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Caroline Colnenne-David, Gilles Grandeau, Marie-Hélène Jeuffroy, Thierry Doré

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1 **Ambitious environmental and economic goals for the future of agriculture are unequally achieved**
2 **by innovative cropping systems**

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4 **Colnenne-David C., Grandeau G., Jeuffroy M.H., Doré T.**

5
6 **Abstract**

7 Agriculture has to face huge challenges in the decades ahead. Four innovative cropping systems were assessed in
8 a “cropping system experiment” in the Ile-de-France region (France) from 2009 to 2014. Three were designed to
9 meet ambitious goals: the total elimination of pesticides (No-Pest), reducing fossil energy consumption by 50%
10 (L-EN), or decreasing greenhouse gas (GHG) emissions by 50% (L-GHG). They were also required to satisfy a
11 wide range of environmental criteria and to maximize yields whilst respecting the major constraint on the system
12 and the environmental targets set. A fourth system (PHEP), in which the environmental and yield targets were
13 achieved with no major constraint, was also assessed. After completion of the first full crop sequence for these
14 innovative systems, the results obtained indicated that it was possible to design and implement innovative systems
15 achieving multiple goals. In our field trial conditions, the pesticide and energy constraints were almost satisfied,
16 whereas the GHG target was missed by a considerable margin. All four innovative systems satisfied environmental
17 criteria in terms of N management, pesticide use, energy consumption and crop diversity. However, herbicide
18 treatment frequency index (TFIH) was higher than expected in the two systems with no-plow practices, L-EN and
19 L-GHG. In the pesticide-free system, soil organic matter content was lower than expected, due to frequent plowing
20 (every 2 years) and low residue levels as a result of the lower yields obtained. Yields were lower for the L-EN
21 system than for the reference system, and yield was variable in the L-GHG system. These innovative systems had
22 better environmental performances than the systems currently used in the Ile-de-France region, with no decrease
23 in gross margins.

24
25 Key words: cropping system experiment, field assessment, greenhouse gas emissions, pesticide, energy.

26
27

28 **1. Introduction**

29 New challenges are continually arising in agriculture, necessitating profound breakthrough innovations in
30 agricultural practices. The most serious issues faced concern: (1) the loss of biodiversity in agroecosystems, (2)
31 the need to reduce chemical inputs, which are known to be harmful to the environment and human health, and (3)
32 the need to decrease the impact of agriculture on climate change, by decreasing greenhouse gas emissions and
33 promoting carbon storage in the soil. Current arable cropping systems are of questionable sustainability, and
34 alternative cropping systems must therefore be designed, to meet the goals of a more sustainable agriculture.
35 Agronomists design and assess innovative cropping systems to tackle a wide range of issues (Doré *et al.*, 2011;
36 Blazy *et al.*, 2009; Sadok *et al.*, 2009). Moreover, given that global food security has become a primary concern
37 (Godfray *et al.*, 2010), there is a need for innovative cropping systems that increase agricultural resource use
38 efficiency (Foley *et al.*, 2011).

39
40 New strategies for crop management and new cropping systems have been designed in recent years. Many have
41 targeted a single principal goal, such as enhancing C sequestration through changes in crop management (*e.g.*,
42 Freibauer *et al.*, 2004; Dimissi *et al.*, 2014), reducing pesticide use (Aubertot *et al.*, 2005; Chikowo *et al.*, 2009),
43 decreasing energy consumption (Singh *et al.*, 2008; Khakbazan *et al.*, 2009), or improving the yield of a single
44 crop (Tapia *et al.*, 2014). However, some studies were “innovation-pushed”: the authors compared cropping
45 systems on the basis of the combination of agricultural practices used (Kulak *et al.*, 2015), rather than on the
46 achievement of target performances with the most appropriate practices. For example, they compared organic and
47 conventional systems (Panasiewicz *et al.*, 2010; Nemecek *et al.*, 2011a), or no-tillage and conventional tillage
48 systems (Abdi *et al.*, 2014; Dimissi *et al.*, 2014), without providing any further information about the objectives
49 to be reached. In most of these examples, only a few criteria were assessed in field trials: the distribution of
50 phosphorus species in the soil profile (Abdi *et al.*, 2014), changes in soil structure and yield performances
51 (Abdollahi *et al.*, 2015), soil biological properties (Ingle *et al.*, 2014), ecophysiological characteristics of spring
52 barley and genotypes under various systems (Panasiewicz *et al.*, 2010), and weed infestation under different long-
53 term tillage systems (Chikowo *et al.*, 2009). However, in some cases, multi-criteria analyses were performed, with
54 various methodologies (Nemecek *et al.*, 2011a, 2011b; Loyce *et al.*, 2012; Kulak *et al.*, 2015). These multi-criteria
55 assessments made it possible to analyze combinations of agricultural practices with opposite impacts on specific
56 criteria, and to consider trade-offs. For example, no-till systems decrease energy consumption, but increase
57 herbicide use (Zentner *et al.*, 2004).

