles of CA, which are closely tied to the field level. Secondly, MASC provides a holistic view of the various performances of the cropping system, because it takes into account the conflicting objectives underlying the economic, social and environmental dimensions of sustainability. Thirdly, this model was also chosen because it can handle various sources of knowledge, managing both quantitative and qualitative information, in the assessment of cropping system performances. MASC was implemented within DEXi computer software (Bohanec, 2014). This software can be used to design qualitative multicriteria models breaking decision problems down into smaller, less complex sub-problems formulated in terms of a hierarchy of criteria and aggregation functions.

Through this formalism, MASC conceptualises the sustainability assessment problem by breaking it down into the three classical dimensions used to define sustainability (social, economic and environmental; Ikerd, 1993, United Nations, 1996). Each dimension represents a hierarchy of sustainability objectives organised into a tree-like structure formed by 65 variables (see Figure 1).

Figure 1

Each variable has a number of qualitative values (or modalities), from 3 to 7, typically taking the form of a “Low→Medium→High” progression, with the addition of classes such as ”Very Low/Very High” and “Rather low/rather high” in some cases. Variables can be classified as basic criteria (*i.e.*, input variables; 39 variables) and aggregate criteria (*i.e.,* aggregate variables; 26 variables).

Basic criteria relate to elementary concerns of sustainable development (*e.g.,* “Profitability”, “Nitrate losses” and “Soil erosion”). These criteria are entered into the model via specific indicators proposed by the model designers. The methods for calculating or evaluating these indicators are detailed in Tables 1 and 2. Six of the 39 indicators proposed are based on direct expertise. The main factors to be taken into account in this expertise are also reported in Tables 1 and 2. Twenty indicators are based on quantitative variables obtained by calculation. For this type of indicator, quantitative values are converted into qualitative variables compatible with the DEXi software through the use of locally defined thresholds. For instance, for the criterion “Profitability”, results for the semi-net margin are based on threshold values covering the diversity of the margin observed in a region (*e.g.* : *Very low* ≤ €200 /ha ≤ *Medium to low* ≤ €400/ha ≤ *Medium to high* ≤ €600/ha). The other 13 indicators are classified as “mixed” as they can deal with both qualitative and quantitative data. These indicators are developed in DEXi software by disaggregating a basic criterion in a subtree, the inputs of which are obtained from a qualitative description of the system or by simple calculation, with the use of threshold values for conversion into qualitative inputs.

In DEXi®, aggregations are performed for each criterion with "utility functions" materialised in tables completed with ‘IF-THEN’ aggregation rules, such as **IF <**the criterion “Expectations of

Society” is “Very low”**> AND IF <**the criterion “Expectations of Farmers” is “Low to medium”**> THEN <**the aggregate criterion “Social Sustainability” is “Very low”**>** (see the example in Figure 1). Each utility function can be filled in manually or semi-automatically, based on the weights applied to each criterion. All the utility functions were included in the model by the designers and can be considered to provide a well-balanced perception of sustainability, given that the weights are generally evenly distributed between criteria. However, users can modify these functions, to adapt the model to their local context and preferences (Craheix *et al.,* 2012b). In this study, we performed assessments with the weights assigned by the designers of the MASC model (Figure 2). Using the aggregation devices of the MASC model, it is possible to rank the cropping systems according to their overall sustainability and its three dimensions (*i.e.* economic, social, and environmental). In DEXi software, an ordinal scale is associated with each qualitative scale (*e.g.* very low=1, low=2, … , very high=5). The mean and standard deviation of the ordinal scales can therefore be calculated and used to represent the results.

Relative to the first version published by Sadok *et al.* (2009), the second version of the model, as used here, presents several improvements that helped to delimit the outline of this assessment. The designers made use of feedback from the initial users (Craheix *et al.,* 2012c) and included new criteria in the tree, to ensure that levels such as the production chain and society were better encompassed in the economic and social dimensions (*e.g.:* "Supply of raw materials", "New supply chain emergence" , "Sanitary quality"). In accordance with a previous adaptation of MASC 1.0 to organic farming systems (Colomb *et al.,* 2012), a new branch, “Long-term productive capacity”, was inserted into the economic dimension of MASC 2.0. This modification makes agronomic viability a key determinant of the economic sustainability of innovative cropping systems, by taking into account both soil fertility and the control of pests and weeds. Finally, based on the DEXiPM model (Pelzer *et al.,* 2012), the "Biodiversity Conservation" branch of the environmental dimension was profoundly modified to restrict assessment to the less mobile groups of organisms, which are heavily dependent on crop interventions at the field scale (*i.e.* flora, soil macrofauna, flying insects and soil micro-organisms). These new criteria were inserted while taking advantage of the sensitivity analysis performed on the MASC model (Carpani *et al.,* 2012; Bergez, 2013). They were designed to both maintain sensitivity of the model and to avoid structural effects leading to involuntarily increase of the weight of some criteria.

Finally, the aptness of the model for evaluating the performances of CA systems was evaluated by following a three-step procedure (Bockstaller *et al.* 2009; 2003) based on: (i) an evaluation of the structure of the model (ii) an evaluation of the outputs generated by the model and (iii) an evaluation of the usefulness of the model in diverse situations of use. At each of these stages, we combined constructive criticism from a broad panel of experts and stakeholders involved in this study (researchers, advisors, farmers) with information published in peer-reviewed articles. This work led to a number of improvements that were directly integrated into the second version of the MASC model used in this study.

2.2 Description of the cropping systems evaluated

In this study, 31 cropping systems were selected from both farm-based and experimental station sites, to represent a wide diversity of practices, from ploughed systems with short crop rotations to systems in which the principles of CA were fully applied (Table 3).

The description of these cropping systems was based on a list of farming practices and the yields obtained for each crop, through a combination of recorded data and expertise. The cropping systems were collected from six different regions of France (*i.e.* Haute-Normandie, Champagne-Ardenne, Rhône-Alpes, Centre, Aquitaine, Franche-Comté), so as to take into account various pedoclimatic contexts. In terms of economic data, we considered, for all the cropping systems assessed, the same purchase prices for inputs and selling prices for crops, based on the average over the preceding five years (*i.e.* 2008-2013).

Table 3

We defined six types of cropping system on the basis of the extent to which the principles of CA were applied (Figure 2). These types were defined in terms of the intensity of tillage and the diversity of crops in the rotation. The permanence of soil cover, the third pillar of CA, was taken into account indirectly in this typology, by combining the information for the first two pillars. The intensity of tillage was assessed by assigning cropping systems to one of three classes: (i) ploughed cropping systems (PL), in which ploughing was performed at least one year in three in the crop rotation, (ii) cropping systems based on reduced tillage (RT), including both low-frequency ploughing (less than one year in three) and regular non-inversion tillage (*i.e.* chisel plough, disc plough, rotary harrow) and (iii) direct seeding cropping systems (DS) with no ploughing and a very low frequency of tillage or of shallow interventions (to a depth of no more than 5 cm). Cropping systems were assigned to one of two groups for crop rotation, to distinguish between rotations with high and low levels of diversification. These two groups were defined on the basis of rotation length, the presence of cover crops, the diversity of crop families and the presence of different and distinct sowing dates in the crop sequence.

