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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.

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

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1 Abstract

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

23 1. Introduction

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

33

34 In response to these challenges, farmers and agronomists have been trying to develop
35 alternative cropping systems. Conservation agriculture (CA) is one of the innovations
36 proposed and is among the most extensively studied new systems developed in recent
37 decades (Scopel *et al.*, 2012). CA systems are based on the following three principles: (i)
38 minimal or no mechanical soil disturbance; (2) diversified crop rotations and (3) permanent
39 soil cover (consisting of a growing crop or a dead mulch of crop residues) (FAO, 2008).
40 Conservation agriculture has been actively promoted by several international research and
41 development organisations, in a wide range of contexts, on the basis of specific field
42 observations and literature reviews (Dumanski *et al.*, 1998; Hobbs *et al.*, 2008; Holland,
43 2004; Lapar and Pandley, 1999; Lestrelin *et al.*, 2012). CA has already been massively
44 adopted on large-scale mechanised farms, particularly in Australia and Americas but its
45 adoption remains limited in other parts of the world such as Africa and Western Europe
46 (Derpsch *et al.*, 2003; Lahmar, 2010). With the low level of dissemination of CA systems in
47 these regions and the diversity of practices associated with these systems, the effective and
48 global performances of this set of innovations remain unclear and the benefits of CA are
49 increasingly being questioned in the scientific community (Giller *et al.*, 2011; Peigné *et al.*,

50 2009; Serpantié *et al.*, 2009). Western European farmers adopting CA approaches often do
51 so without completely respecting all of the principles of CA. This makes it possible for them
52 to broaden the range of options open and to adapt the principles of CA to local conditions.
53 However, it also greatly affects the efficiency and impact of CA systems in the short and long
54 term (Scopel *et al.*, 2012). In the face of the diversity of (i) practices associated with CA, (ii)
55 goals assigned to agricultural systems, and (iii) pedoclimatic contexts, there is still no
56 empirical evidence about the overall performance of CA in the French context (Lhamar,
57 2010). There is therefore a crucial need to determine the reliability of this innovation with
58 respect to conventional practices (generally involving more intensive soil tillage and less
59 diversified crop rotations), and to clarify the benefits and drawbacks of the full or partial
60 application of conservation agriculture in this context.

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

78 desired effects in France, and should make it possible to identify ways of improving these
79 cropping systems as well.

80

81 **2. Materials and methods**

82 **2.1 Presentation of the MASC model**

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

100

101 Through this formalism, MASC conceptualises the sustainability assessment problem by
102 breaking it down into the three classical dimensions used to define sustainability (social,
103 economic and environmental; Ikerd, 1993, United Nations, 1996). Each dimension

104 represents a hierarchy of sustainability objectives organised into a tree-like structure formed
105 by 65 variables (see Figure 1).

106 **Figure 1**

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

112

113 Basic criteria relate to elementary concerns of sustainable development (*e.g.*, “Profitability”,
114 “Nitrate losses” and “Soil erosion”). These criteria are entered into the model via specific
115 indicators proposed by the model designers. The methods for calculating or evaluating these
116 indicators are detailed in Tables 1 and 2. Six of the 39 indicators proposed are based on
117 direct expertise. The main factors to be taken into account in this expertise are also reported
118 in Tables 1 and 2. Twenty indicators are based on quantitative variables obtained by
119 calculation. For this type of indicator, quantitative values are converted into qualitative
120 variables compatible with the DEXi software through the use of locally defined thresholds.
121 For instance, for the criterion “Profitability”, results for the semi-net margin are based on
122 threshold values covering the diversity of the margin observed in a region (*e.g.* : *Very low* ≤
123 €200 /ha ≤ *Medium to low* ≤ €400/ha ≤ *Medium to high* ≤ €600/ha). The other 13 indicators
124 are classified as “mixed” as they can deal with both qualitative and quantitative data. These
125 indicators are developed in DEXi software by disaggregating a basic criterion in a subtree,
126 the inputs of which are obtained from a qualitative description of the system or by simple
127 calculation, with the use of threshold values for conversion into qualitative inputs.