58

59 To our knowledge, no study has yet both (i) designed *in silico* innovative and consistent cropping systems
60 addressing a multiplicity of current issues, and (ii) assessed them in a cropping system experiment involving the
61 analysis of multiple performances. We designed *in silico* innovative cropping systems addressing multiple issues
62 of importance (Colnenne-David and Doré, 2015a), and conducted system experiments to assess their ability to
63 achieve several goals. Four innovative cropping systems targeting various environmental goals and yield
64 objectives were designed by the prototyping method described by Vereijken (1997). Their performances were
65 assessed *ex ante* with various tools and models: the Indigo® method (www7.inra.fr/indigo) for environmental
66 performances, the Simeos® tool (using the AMG model, Andriulo *et al.*, 1999) and the Roth C model for carbon
67 sequestration, as in the study by Colnenne-David and Doré, 2015a. For each combination of objectives, the most
68 promising candidate system was then implemented in a cropping system experiment.

69

70 We present here the cropping system experiment results for these four innovative cropping systems, for the first
71 full crop sequence. We analyzed the performance of the cropping systems in several different ways: (1) we
72 compared the innovative cropping systems implemented in the field trial with the prototypes (Colnenne-David and
73 Doré, 2015a); (2) we compared the three innovative systems designed to meet particular constraints with a
74 constraint-free innovative system used as the reference system and (3) we compared the innovative systems and
75 the current system in the Ile-de-France region, where the field trial took place.

76

77 **2. Materials and methods**

78 **2.1. General description of the four innovative cropping systems**

79 Four innovative cropping systems with quantified constraints, and environmental and yield targets were designed
80 jointly with various stakeholders, including farmers, in 2008 (table 1, Colnenne-David and Doré, 2015a). The
81 “productive with high environmental performance” (PHEP) system was designed to minimize environmental
82 impact (decreasing nitrate and pesticide pollution, enhancing crop diversity or reducing fossil energy consumption
83 relative to current cropping systems) and to reach the maximum possible yield given the environmental targets, as
84 described by Colnenne-David and Doré, 2015a. This cropping system, which was designed without major
85 environmental constraints, was used as the reference system for comparisons with the other systems. Each of the
86 other three systems was designed to meet an additional environmental constraint, constituting a major
87 breakthrough in terms of the objectives for current cropping systems: the elimination of pesticide use (No-Pest),

88 reducing fossil energy consumption by 50% relative to the PHEP system (L-EN), or halving greenhouse gas
89 emissions relative to the PHEP system (L-GHG). These cropping systems were also designed to minimize
90 environmental impact whilst providing the maximum possible yield under the constraint imposed and respecting
91 the environmental targets. During the design step, the constraints and targets were prioritized as follows: the
92 environmental constraint had to be satisfied first, the set of other environmental targets then had to be attained,
93 and, finally, yield had to be maximized. The systems retained for field assessment corresponded to the combination
94 of agricultural practices resulting in the highest yields *in silico* among the candidate systems both satisfying
95 environmental constraints and meeting environmental targets.