Figure 1

3. Results

3.1 Analysis of the main sustainability criteria scores

The overall sustainability scores of the various cropping system types (Figure 3) were between 3 (“rather low”) and 6 (“high”). Systems based on diversified rotations had the best overall sustainability scores, with a mean score of more than 5 (“rather high”), regardless of the tillage conditions. Diversification of the rotation thus had a stronger positive effect than decreasing soil tillage on the overall sustainability score obtained with MASC. Conversely, decreasing soil tillage only had a marked impact on the results in systems with low levels of crop diversification. In this situation (LC), only systems with superficial soil tillage only (RT-LC) had overall sustainability scores above four (“medium”). Systems combining direct seeding and a low diversification of the rotation had lower overall sustainability scores (3/7, “rather low”), close to those of conventional systems (PL-LC).

Figure 3

We then used the results for the three underlying dimensions of sustainability to refine our analysis. For the economic dimension of sustainability, the conventional system (PL-LC type) had a mean score of 3 (“medium”), but all the other types had mean scores of between 4 (*i.e.* “rather high”) and 5 (*i.e.* “high”).

For the social dimension of sustainability, the DS type presented the worst results, particularly for low levels of diversification of the crop rotation. By contrast, the PL and RT types had better mean scores, between 4 (*i.e.* “high”) and 5 (*i.e.* “very high”).

For the environmental dimension of sustainability, there was clearly a positive interaction between reducing tillage and diversifying crop rotations. For environmental sustainability, none of the cropping systems based on short and less diversified crop rotations had a score of 3 (“medium”) or more. Environmental performance was more variable for reduced tillage (RT) systems than for the other types of system.

3.2 Analysis of scores for basic criteria

The results of each dimension were too synthetic to account for the overall ranking on their own. A more detailed analysis of the basic criteria was therefore required to identify the major strengths and weaknesses of the cropping systems studied. Only the results for the principal basic criteria discriminating between the systems evaluated in terms of performance are presented here.

More detailed results for the economic dimension (Figure 4) indicated that systems with low frequencies and shallow depths of soil tillage (*i.e.* the RT and DS types) were at least as profitable as ploughed systems. These systems obtained better results for the “economic efficiency” criterion, reflecting a lower economic dependence on inputs (*e.g.* fuel, fertiliser, pesticides). Nevertheless, reduced tillage systems and systems with only very superficial tillage operations had worse results than ploughed systems for the criteria “weed control” and “control of insect pests and diseases”. In parallel, systems based on long diversified rotations, particularly those including legumes (as the principal or cover crop) were generally more profitable and had a higher economic efficiency than less diversified systems. These systems also had better scores for the criteria “weed control” and “sanitary quality” (estimating the sanitary risk associated with the presence of mycotoxins). However, systems combining a diversified crop rotation with reduced or very superficial soil tillage did not obtain better results than other systems for the indicator “control of insect pests and diseases”.

Figure 4

For the social dimension (Figure 5), we observed that reduced tillage and direct seeding systems (*i.e.* RT and SD) obtained better scores for the criterion “work overload” than ploughed systems. This criterion reflects the capacity of a system to decrease the number of hours of work required at busy times (*e.g.* sowing, weed control and harvesting). However, these systems were penalised for their small contribution to employment, due to the small number of hours of work required per hectare and per year. Our results indicated that the lower intensity of soil tillage in these systems also had a negative impact on the criteria “health risk for farmers” due to the large number of applications of phytosanitary products. The results for the “system complexity” criterion also reflected the greater difficulty for farmers to control the need for interventions in these cropping systems.

Figure 5

However, the deleterious effects of direct seeding systems were nevertheless smaller in more diversified crop rotations (DS-HC in Figure 3). In these rotations, the presence of a greater diversity of main and cover crops seemed to have a positive impact on the criterion “contribution to local employment”, by increasing the mean number of hours of work per year, and on the criterion “pesticide use-related health risk”, due to smaller numbers of pesticide applications (Figure 4). The social impact of a greater diversity of crops in the rotation was nevertheless essentially negative for the criteria “system complexity” and “technical and economic monitoring time”. Indeed, the main and cover crops in these rotations, which differed from those present in less diversified rotations, were often a bit more difficult to manage (*e.g.* insertion and destruction of new cover crops) and the larger number of different crops also increases the time that the farmer must spend updating his technical and economic knowledge about his crops.

For the environmental dimension, cropping systems with long and diversified crop rotations (HC) obtained the best scores, particularly when combined with reduced tillage (RT) or direct seeding practices (DS) (Figure 3). As indicated by the more detailed results in Figure 6, these systems had better results than ploughed systems for the criteria “soil macrofauna conservation”, “soil erosion control” and “soil organic matter content control”. However, their performances were similar to those of ploughed systems for the criterion “energy consumption” and “control of NO_3 losses”.

Diversified rotations performed better than less diversified systems for the criterion “energy consumption”. Thus, whereas reducing tillage decreases direct fuel energy consumption, diversifying the rotation, particularly if legumes are included, makes it possible to decrease more strongly the input of mineral nitrogen, a major contributor to the indirect consumption of energy. In this respect, SD-LC systems had the worst results, due to the use of larger amounts of synthetic nitrogen fertiliser to nourish the higher proportion of cash crops in these cropping systems. The diversification of rotations, particularly if cover crops are included, was mildly advantageous for the criteria “soil erosion control” and “control of NO_3 losses”. The results obtained for the criteria “organic matter content control” and “soil macrofauna conservation” differed little between rotations as a function of the level of diversification.

Figure 6

4. Discussion

4.1 Variability of the results

The results obtained for the aggregate and basic criteria revealed a relatively high level of variability within each of the cropping system types evaluated. This variability was no greater for conventional agriculture systems than for systems following the principles of CA more closely. This variability was sufficiently large for better overall sustainability scores to be obtained, in some situations, by ploughed systems or systems based on short rotations with low levels of diversification than by systems adhering more closely to the principles of CA. This high degree of variability highlights the importance of not focusing too heavily on the determinants used to construct this typology (intensity of soil tillage and diversification of crops in the rotation) at the expense of the broad range of technical options available in each cropping system type (*e.g.* choice of material, intervention dates, crop varieties).

It should also be noted that soil tillage and the diversity of crops included in the rotation are not the only determinants accounting for the performance of cropping systems, in terms of basic and aggregate indices. Many other farming operations, such as the level of use of fertilisers and pesticides, and site-specific factors, including soil characteristics and local climatic conditions, can account for differences in performance within a given cropping system type (Erenstein, 2003; Knowler and Bradshaw, 2007). More precise studies are required to unravel the multiple complex interactions between management factors and to determine the precise locations and conditions most suitable for CA.

It should also be borne in mind that differences in performance between years were not taken into account in this study, because the evaluations are based on an “average description” of the systems and their climatic and economic environments. In general, few scientific studies take into account the interannual variability of economic, social and environmental performances in CA systems. There is nevertheless considerable variability in performance, particularly during the transition phase, which largely determines the attractiveness of CA to farmers. In this respect, as pointed out by Giller *et al.* (2011; 2009), a more precise analysis of the robustness of performances in CA is a key issue that should be addressed by researchers, to determine, in particular, the effect of climatic variability on these systems.