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

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

144 Relative to the first version published by Sadok *et al.* (2009), the second version of the
145 model, as used here, presents several improvements that helped to delimit the outline of this
146 assessment. The designers made use of feedback from the initial users (Craheix *et al.*,
147 2012c) and included new criteria in the tree, to ensure that levels such as the production
148 chain and society were better encompassed in the economic and social dimensions (*e.g.*:
149 "Supply of raw materials", "New supply chain emergence" , "Sanitary quality"). In accordance
150 with a previous adaptation of MASC 1.0 to organic farming systems (Colomb *et al.*, 2012), a
151 new branch, “Long-term productive capacity”, was inserted into the economic dimension of
152 MASC 2.0. This modification makes agronomic viability a key determinant of the economic
153 sustainability of innovative cropping systems, by taking into account both soil fertility and the
154 control of pests and weeds. Finally, based on the DEXiPM model (Pelzer *et al.*, 2012), the
155 "Biodiversity Conservation" branch of the environmental dimension was profoundly modified
156 to restrict assessment to the less mobile groups of organisms, which are heavily dependent

157 on crop interventions at the field scale (*i.e.* flora, soil macrofauna, flying insects and soil
158 micro-organisms). These new criteria were inserted while taking advantage of the sensitivity
159 analysis performed on the MASC model (Carpani *et al.*, 2012; Bergez, 2013). They were
160 designed to both maintain sensitivity of the model and to avoid structural effects leading to
161 involuntarily increase of the weight of some criteria.

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

170 **2.2 Description of the cropping systems evaluated**

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

174
175 The description of these cropping systems was based on a list of farming practices and the
176 yields obtained for each crop, through a combination of recorded data and expertise. The
177 cropping systems were collected from six different regions of France (*i.e.* Haute-Normandie,
178 Champagne-Ardenne, Rhône-Alpes, Centre, Aquitaine, Franche-Comté), so as to take into
179 account various pedoclimatic contexts. In terms of economic data, we considered, for all the
180 cropping systems assessed, the same purchase prices for inputs and selling prices for crops,
181 based on the average over the preceding five years (*i.e.* 2008-2013).

182 **Table 3**

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

198 **Figure 1**

199 **3. Results**

200 **3.1 Analysis of the main sustainability criteria scores**

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

209 seeding and a low diversification of the rotation had lower overall sustainability scores (3/7,
210 “rather low”), close to those of conventional systems (PL-LC).

211 **Figure 3**

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

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

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

224 **3.2 Analysis of scores for basic criteria**

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

230 More detailed results for the economic dimension (Figure 4) indicated that systems with low
231 frequencies and shallow depths of soil tillage (*i.e.* the RT and DS types) were at least as
232 profitable as ploughed systems. These systems obtained better results for the “economic
233 efficiency” criterion, reflecting a lower economic dependence on inputs (*e.g.* fuel, fertiliser,
234 pesticides). Nevertheless, reduced tillage systems and systems with only very superficial

235 tillage operations had worse results than ploughed systems for the criteria “weed control” and
236 “control of insect pests and diseases”. In parallel, systems based on long diversified
237 rotations, particularly those including legumes (as the principal or cover crop) were generally
238 more profitable and had a higher economic efficiency than less diversified systems. These
239 systems also had better scores for the criteria “weed control” and “sanitary quality”
240 (estimating the sanitary risk associated with the presence of mycotoxins). However, systems
241 combining a diversified crop rotation with reduced or very superficial soil tillage did not obtain
242 better results than other systems for the indicator “control of insect pests and diseases”.

243 **Figure 4**

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

254

255 **Figure 5**

256 However, the deleterious effects of direct seeding systems were nevertheless smaller in
257 more diversified crop rotations (DS-HC in Figure 3). In these rotations, the presence of a
258 greater diversity of main and cover crops seemed to have a positive impact on the criterion
259 “contribution to local employment”, by increasing the mean number of hours of work per year,
260 and on the criterion “pesticide use-related health risk”, due to smaller numbers of pesticide

261 applications (Figure 4). The social impact of a greater diversity of crops in the rotation was
262 nevertheless essentially negative for the criteria “system complexity” and “technical and
263 economic monitoring time”. Indeed, the main and cover crops in these rotations, which
264 differed from those present in less diversified rotations, were often a bit more difficult to
265 manage (e.g. insertion and destruction of new cover crops) and the larger number of different
266 crops also increases the time that the farmer must spend updating his technical and
267 economic knowledge about his crops.

268 For the environmental dimension, cropping systems with long and diversified crop rotations
269 (HC) obtained the best scores, particularly when combined with reduced tillage (RT) or direct
270 seeding practices (DS) (Figure 3). As indicated by the more detailed results in Figure 6,
271 these systems had better results than ploughed systems for the criteria “soil macrofauna
272 conservation”, “soil erosion control” and “soil organic matter content control”. However, their
273 performances were similar to those of ploughed systems for the criterion “energy
274 consumption” and “control of NO₃ losses”.

275 Diversified rotations performed better than less diversified systems for the criterion “energy
276 consumption”. Thus, whereas reducing tillage decreases direct fuel energy consumption,
277 diversifying the rotation, particularly if legumes are included, makes it possible to decrease
278 more strongly the input of mineral nitrogen, a major contributor to the indirect consumption of
279 energy. In this respect, SD-LC systems had the worst results, due to the use of larger
280 amounts of synthetic nitrogen fertiliser to nourish the higher proportion of cash crops in these
281 cropping systems. The diversification of rotations, particularly if cover crops are included,
282 was mildly advantageous for the criteria “soil erosion control” and “control of NO₃ losses”.
283 The results obtained for the criteria “organic matter content control” and “soil macrofauna
284 conservation” differed little between rotations as a function of the level of diversification.