96

97 **2.2. Main agronomic characteristics of the four innovative cropping systems**

98 The four cropping systems were based on the agronomic strategies described in table 1 (Colnenne-David and Doré,
99 2015a).

100

101 **2.3. Experimental trial**

102 Since 2008, the innovative cropping systems have been implemented in a cropping system experiment, located at
103 the AgroParisTech experimental farm at Grignon, in the Ile-de-France region (*i.e.* Paris Basin, N 48.84°, E 1.95°).
104 This site has a deep, homogeneous loamy clay soil (FAO, 1998). Mean annual rainfall, calculated over a 20-year
105 period was about 650 mm per year at this site. The crop immediately preceding this experiment was winter barley
106 and the field had been plowed (30 cm depth). The trial covered a total area of 6.2 ha, divided into large plots
107 (almost 4000 m²) to facilitate the rational use of farm machinery in conditions representative of those on farms.
108 Due to both the limited area available for the trial and the need for large plots, each system was randomly
109 distributed in a block design with only three replicates. The size of the trial was such that we were unable to grow
110 all of the crops of each crop sequence in each innovative system each year. The interannual variability results were
111 taken into account by sowing three different crops from the crop sequence of each system in the three replicates
112 for the year concerned, for each of the innovative systems (*e.g.* in 2009, winter wheat, winter oilseed rape and
113 spring barley were sown in the three different replicates of the PHEP system). The first full crop sequence covered
114 the 2009-2014 period: five successive crops for the PHEP and L-EN systems (2009-2013), and six for the No-Pest
115 and L-GHG systems (2009-2014).

116

117 **2.4. Measurements**

118 **2.4.1. Calculation of indicators**

119 Assessment of the environmental performance of the cropping systems was based on energy consumption, GHG
120 emissions, C sequestration and various environmental criteria, for real practices in the cropping system experiment.
121 Each environmental indicator was calculated over an entire crop sequence, and expressed on a per hectare and per
122 year basis. Criter® software (V4.0.), based on the Indigo® method and easy to manage, was used to calculate a
123 set of environmental indicators taking values of 1 (worst) to 10 (best), with 7 selected as the target value for the
124 entire crop sequence (Bockstaller *et al.*, 2009; Reau *et al.*, 2012).

125

126 **2.4.2. Pesticide indicators**

127 Three pesticide indicators provided qualitative information about the volatilization, runoff and leaching into
128 groundwater of pesticides, thereby providing an indication of potential environmental damage. The treatment
129 frequency index (TFI), developed by Gravesen (2003) and widely used to assess cropping systems in France
130 (Ecophyto R&D, 2011; Jacquet *et al.*, 2011), was also calculated, to assess the intensity of pesticide (fungicides,
131 herbicides, insecticides, molluscicides) use. This index takes into account the number of pesticide applications and
132 the amounts applied. For each crop, TFI was calculated as follows: $TFI = \sum_T AD_T / RD_T$, where T is the pesticide
133 application, AD is the amount applied per hectare ($l \cdot ha^{-1}$ or $kg \cdot ha^{-1}$) and RD is the amount authorized per hectare
134 ($l \cdot ha^{-1}$ or $kg \cdot ha^{-1}$) (OECD <http://www.oecd.org/site/worldforum/33703867.pdf>; Pingault *et al.*, 2009). The
135 recommended doses were those indicated in the E-phy database of the French Ministry of Agriculture (Ephy
136 website, 2014). This indicator describes pesticide use through a single synthetic variable, facilitating comparison
137 between systems. TFI, TFIH and "TFI others" correspond to overall pesticide use, herbicide use and the use of
138 fungicides plus insecticides plus molluscicides, respectively. Neither growth regulators nor nematicides were
139 sprayed on crops.

140

141 **2.4.3. Energy consumption, energy output and energy use efficiency**

142 Energy consumption was assessed with the GES'TIM database (2010). Direct and indirect non-renewable energy
143 consumption (*i.e.* energy inputs, EI, expressed in $MJ \cdot ha^{-1} \cdot year^{-1}$) corresponded to the fuel, lubricants and electricity
144 used to power farm machinery and tractors. Indirect energy consumption was defined as the energy used in the
145 manufacture, formulation, packaging and maintenance of inputs, such as machinery, fertilizers and pesticides.