4.2 Output evaluation and the main lessons learned

As previously stated and recommended by Bockstaller *et al.* (2009, 2003), the *a priori* evaluation of the structure of the model for its use in conservation agriculture was followed by an *a posteriori* analysis of the results produced. Due to the immeasurable nature of sustainability and the number of indicators used to evaluate it, we were unable to perform an evaluation based on comparisons with measurements or direct observations in the field. The pertinence of the results will therefore be assessed here by comparison with published results from scientific studies focusing on the performances of conservation agriculture in similar contexts. We avoided tautological validation by paying particular attention to avoiding the citation of articles used to construct or improve the structure of the indicators.

There is little scientific evidence for an economic impact of CA in the European context. Nevertheless, according to Lahmar (2010) and Scopel *et al.* (2012), cost savings in terms of fuel, labour and machinery remain the most important economic features of conservation agriculture, driving its adoption in Europe. These observations are consistent with the results obtained for the "economic efficiency" indicator. According to the same authors, the impact on profitability of the adoption of the principles of CA remains difficult to estimate due to the diversity of contexts and practices. Nevertheless, according to Scopel *et al*. (2012), these practices generally appear to be profitable when they are technically well mastered. This is an important aspect, because decreasing soil tillage tends to increase the risks of infestation with weeds (Debaeke and Orlando 1994) and necrotrophic parasites, which may survive and develop on crop residues at the soil surface (Glen and Symondson, 2003, Kreye, 2004). These observations are consistent with the results provided by MASC in this study, indicating that this short-term economic benefit could be counterbalanced by a yield decrease, due to higher levels of infestation with weeds, pests and diseases or additional costs relating to their control. According to Lahmar (2010), such problems may lead some European farmers to prefer specific crops that are more easily managed with CA or to return to conventional practices. However, these outcomes go against the empirical experience of some of the farmers and advisors involved in this study, who reported that such systems were actually less susceptible to pests, diseases and weeds because the lower level of soil disturbance results in a greater biodiversity of natural enemies, and well adapted crop rotations prevent the build-up of pests and weeds. These observations are consistent with several other scientific findings (Derpsch *et al.*, 2003; Palm *et al.,* 2014; Sturz *et al.*, 1997). Thus, although the results of this study highlight some of the weaknesses of CA cropping systems, they also identify a weakness of the MASC model, in terms of its ability to estimate the agronomic effects of biodiversity from a description of the practices employed and the context. As suggested by Bell and Morse (2008), the designers of the MASC model built their indicators from the available scientific knowledge, whilst trying to keep their use relatively simple. This probably led to the retention of rules that are too generalised and that do not precisely cover the diversity of pedoclimatic situations and techniques observed in this study. As pointed out by Médiène *et al.* (2011), we still have little scientific information concerning the responses of biological process to agricultural practices in a given pedoclimatic context. Thus, as highlighted by Palm *et al.* (2014), the complex trade-off between the services provided and the deleterious effects caused by the greater biodiversity resulting from reduced tillage and diversification of the crop rotation remains unclear. Specific studies on this topic are therefore required to identify the determinants involved and to make it possible to propose more accurate indicators.

Reduced and no tillage systems had poorer performances for the social dimensions of the model than other cropping systems with more intensive tillage. DS cropping systems performed less well than other systems for the criteria “system complexity”, “health risk of pesticide use” and “contribution to local employment”. These results are basically consistent with most of the published results concerning the performances of CA. Overall, CA is often seen as a complex set of interrelated practices that typically requires several rounds of adaptation to become fully viable. It involves learning on the part of the farmer, local adaptation, and breaking with a long-standing tradition of soil tillage and the removal of crop residues (Giller *et al.,* 2011; Lahmar, 2010).

The lack of tillage in SD cropping systems, particularly those with a low level of crop diversification in the rotation, often results in the proliferation of weeds, necessitating the more frequent application of larger amounts of herbicide by farm workers (Chapelle-Barry, 2008), resulting in the exposure of these workers to a higher risk of toxicity. Moreover, the overall decrease in working time associated with reduced tillage systems, which is generally attractive for farmers, is considered to be a negative aspect in the MASC model, because it may lead to a decrease in agricultural employment in the area. This criterion draws attention to one of the potential risks of the widespread adoption of CA. However, the accuracy of this assessment is restricted to the information available at the field scale. According to Lahmar (2010), the labour saved by not tilling the soil could be diverted to other agricultural or non-agricultural activities on a larger scale. This highlights how the “granularity” of the spatiotemporal scales of the cropping system is less relevant for addressing issues that are partly dependent on higher levels of organisation, such as the farm or an agricultural region (*e.g.* indicators “work overload” and “emergence of a new supply chain”). The results for this criterion should therefore be interpreted with caution, focusing purely on the contribution of the cropping system, everything else being equal.

The main benefits in terms of the environmental dimension of cropping systems closely following CA principles (*i.e.* RT-HC and SD-HC) are consistent with the observations of several authors in temperate regions in Europe. Reduced and no tillage systems, particularly if the crop residues are left on the soil surface, tend to lead to an increase in carbon sequestration within the soil. In terms of biodiversity conservation, positive effects of CA on the soil macrofauna, flora and micro-organisms have also been reported by many authors

(Debaeke and Orlando, 1994; Emmerling, 2001; Peigné *et al*., 2009; Vian *et al*., 2009). CA has also been reported to limit soil erosion, by improving water infiltration, due to the higher soil organic matter content and the presence of crop residues at the soil surface. The larger population of earthworms in conservation tillage conditions is also known to favour water flow and infiltration (Frielinghaus, 2007). Decreasing the frequency of tillage decreases the direct consumption of fossil energy, but diversifying the rotation by introducing legumes appears to be a more efficient way of decreasing energy consumption. The introduction of legumes into the rotation makes it possible to decrease the total amount of nitrogen fertiliser applied. Several authors have reported a strong correlation between the total energy consumption of cropping systems and the amount of nitrogen fertiliser applied.

The MASC model provided an overview of the performances of cropping systems as a function of the degree to which CA principles were applied, within the French context. As suggested by Giller *et al.* (2009) the assessment of a large number of cropping systems and the analysis of their performances according to whether the principles of CA were applied, fully, partially or not at all, make it easy to determine which of these principles contribute to the desired effect. The results of this study suggest that decreasing, or even abolishing tillage, one of the major symbolic pillars of CA systems, is not the most effective way to increase the overall sustainability of cropping systems. Direct seeding systems with short and undiversified rotations gave the worst sustainability results, with scores slightly lower than those for conventional systems. Conversely, the adoption of long diversified crop rotations, regardless of the soil tillage conditions, appeared to be essential for attaining a high level of overall sustainability. Therefore, rotations including diverse cash and cover crops are an essential element of CA systems, as they provide an effective way to manage pests and weeds in the absence of soil tillage. The promotion of greater biodiversity at the field level favours the better use of natural resources, a more regular distribution of labour and more diversified farm incomes (Calegari *et al.,* 2008; Médiène *et al.,* 2011; Scopel *et al.,* 2012). Therefore, consistent with the assertions of most authors (Derpsch *et al.*, 2003; Erenstein, 2003; FAO, 2008; Hobbs, 2007; Scopel *et al.*, 2012), CA is an “holistic” package that works well only when all three pillars are applied simultaneously.