285 **Figure 6**

286 **4. Discussion**

287 **4.1 Variability of the results**

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

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

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

314 addressed by researchers, to determine, in particular, the effect of climatic variability on
315 these systems.

316

317 **4.2 Output evaluation and the main lessons learned**

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

327

328 There is little scientific evidence for an economic impact of CA in the European context.
329 Nevertheless, according to Lahmar (2010) and Scopel *et al.* (2012), cost savings in terms of
330 fuel, labour and machinery remain the most important economic features of conservation
331 agriculture, driving its adoption in Europe. These observations are consistent with the results
332 obtained for the “economic efficiency” indicator. According to the same authors, the impact
333 on profitability of the adoption of the principles of CA remains difficult to estimate due to the
334 diversity of contexts and practices. Nevertheless, according to Scopel *et al.* (2012), these
335 practices generally appear to be profitable when they are technically well mastered. This is
336 an important aspect, because decreasing soil tillage tends to increase the risks of infestation
337 with weeds (Debaeke and Orlando 1994) and necrotrophic parasites, which may survive and
338 develop on crop residues at the soil surface (Glen and Symondson, 2003, Kreye, 2004).
339 These observations are consistent with the results provided by MASC in this study, indicating
340 that this short-term economic benefit could be counterbalanced by a yield decrease, due to

341 higher levels of infestation with weeds, pests and diseases or additional costs relating to their
342 control. According to Lahmar (2010), such problems may lead some European farmers to
343 prefer specific crops that are more easily managed with CA or to return to conventional
344 practices. However, these outcomes go against the empirical experience of some of the
345 farmers and advisors involved in this study, who reported that such systems were actually
346 less susceptible to pests, diseases and weeds because the lower level of soil disturbance
347 results in a greater biodiversity of natural enemies, and well adapted crop rotations prevent
348 the build-up of pests and weeds. These observations are consistent with several other
349 scientific findings (Derpsch *et al.*, 2003; Palm *et al.*, 2014; Sturz *et al.*, 1997). Thus, although
350 the results of this study highlight some of the weaknesses of CA cropping systems, they also
351 identify a weakness of the MASC model, in terms of its ability to estimate the agronomic
352 effects of biodiversity from a description of the practices employed and the context. As
353 suggested by Bell and Morse (2008), the designers of the MASC model built their indicators
354 from the available scientific knowledge, whilst trying to keep their use relatively simple. This
355 probably led to the retention of rules that are too generalised and that do not precisely cover
356 the diversity of pedoclimatic situations and techniques observed in this study. As pointed out
357 by Médiène *et al.* (2011), we still have little scientific information concerning the responses of
358 biological process to agricultural practices in a given pedoclimatic context. Thus, as
359 highlighted by Palm *et al.* (2014), the complex trade-off between the services provided and
360 the deleterious effects caused by the greater biodiversity resulting from reduced tillage and
361 diversification of the crop rotation remains unclear. Specific studies on this topic are therefore
362 required to identify the determinants involved and to make it possible to propose more
363 accurate indicators.

364 Reduced and no tillage systems had poorer performances for the social dimensions of the
365 model than other cropping systems with more intensive tillage. DS cropping systems
366 performed less well than other systems for the criteria “system complexity”, “health risk of
367 pesticide use” and “contribution to local employment”. These results are basically consistent

368 with most of the published results concerning the performances of CA. Overall, CA is often
369 seen as a complex set of interrelated practices that typically requires several rounds of
370 adaptation to become fully viable. It involves learning on the part of the farmer, local
371 adaptation, and breaking with a long-standing tradition of soil tillage and the removal of crop
372 residues (Giller *et al.*, 2011; Lahmar, 2010).

373 The lack of tillage in SD cropping systems, particularly those with a low level of crop
374 diversification in the rotation, often results in the proliferation of weeds, necessitating the
375 more frequent application of larger amounts of herbicide by farm workers (Chapelle-Barry,
376 2008), resulting in the exposure of these workers to a higher risk of toxicity. Moreover, the
377 overall decrease in working time associated with reduced tillage systems, which is generally
378 attractive for farmers, is considered to be a negative aspect in the MASC model, because it
379 may lead to a decrease in agricultural employment in the area. This criterion draws attention
380 to one of the potential risks of the widespread adoption of CA. However, the accuracy of this
381 assessment is restricted to the information available at the field scale. According to Lahmar
382 (2010), the labour saved by not tilling the soil could be diverted to other agricultural or non-
383 agricultural activities on a larger scale. This highlights how the “granularity” of the
384 spatiotemporal scales of the cropping system is less relevant for addressing issues that are
385 partly dependent on higher levels of organisation, such as the farm or an agricultural region
386 (e.g. indicators “work overload” and “emergence of a new supply chain”). The results for this
387 criterion should therefore be interpreted with caution, focusing purely on the contribution of
388 the cropping system, everything else being equal.