146

147 Energy outputs (EO, expressed in $\text{MJ}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$) were calculated as the gross energy content of the harvested
148 products. This indicator was calculated for each crop in each year, as follows: $\text{EO} = \text{Y} * \text{CV}$, where Y is the yield
149 of the harvested crop ($\text{t}\cdot\text{ha}^{-1}$), and CV is its calorific value ($\text{MJ}\cdot\text{t}^{-1}$). Yield values were calculated as the mean of six
150 samples (each from an area of 75 to 140 m^2 , depending on the length of the plot harvested) collected at maturity
151 with a combine harvester from each plot. CV was assessed with the GES'TIM database (2010). Energy use
152 efficiency (EUE) was calculated by dividing EO by EI for the whole cropping system.

153

154 **2.4.4. Carbon balance**

155 Carbon balance ($\text{kgCO}_2\text{eq}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$) was calculated taking both C sequestration in the soil and total GHG
156 emissions into account. C sequestration in the soil ($\text{kgCO}_2\text{eq}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$) was assessed with the Simeos® tool
157 (2014), as recommended by Saffih-Hdadi and Mary (2008), and climatic data from a meteorological station located
158 150 m from the trial. The soil characteristics of the plowed layer (0–30 cm) used for the calculations were as
159 follows: clay content 20.6%, silt content 71.9%, sand content 7.4%, bulk density 1.4, initial C content $13 \text{ g}\cdot\text{kg}^{-1}$
160 dry matter, typical of soils in the Ile-de-France region. Annual yields, calculated from our experimental data, were
161 used to estimate the expected annual biomass separately for the residues above and below the ground. Direct and
162 indirect GHG emissions were estimated with the GES'TIM database (2010), with Intergovernmental Panel on
163 Climate Change coefficients, focusing on two main greenhouse gases: nitrous oxide (N_2O) and carbon dioxide
164 (CO_2). Direct emissions included N_2O emissions from N fertilizers and the CO_2 produced by the combustion of
165 fossil fuels by farm machinery. The CO_2 respired by soil organisms was not taken into account in these
166 assessments. Indirect emissions corresponded to the use of fossil energy in the manufacture and maintenance of
167 farm inputs.

168 Carbon balance was calculated over a period of 50 years, in accordance with Intergovernmental Panel on Climate
169 Change proposals and current knowledge of C sequestration kinetics in the soil. In this calculation, any GHG
170 entering the cropping system was attributed a negative value, whereas GHG leaving the system took a positive
171 value. The overall balance was therefore positive if more GHGs were emitted than sequestered in the system.

172

173 **2.4.5. Nitrogen indicators**

174 Three nitrogen indicators were calculated with the Criter® tool (v. 4.0.). Two of these indicators provided
175 qualitative information about ammonia (NH_3) volatilization and N_2O emissions. NH_3 volatilization was assessed
176 for each fertilizer type, set of soil chemical characteristics (specifically calcium content) and fertilizer burial status.

177 N₂O emissions were calculated as described by Bouwman *et al.* (1996): the emission factor was 1.25% N₂O-N per
178 kg N of spread mineral fertilizer. The target value for this indicator (*i.e.* 7) corresponds to 20 kg of NH₃ volatilized
179 per hectare and per year, and 3 kg of N₂O emissions per hectare and per year. Nitrogen leaching into groundwater
180 was also assessed with the Criter® tool (v. 4.0.), and expressed as a quantitative value (kgNO₃⁻.ha⁻¹.year⁻¹). The
181 assessment took into account both the amount of fertilizer applied and the date of the application, together with
182 rainfall over the leaching periods, from the end of winter until summer and during the winter season after crop
183 harvest (*i.e.* from 01/08 to 31/03 at Grignon).