4.3 End-use evaluation of the MASC model and precautions for use

This study provides a form of evaluation of the model in terms of its utility in the situation of application. According to Bockstaller *et al.* (2003), an assessment model may lack usefulness for several reasons: a target of great relevance to potential users may have been left out, some data required for calculations may not be available or the outputs of the assessment may be incomprehensible or illegible.

The positive feedback received from several of the stakeholders (*e.g.* researchers, extension workers and farmers) involved in this study suggests that the major preoccupations of users were adequately taken into account (Craheix *et al.*, 2012b; Craheix *et al.,* 2012c). Thus, the holistic approach of the MASC model, based on a sustainability assessment, provides a suitable overview of the performance of cropping systems, by taking into account simultaneously (i) the multiple objectives of the economic, social and environmental dimensions; ii) various time scales, ranging from the short term to the long term and (iii) the concerns raised at various levels, including the expectations of farmers and of society as a whole. However, although this assessment framework may be seen as very integrative and objective, caution is required in the use of such models and the interpretation of the results obtained, due to the underlying subjectivity inherent in the criteria chosen and their aggregation (Bell and Morse, 2008). Designers try to counterbalance this apparent binding framework by encouraging debate with end-users when interpreting results. Designers have also introduced flexibility by allowing users to modify both the method by which basic criteria are assessed (*i.e.* choice of indicators) and the weights assigned to the various criteria, so as to integrate their own preferences and visions of sustainable development into the parameter settings. Interesting results have already been reported in France, where the MASC model was used to get farmers involved in the evaluation of their cropping systems through the discussion and modification of parameter settings (Craheix *et al.*, 2012b). In this study cropping systems were ranked with the default version of MASC, based on a balanced perception of sustainability. It should be borne in mind that the rankings would be probably different if the weights were modified (*e.g.* by increasing the relative weight of the environmental dimension for instance). Therefore, according to the designers of the MASC model and as suggested by Bell and Morse (2008), the development and use of the multicriteria assessment method for sustainability requires maximum transparency and flexibility and should never be limited to the interpretation of aggregate results alone.

Regarding the ease of use of the model in terms of the availability of the data required and the comprehensibility of the outputs, the ability of MASC to deal with qualitative information appeared very useful in these real-use situations. Firstly, as noted above, processing qualitative information makes it possible to use quantitative values by simply using thresholds to render them qualitative. This flexibility makes it possible for the MASC model to combine various data, such as simple measurements (*e.g.* yields), calculated data (*e.g.* semi-net margin) and empirical knowledge (*e.g.* physical difficulties of crop interventions) into the indicators, so as to make the best use of commonly available information. Secondly, it makes it possible to integrate the decision-maker's own views (concerning the "system complexity" criterion, for example) into the model, as these views are not necessarily expressed through formal, quantitative models. Finally, regarding the legibility of the outputs, as suggested by Munda *et al.* (2005), qualitative and linguistic forms (such as "low", "medium" or " high") appeared to be well understood by the stakeholders concerned as natural representations of human judgments and cognitive observations. Furthermore, qualitative decision rule-based methods are considered relevant for non-compensatory decision strategies involving the aggregation of results for different criteria (Ma, 2006), making it easier to tackle the issues of a lack of comparability and immeasurability that often underlie the dimensions of sustainability in agricultural systems (Sadok *et al.,* 2008). Nevertheless, the homogenisation of calculated variables into qualitative variables, which are by nature discrete, together with the classification of the systems studied into large classes, may lead to marked differences in judgement concerning performances that are actually relatively similar. The choice of the thresholds separating qualitative classes for particular criteria was adapted here so as to minimise this risk.

5. Conclusion

Assessing the relevance of innovations, such as CA, remains a difficult exercise, because several objectives, some of which conflict, and criteria of different natures must be taken into account. Multicriteria decision aid models, such as MASC®, have been developed to overcome these apparent difficulties by providing a holistic approach to the problem based on an assessment of the sustainability of cropping systems. The use of this model in the French context provides a more comprehensive assessment of the various performances of CA, through comparisons with conventional systems and intermediate systems in which the principles of CA are applied only partially. The results obtained thus provide a better perception of the overall relevance of CA and improve our understanding of the principles contributing to the desired effect.

Firstly, the results of this study indicate that CA is a promising alternative to conventional practices that can improve the sustainability of cropping systems in France, provided that it is applied in full. Secondly, a detailed analysis of intermediate systems partially applying the principles of CA revealed that there was a positive interaction between the reduction of tillage and the diversification of the crop rotation for the environmental dimension. However, diversification of the crop rotation was found to be the best way to increase the overall sustainability of cropping systems. Cropping systems involving diversified rotations achieved good results, regardless of the tillage regime, whereas direct seeding-based systems not coupled with a diversified rotation had the lowest sustainability scores. Thus, decreasing soil tillage appeared to be less effective in this study than diversifying the crop rotation, and should therefore not be applied in isolation.

According to these findings, CA, as a holistic package, is an interesting way to improve the sustainability of agricultural systems in the French context. However, when this strategy is preferred, the social and agronomic difficulties reported in this study should be taken into account. A gradual transition from ploughed conventional systems towards CA systems should be encouraged, with the early consideration of a specific cover crop management strategy involving crops from different families. Finally, the results of this study require confirmation and completion with field measurements, for a larger number of more diverse cropping systems, with the evaluation of CA over larger scales (the farm and regional scales). Furthermore, the validity of our findings could not be easily extended to areas where AC is more widespread and where the conditions of soil and climate, including drought intensity and frequency, are different from those of Western Europe.

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Table captions

Table 1: Methods for evaluating the basic criteria of the economic and social dimensions of the MASC model: QT - indicators based on quantitative and calculated data; QL - indicators based on expert evaluation through the use of qualitative information; ST - indicators based on a subtree design, using DEXi software to combine qualitative expertise and quantitative data through calculation. For these indicators, weights (expressed in %) are assigned to the factors considered.

Table 2: Methods for evaluating basic criteria for the environmental dimension of the MASC model: QT - indicators based on quantitative and calculated data; QL - indicators based on expert evaluation through the use qualitative information; ST - indicators based on a subtree design, using DEXi software to combine qualitative expertise and quantitative data through calculation. For these indicators, weights (expressed in %) are assigned to each of the factors considered.