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

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

405

406 The MASC model provided an overview of the performances of cropping systems as a
407 function of the degree to which CA principles were applied, within the French context. As
408 suggested by Giller *et al.* (2009) the assessment of a large number of cropping systems and
409 the analysis of their performances according to whether the principles of CA were applied,
410 fully, partially or not at all, make it easy to determine which of these principles contribute to
411 the desired effect. The results of this study suggest that decreasing, or even abolishing
412 tillage, one of the major symbolic pillars of CA systems, is not the most effective way to
413 increase the overall sustainability of cropping systems. Direct seeding systems with short
414 and undiversified rotations gave the worst sustainability results, with scores slightly lower
415 than those for conventional systems. Conversely, the adoption of long diversified crop
416 rotations, regardless of the soil tillage conditions, appeared to be essential for attaining a
417 high level of overall sustainability. Therefore, rotations including diverse cash and cover
418 crops are an essential element of CA systems, as they provide an effective way to manage
419 pests and weeds in the absence of soil tillage. The promotion of greater biodiversity at the
420 field level favours the better use of natural resources, a more regular distribution of labour
421 and more diversified farm incomes (Calegari *et al.*, 2008; Médiène *et al.*, 2011; Scopel *et al.*,

422 2012). Therefore, consistent with the assertions of most authors (Derpsch *et al.*, 2003;
423 Erenstein, 2003; FAO, 2008; Hobbs, 2007; Scopel *et al.*, 2012), CA is an “holistic” package
424 that works well only when all three pillars are applied simultaneously.

425 **4.3 End-use evaluation of the MASC model and precautions for use**

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

431 The positive feedback received from several of the stakeholders (e.g. researchers, extension
432 workers and farmers) involved in this study suggests that the major preoccupations of users
433 were adequately taken into account (Craheix *et al.*, 2012b; Craheix *et al.*, 2012c). Thus, the
434 holistic approach of the MASC model, based on a sustainability assessment, provides a
435 suitable overview of the performance of cropping systems, by taking into account
436 simultaneously (i) the multiple objectives of the economic, social and environmental
437 dimensions; ii) various time scales, ranging from the short term to the long term and (iii) the
438 concerns raised at various levels, including the expectations of farmers and of society as a
439 whole. However, although this assessment framework may be seen as very integrative and
440 objective, caution is required in the use of such models and the interpretation of the results
441 obtained, due to the underlying subjectivity inherent in the criteria chosen and their
442 aggregation (Bell and Morse, 2008). Designers try to counterbalance this apparent binding
443 framework by encouraging debate with end-users when interpreting results. Designers have
444 also introduced flexibility by allowing users to modify both the method by which basic criteria
445 are assessed (*i.e.* choice of indicators) and the weights assigned to the various criteria, so as
446 to integrate their own preferences and visions of sustainable development into the parameter
447 settings. Interesting results have already been reported in France, where the MASC model
448 was used to get farmers involved in the evaluation of their cropping systems through the

449 discussion and modification of parameter settings (Craheix *et al.*, 2012b). In this study
450 cropping systems were ranked with the default version of MASC, based on a balanced
451 perception of sustainability. It should be borne in mind that the rankings would be probably
452 different if the weights were modified (e.g. by increasing the relative weight of the
453 environmental dimension for instance). Therefore, according to the designers of the MASC
454 model and as suggested by Bell and Morse (2008), the development and use of the
455 multicriteria assessment method for sustainability requires maximum transparency and
456 flexibility and should never be limited to the interpretation of aggregate results alone.

457 Regarding the ease of use of the model in terms of the availability of the data required and
458 the comprehensibility of the outputs, the ability of MASC to deal with qualitative information
459 appeared very useful in these real-use situations. Firstly, as noted above, processing
460 qualitative information makes it possible to use quantitative values by simply using
461 thresholds to render them qualitative. This flexibility makes it possible for the MASC model to
462 combine various data, such as simple measurements (e.g. yields), calculated data (e.g.
463 semi-net margin) and empirical knowledge (e.g. physical difficulties of crop interventions) into
464 the indicators, so as to make the best use of commonly available information. Secondly, it
465 makes it possible to integrate the decision-maker's own views (concerning the "system
466 complexity" criterion, for example) into the model, as these views are not necessarily
467 expressed through formal, quantitative models. Finally, regarding the legibility of the outputs,
468 as suggested by Munda *et al.* (2005), qualitative and linguistic forms (such as "low",
469 "medium" or " high") appeared to be well understood by the stakeholders concerned as
470 natural representations of human judgments and cognitive observations. Furthermore,
471 qualitative decision rule-based methods are considered relevant for non-compensatory
472 decision strategies involving the aggregation of results for different criteria (Ma, 2006),
473 making it easier to tackle the issues of a lack of comparability and immeasurability that often
474 underlie the dimensions of sustainability in agricultural systems (Sadok *et al.*, 2008).
475 Nevertheless, the homogenisation of calculated variables into qualitative variables, which are