Table 3: Simplified presentation of the cropping systems studied in each region. Each line of this table corresponds to the description of one of the 31 cropping systems assessed. A code is assigned to each cropping system to specify its affiliation a given type (DS: direct seeding, RT: reduced tillage, PL: frequent use of ploughing, LC: Low diversification of crop rotations, HC: High diversification of crop rotations). For the cultivated crops: AFA alfalfa, FAB faba bean, FES fescue, HP hemp, FF fibre flax, MAG grain maize, MAS silage maize, OR oilseed rape, SBEET sugarbeet, SOY soybean, SPEA spring pea, SUN sunflower, TRIT triticale, WB winter barley, WPEA winter pea, WW winter wheat. The cover crops are indicated in brackets: (Must.) mustard, (mgl) mixture of grass and legumes, (b.wheat) buckwheat, (fab) faba bean, (oat) oat, (rye) rye. For the origin of the observations: F on-farm observations, S for observations at experimental stations.

Figure captions

Figure 1: Sustainability criteria information processing and aggregation in the MASC 2.0 decision tree. Numerical values in the decision tree displayed in red boxes represent the weights (expressed in %) proposed by the designers of the MASC model.

Figure 2: Typology of the cropping systems defined by expertise to qualify the degree to which CA principles are implemented. DS: direct seeding, RT: reduced tillage, PL: frequent use of ploughing, LC: Low diversification of crop rotations, HC: High diversification of the crop rotations.

Figure 3: Mean score (and standard deviation), by cropping system type, for the most aggregated criterion (*i.e.* overall sustainability) and for the three dimensions of sustainability. Cropping system types characterised by a “Low diversification of crop rotations” are presented in light grey, and types with a “High diversification of crop rotations” are presented in dark grey.

Figure 4: Mean score (and standard deviation) by cropping system type for criteria in the economic branch of the MASC model. PL: Frequent use of ploughing, RT: reduced tillage, DS: direct seeding. Types characterised by a “Low diversification of crop rotations” are presented in light grey, and types with a “High diversification of crop rotations” are presented in dark grey.

Figure 5: Mean score (and standard deviation) by cropping system type, for the criteria in the social branch of the MASC model. PL: Frequent use of ploughing, RT: reduced tillage, DS: direct seeding. Cropping system types characterised by a “Low diversification of crop rotations” are presented in light grey, and types with a “High diversification of crop rotations” are presented in dark grey.

Figure 6: Mean score (and standard deviation), by cropping system type, for some of the criteria in the environmental branch of the MASC model. PL: Frequent use of ploughing, RT: reduced tillage, DS: direct seeding. Cropping system types characterised by a “Low diversification of crop rotations” are presented in light grey, and types with a “High diversification of crop rotations” are presented in dark grey.

Figure

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Figure 1

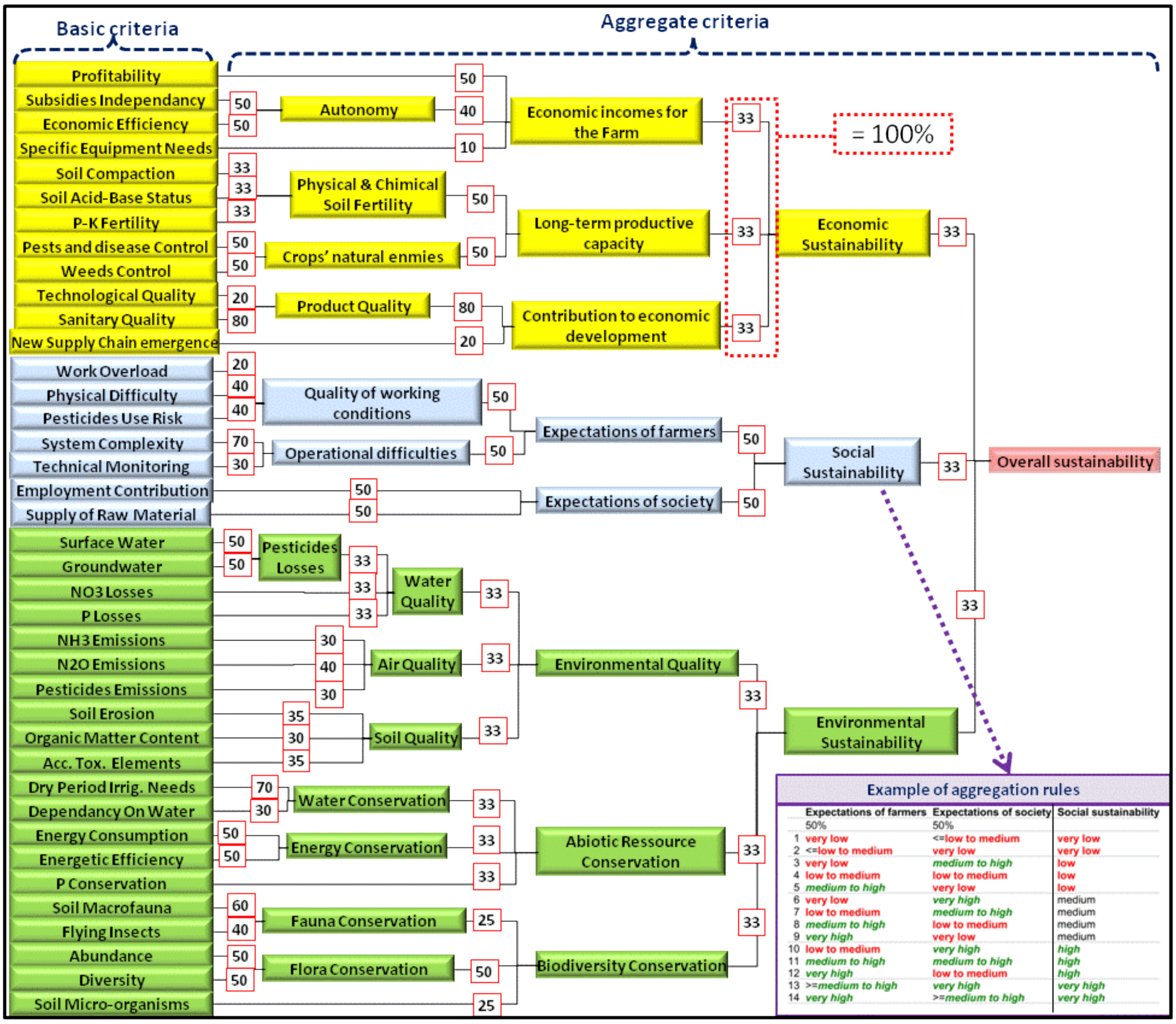
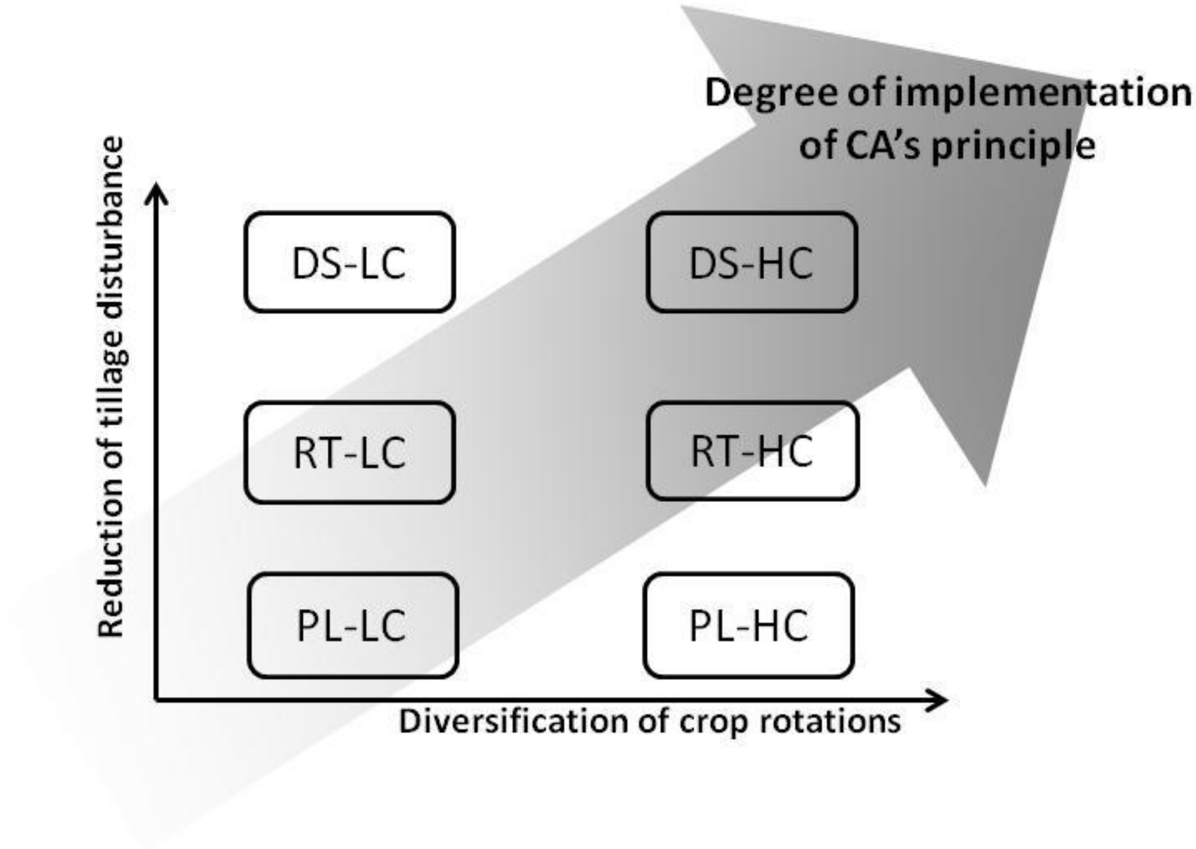


Figure 2


Degree of implementation
of CA's principle
Reduction of tillage disturbance
DS-LC
DS-HC
RT-LC
RT-HC
PL-LC
PL-HC
Diversification of crop rotations

Figure
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Figure 3

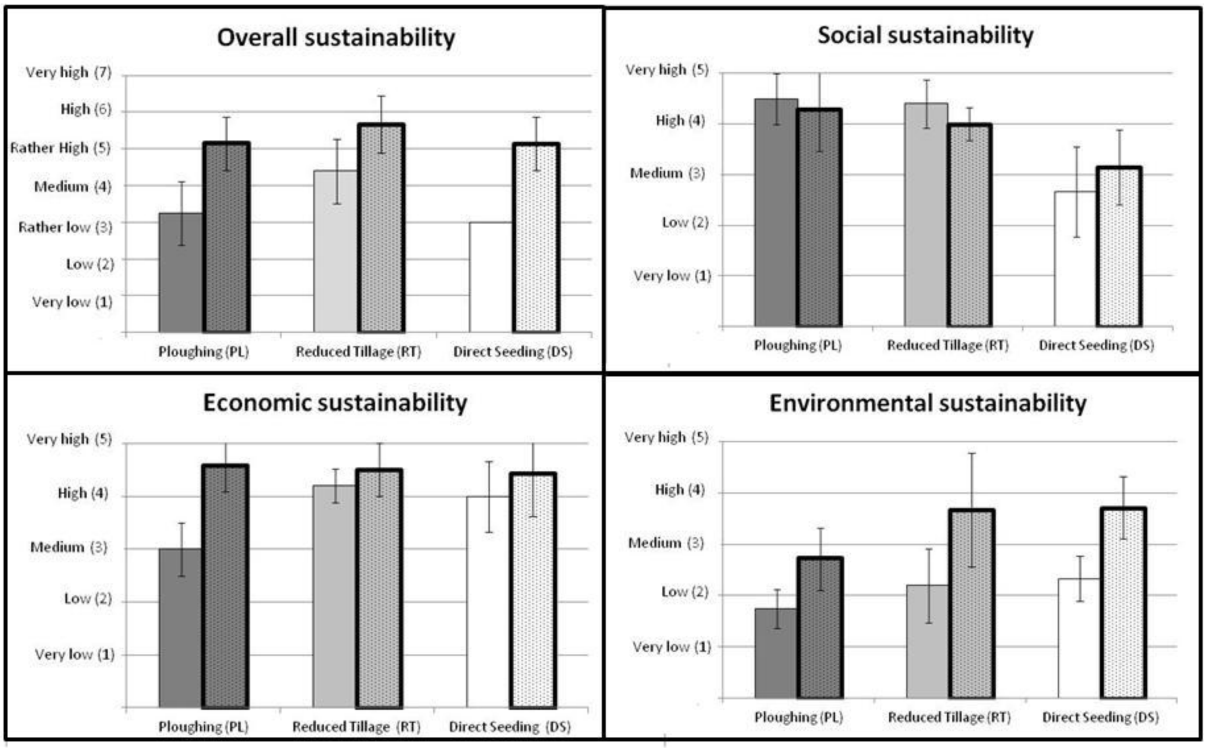

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Figure 4

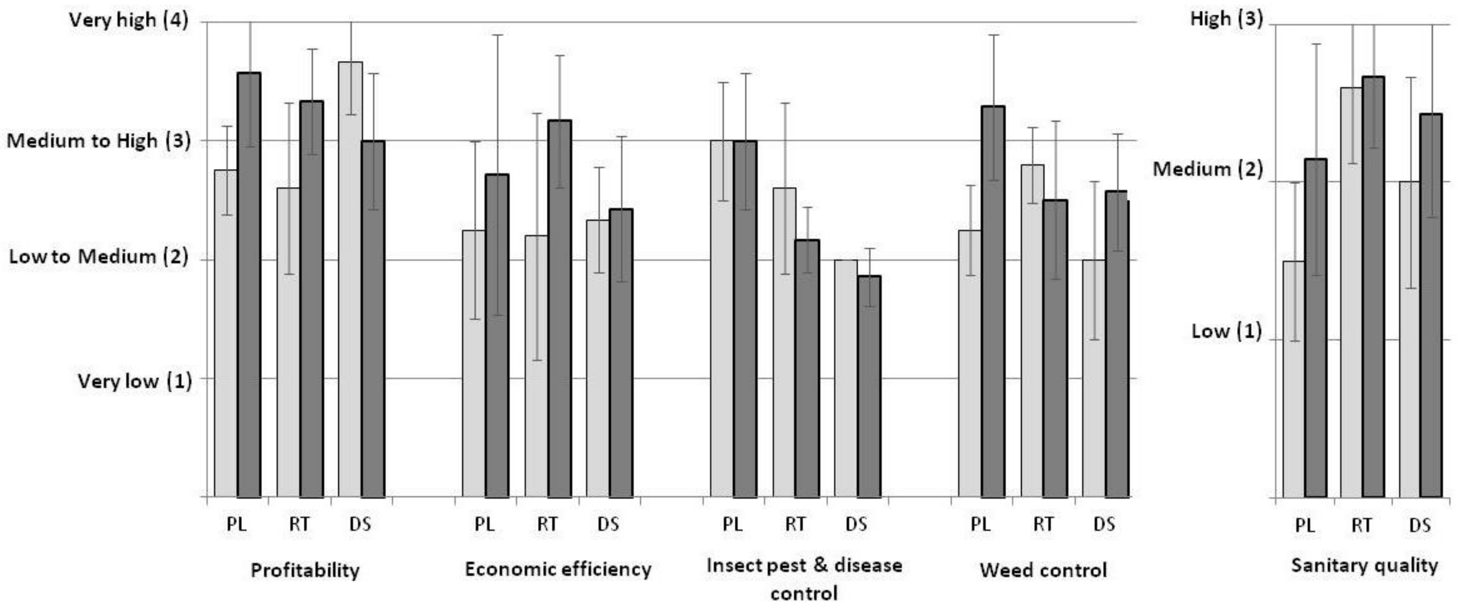

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Figure 5

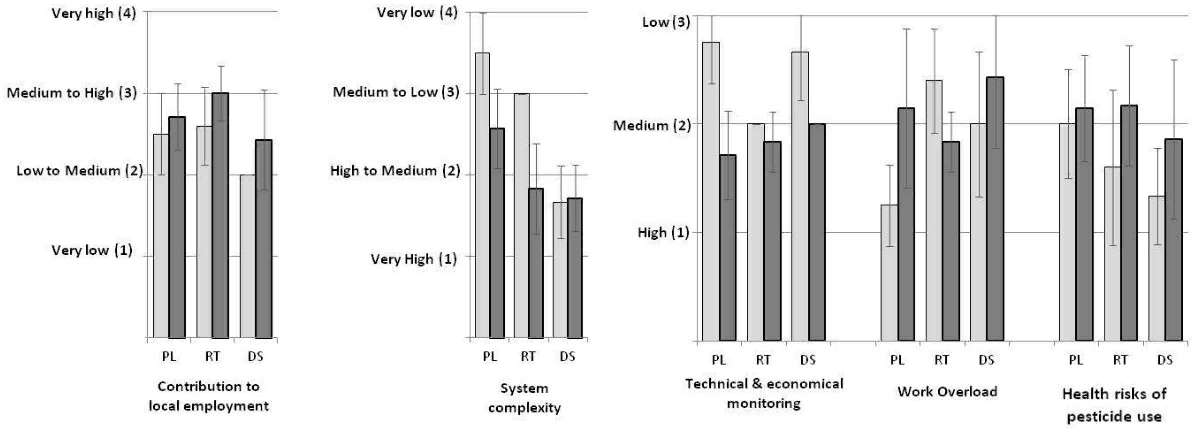

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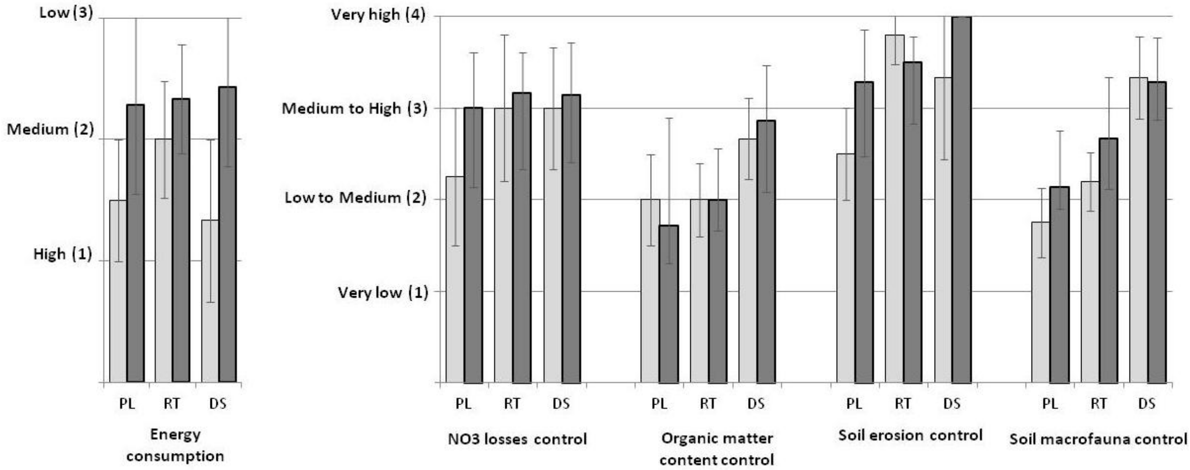
Figure 6



Table

Table 1

	Basic criteria	Mode	Reference methods or main factors considered
Economic dimension	Profitability	QT	Semi-net margin, considering subsidies and mechanical cost (€ .ha^{-1}.$year^{-1}$).
	Subsidies Independency	QT	Mean ratio of semi-net margin to subsidies (% .ha^{-1}.$year^{-1}$).
	Economic efficiency	QT	Mean ratio of semi-net margin to operational costs (% .ha^{-1}.$year^{-1}$).
	Specific equipment needs	QL	Additional costs to purchase specific machinery.
	Soil compaction	ST	**Regeneration factors (60%)**: climate effects (13%); tillage effects (13%); biological effects (13%) / **Damaging factors (40%)**: harvest in wet climatic conditions (60%) specific equipment to reduce soil compaction (40%).
	Soil acid-base status	ST	Initial soil pH (35%); buffering capacity of soil (15%); basic fertiliser effects (25%); effects of acidifying practices (25%).
	P-K fertility	ST	Initial soil fertility (35%); soil buffer capacity (15%); nutrient balance (33%); organic matter recycling (16%).
	Control of insect pests and diseases	ST	Diversity of the families of crops (50%); management of harvest residues (30%); effects of genetic, chemical and biological control (20%).