476 by nature discrete, together with the classification of the systems studied into large classes,
477 may lead to marked differences in judgement concerning performances that are actually
478 relatively similar. The choice of the thresholds separating qualitative classes for particular
479 criteria was adapted here so as to minimise this risk.

480

481 **5. Conclusion**

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

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

501 tillage appeared to be less effective in this study than diversifying the crop rotation, and
502 should therefore not be applied in isolation.

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

514

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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 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 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 1

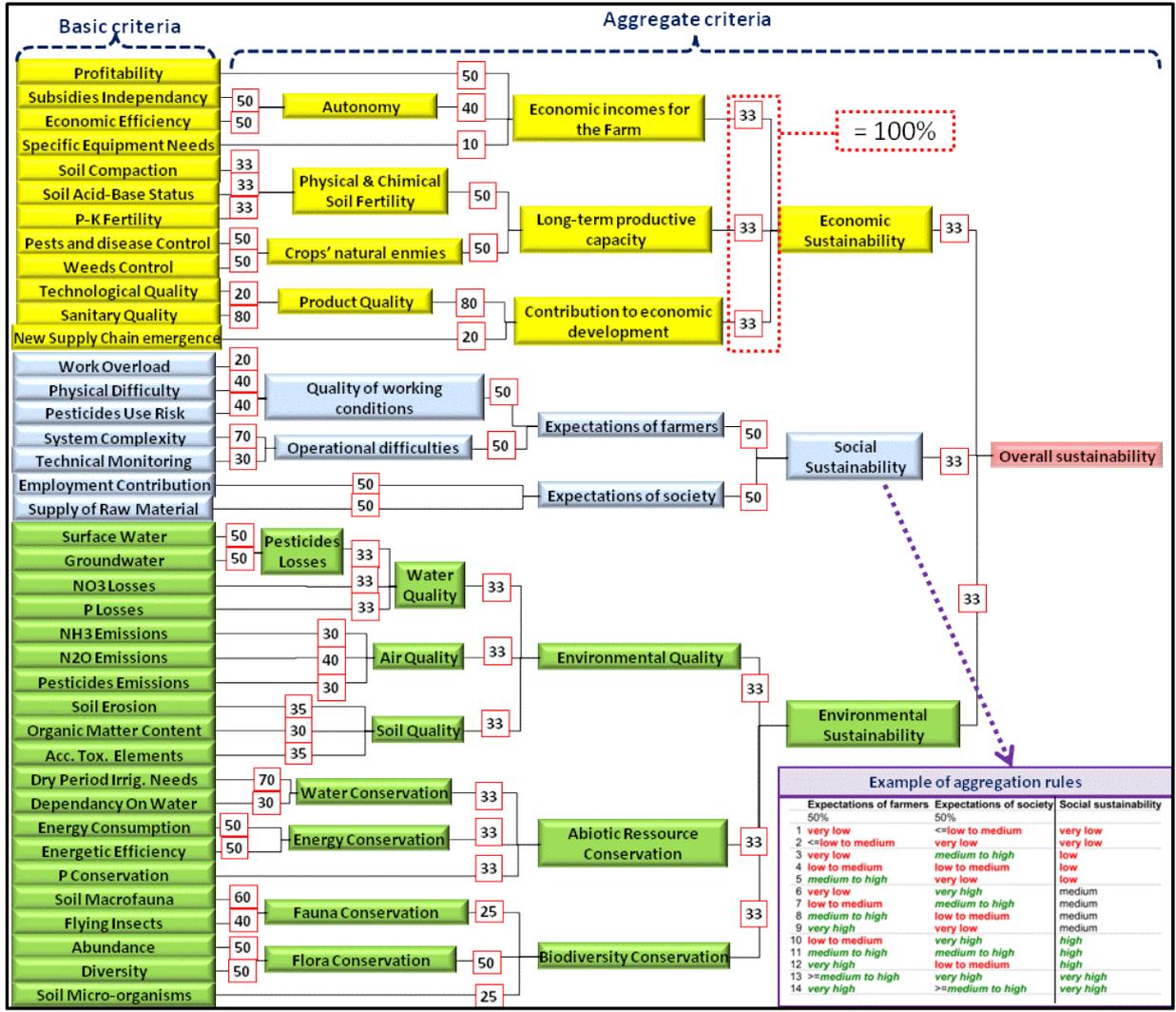


Figure 2

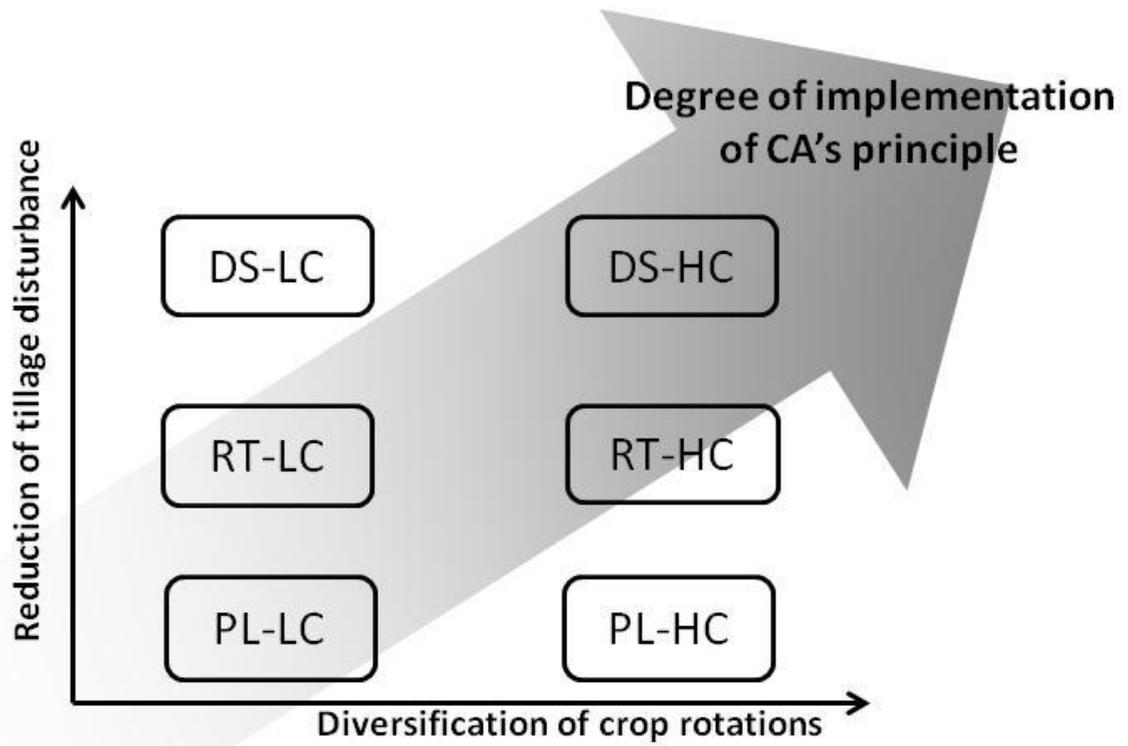
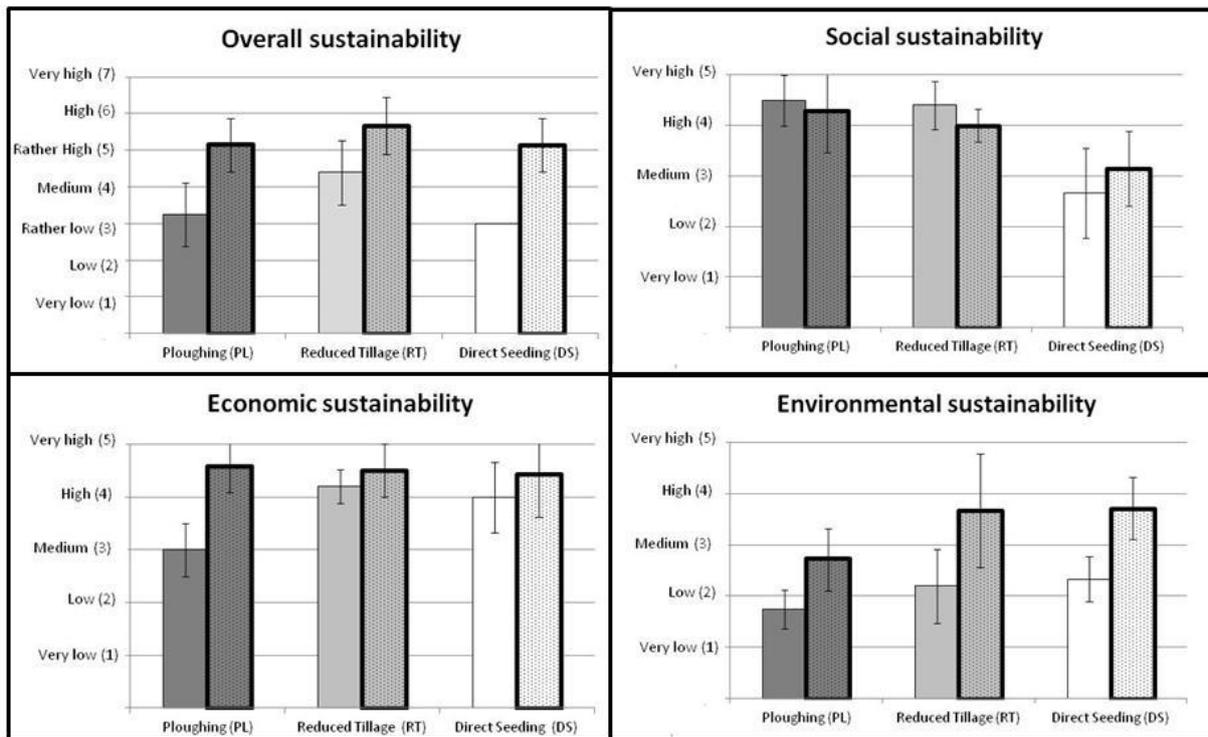