	Weed control	ST	Diversity of crop sowing dates (50%); ploughing effect (20%); effects of mechanical, chemical and cover control (30%).
	Technological quality	QL	Risk of failure to meet the level of quality required by the agro-food production chain.
	Sanitary quality	QT	Mean, over the entire rotation, of annual indices describing the contamination risk of cereals by mycotoxins (taking into account the previous crop, the management of harvest residues and varietal susceptibility).
	New Supply Chain emergence	QT	Proportion, in the rotation, of crops marginally represented in the region.
Social dimension	Workload distribution	QL	Expertise concerning the distribution of the most time-consuming interventions (*e.g.* ploughing, sowing, harvesting).
	Physical difficulty	QL	Expertise considering the physical difficulty of each crop intervention.
	Pesticide use risk	QT	Annual mean of chemical interventions classified as toxic (ha^{-1}.$year^{-1}$).
	System complexity	QT	Annual mean of indices defined with farms & advisors to consider the main difficulties in crop management (*i.e.* presence of cover crop, mechanical weeding) (i. $year^{-1}$).
	Technical monitoring	QL	Estimation of the effort required by a farmer to keep up to date with knowledge about the technical and economic environment of each crop (number of different crops in the rotation).
	Employment contribution	QT	Mean annual labour time (h. ha^{-1}.$year^{-1}$).
	Supply of raw material	QT	Mean difference between the observed yields of each crop and those achieved in intensive production systems in the region (%.ha^{-1}.$year^{-1}$).

Table

Table 2

	Basic criteria	Mode	Reference methods or main factors considered
Environmental dimension	Pesticides (surface water)	QT	I-PHY_{SW} indicator in the Indigo method (Bockstaller *et al.,* 1997).
	Pesticides (ground water)	QT	I-PHY_{GW} indicator in the Indigo method (Bockstaller *et al.,* 1997).
	NO_3 Losses	QT	I-NO3 indicator in the Indigo method (Bockstaller *et al.,* 1997).
	Phosphorus losses	ST	Initial soil phosphorus content (20%), soil erosion (30%), mean amount of phosphorus provided (30%) and method of incorporation (20%).
	NH_3 emissions	QT	I-NH3 indicator in the Indigo method (Bockstaller *et al.,* 1997).
	N_2O emissions	QT	I-NO2 indicator in the Indigo method (Bockstaller *et al.,* 1997).
	Pesticide emissions	QT	I-PHY_{air} indicator in the Indigo method (Bockstaller *et al.,* 1997).
	Soil Erosion	ST	Soil cover in period of risk (55%); Tillage effects (35%); Soil compaction (10%).
	Organic matter content	QT	I-MO indicator in the Indigo method (Bockstaller *et al.,*1997).
	Accumulation of toxic. elements	QL	Expertise based on the presence/absence of acidification risks and pollution with heavy metals or organic micropollutants.
	Dry period irrigation needs	QT	Water consumption for irrigation during critical periods ($m^3.ha^{-1}.year^{-1}$).
	Dependence on water	ST	Crop water demands (50%); Proportion of crop water demands covered by irrigation (50%).
	Energy consumption	QT	I-EN indicator in the Indigo method (Bockstaller *et al.,*1997).
	Energy efficiency	QT	Mean ratio between energy consumption of each crop and energy provided by harvested products ($Mj^{-1}.Mj^{-1}$/ha/year).
	Phosphorus conservation	QT	Mean phosphate rock consumption (kg $P_2O_5.ha^{-1}.year^{-1}$).
	Soil macrofauna	ST	Tillage effects (40%); Effects of added organic matter (35%); TFLi: Treatment Frequency Index (Gravesen, 2003) of all insecticides (25%).
	Flying insects	ST	Diversity of the crop families (50%); TFLi: Treatment Frequency Index (Gravesen, 2003) of all insecticides (50%).
	Flora abundance	ST	Inverse of the result provided by the criterion “weed control”.
	Flora diversity	ST	Diversity of sowing dates (50%); use of broad-spectrum herbicides (35%); field margin management (15%).
	Soil micro-organisms	ST	Diversity of crop families (25%); Effects of added organic matter (50%); TFIt: Treatment Frequency Index (Gravesen, 2003) of all pesticides (25%).

Table

Table 3

Type	Crop sequence	Region	Origin	Soil	Frequency of ploughing
PL-LC	MAG-WW (Must.)	Haute-Normandie	F	Deep silty soil	1/2
	OR-WW-WPEA-WW-SB	Haute-Normandie	F	Deep silty soil	2/5
	OR-WW-WB	Champagne-Ardenne	F	Calcareous clay	1/3
	MAG-WW	Aquitaine	F	Sandy clay	2/2
	MAG-WW	Aquitaine	F	Sandy silt	2/2
PL-HC	(Must.)SBEET-WW-(Must.)MAG-WW-(Must.)SB	Haute-Normandie	F	Deep silty soil	5/5
	OR-WW-FAB-WW-(Must.)MAG-WW		F		2/6
	OR-WW-HP-FES-OR-PEA-WW-WB		F		8/8
	OR-WW-(mgl)SB-(mgl)SUN-WW-(mgl)SB	Champagne-Ardenne	F	Calcareous clay	3/6
	OR-WW-(mgl)WB-(mgl)PEA-WW(mgl)SBEET-SB-(mgl)SPEA-(mgl)		F	Chalk	8/8
	OR-WW-(mgl)SB-(mgl)-SBEET-WW-(mgl)SB-		F		3/6
	OR-(mgl)-WB-SBEET-AFA-AFA-WW-(mgl)SB-(mgl)SPEA		F		3/8
	AFA-AFA-AFA-MAI-SOY-WW-(rye)SOY-WW	Rhône-Alpes (organic farming)	S	Deep sandy silt	6/8
RT-LC	OR-WW-SB-WW-FAB	Haute-Normandie	F	Deep silty soil	1/5
	OR-WW-WB-WPEA	Champagne -Ardenne	F	Calcareous clay	1/4
	OR-WW-WB	Centre	S	Calcareous clay	0/3
RT-HC	FES-FES-WW-WB-FAB-WW-HP-WW-SB	Haute-Normandie	F	Deep silty soil	0/9
	OR-WW-(Must.)FF-WW-WB-(Must.)SPEA-WW-(Must.)SB	Haute-Normandie	F	Deep silty soil	0/8
	OR-WW-(must.)FAB-WW-(must.)SPEA-WW	Haute-Normandie	F	Deep silty soil	0/6
	AFA-AFA-AFA-MAI-SOY-WW-(rye)SOY-WW	Rhône-Alpes (organic farming)	S	Deep sandy silt	0/8
	OR-WW-WB-SUN-WW	Centre	S	Silt loam	0/5
DS-LC	OR-WW	Franche-Comté	F	Calcareous clay	0/2
	OR-WW-WB	Centre	S	Calcareous clay	0/3
	(mgl) MAG-WW	Aquitaine	F	Sandy silt	0/2
DS-HC	OR-WW-(mgl)SOY	Franche-Comté	F	Calcareous clay	0/3
	OR-WW-(oat)SOY-WW	Franche-Comté	F	Calcareous clay	0/4
	OR-WW-(mgl)SB-(Must.)SPEA	Champagne -Ardenne	F	Chalk	0/4
	AFA-AFA-AFA-MAI-(oat)SOY-WW-(rye)SOY-WW	Rhône-Alpes (organic farming)	S	Sandy clay	0/8
	OR-(fab)WW-WB-(rye)SUN-WW-(b.wheat)WPEA	Centre	S	Calcareous clay	0/6
	(mgl)MAG-(mgl)MAE-TRIT	Aquitaine	F	Sandy clay	0/3
	OR-WW-(mgl)SUN-WW-(mgl)FAB	Centre	S	Silt loam	0/5