Figure 3



Figure

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Figure 4

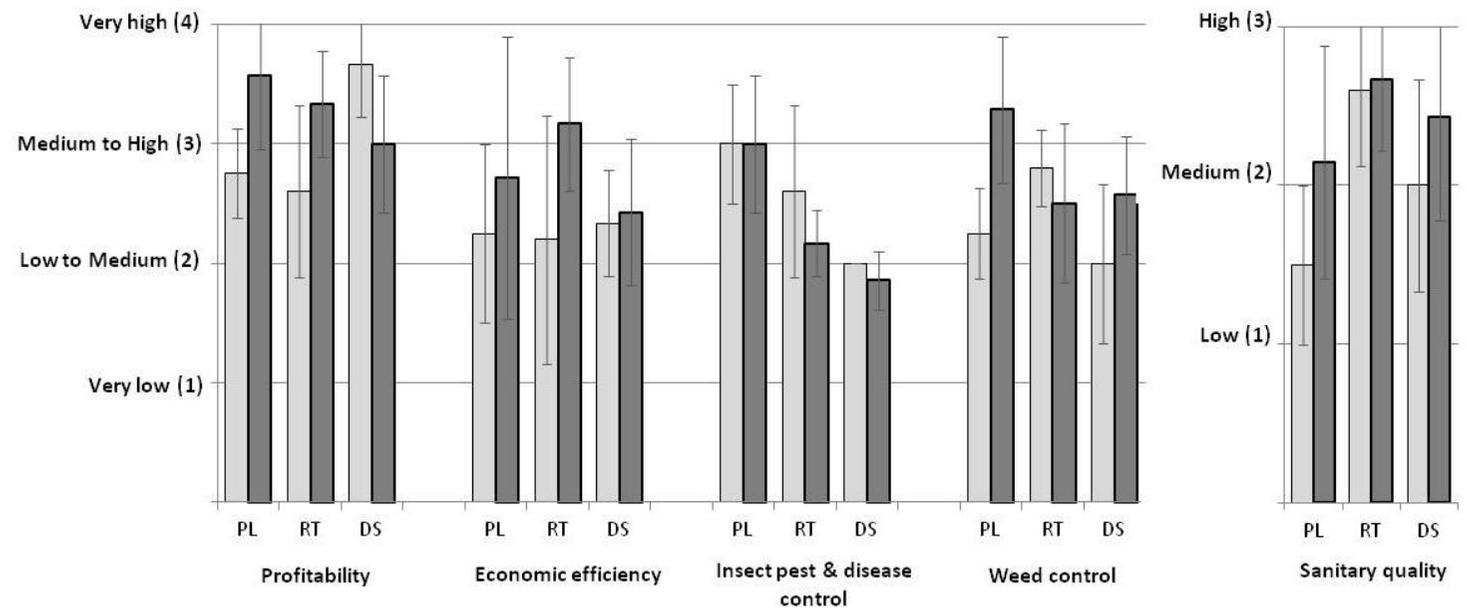


Figure 5

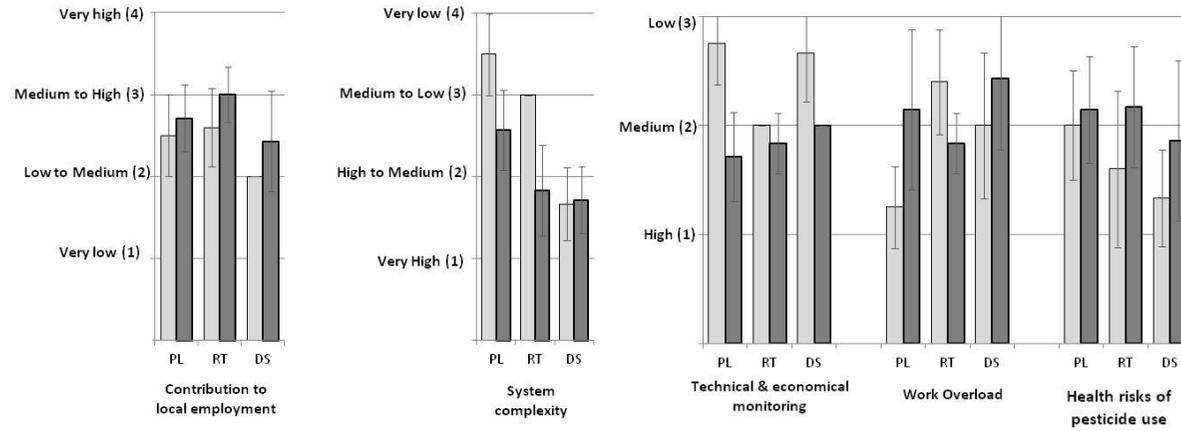


Figure 6

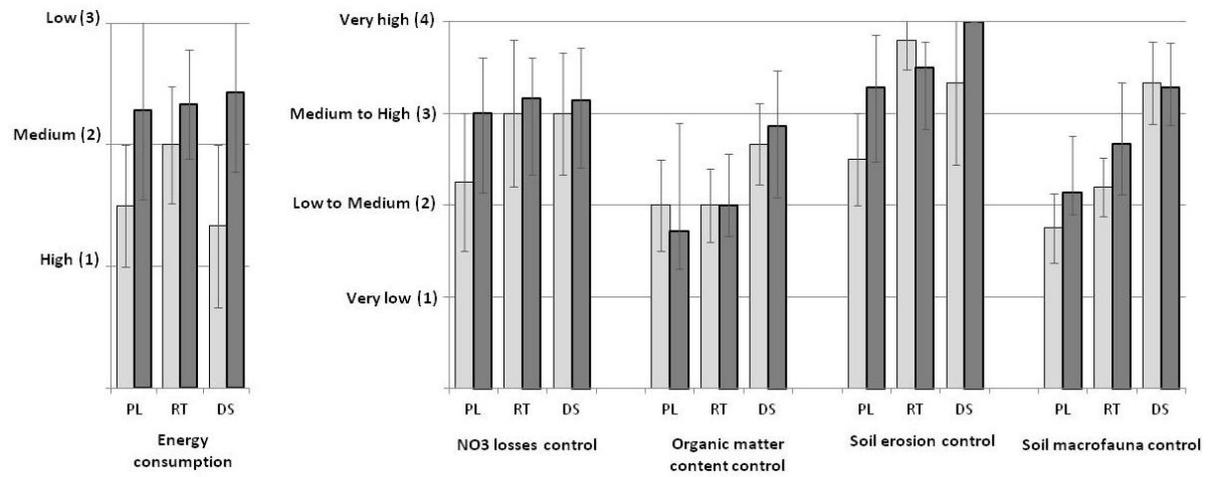


Table 1

	Basic criteria	Mode	Reference methods or main factors considered
Economic dimension	Profitability	QT	Semi-net margin, considering subsidies and mechanical cost ($\text{€} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$).
	Subsidies Independency	QT	Mean ratio of semi-net margin to subsidies ($\% \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$).
	Economic efficiency	QT	Mean ratio of semi-net margin to operational costs ($\% \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$).
	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 ($\text{ha}^{-1} \cdot \text{year}^{-1}$).
	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 ($\text{h} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$).
	Supply of raw material	QT	Mean difference between the observed yields of each crop and those achieved in intensive production systems in the region ($\% \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$).

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 <i>et al.</i> , 1997).
	Pesticides (ground water)	QT	I-PHY _{GW} indicator in the Indigo method (Bockstaller <i>et al.</i> , 1997).
	NO ₃ Losses	QT	I-NO3 indicator in the Indigo method (Bockstaller <i>et al.</i> , 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 <i>et al.</i> , 1997).
	N ₂ O emissions	QT	I-NO2 indicator in the Indigo method (Bockstaller <i>et al.</i> , 1997).
	Pesticide emissions	QT	I-PHY _{air} indicator in the Indigo method (Bockstaller <i>et al.</i> , 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 <i>et al.</i> , 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 <i>et al.</i> , 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 ₂ O 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%); TFLi: Treatment Frequency Index (Gravesen, 2003) of all pesticides (25%).

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