184

185 **2.4.6. Crop diversity indicator**

186 This indicator takes into account both the number of different species sown in the crop sequence, and the number
187 of genotypes for each species included in the crop sequence. It is calculated at the scale of a full crop sequence.
188 The contribution of catch crops is halved, as their growth period is shorter than that of the main crop (Criter®
189 software, V4.0).

190

191 **2.4.7. Economic indicators**

192 We took the variability of prices and costs over time into account, by calculating mean values for France for the
193 2005-2012 period (INSEE). Changes in CAP (Common Agricultural Policy) directives resulted in CAP subsidies
194 being based on a shorter period in 2010-2012. These subsidies averaged €325 ha⁻¹.year⁻¹ in the Yvelines, the area
195 in which this trial was located. Gross outputs (€.ha⁻¹) were calculated by multiplying yield (t.ha⁻¹) by the farm-gate
196 price (€.t⁻¹) received for harvest products. Total variable costs (€.ha⁻¹) included total input costs (*e.g.* mineral
197 fertilizer, seeds, pesticides) and machinery costs (*e.g.* machinery maintenance, fuel, labor for operations). The
198 costs per hectare of different operations were determined from the data in a published database specific to North-
199 Eastern France in 2013. Price variability was taken into account by calculating mean fuel price (€0.8 l⁻¹) over the
200 2008-2013 period. Gross margins (€.ha⁻¹) were calculated as the difference between "gross outputs plus CAP
201 subsidies" and total variable costs.

202

203 **2.5. Three comparisons of cropping system performances**

204 The performances of the innovative cropping systems implemented in the field trial were first compared with that
205 of the prototype (the prototype characteristics were described by Colnenne-David and Doré, 2015a) in a multi-
206 criteria analysis for each innovative system (*i.e.* for each innovative system and for each performance, ratios were

207 calculated as follows: *ex post* performance / *ex ante* performance). The performances of the three innovative
208 systems subject to constraint (the No-Pest, L-EN and L-GHG systems) were also compared to those of the PHEP
209 system, by calculating ratios as follows: for each innovative system under constraint and for each performance,
210 performance in the innovative system under constraint / performance of the PHEP system. Finally, performance
211 ratios were calculated for the four innovative systems relative to the current system in the Ile-de-France region,
212 defined on the basis of the data collected in 2006 (Agreste, <https://agreste.agriculture.gouv.fr/>; Colnenne-David
213 and Doré, 2015a) (*i.e.* for each innovative system (the PHEP, No-Pest, L-EN and L-GHG systems) and for each
214 performance, ratios were calculated as follows: performance of the innovative system / performance of the current
215 system in the Ile-de-France region).

216

217 **2.6. Statistical and multi-criteria analyses**

218 The performance and yield data were analyzed with by comparing means and carrying out analysis of variance
219 (ANOVA) with R statistical core software (R Development Core Team R, 2014). If the result was significant
220 ($p < 0.05$), the Tukey test for multiple comparisons was performed, for means with a *p-value* of 0.05 or less. When
221 the variance was zero (*e.g.* the TFI values of all replicates of the No-Pest system were zero), only the confidence
222 intervals ($p < 0.05$) were calculated.

223

224 **3. Results**

225 **3.1. Assessment of the environmental performance of cropping systems**

226 **3.1.1. Pesticide use**

227 **3.1.1.1 The pesticide constraint in the No-Pest cropping system: comparison between the No-Pest and PHEP** 228 **systems**

229 The pesticide constraint was satisfied because no pesticides were applied in the No-Pest cropping system.

230 **3.1.1.2. Pesticide use in the four innovative cropping systems**

231 The values of zero obtained for TFI, TFIH and TFIothers in the No-Pest system were significantly lower ($p < 0.05$)
232 than those calculated for the other three innovative systems (table 2). TFI values were not significantly different
233 ($p < 0.05$) between the three systems using pesticides (*i.e.* the PHEP, L-GHG and L-EN systems). In our
234 experimental conditions, the association of no-plow practices with flax crops resulted in the highest levels of
235 herbicide use, with significantly higher TFIH values for the L-EN system than for the other three systems (TFIH
236 values for the various systems: L-EN=2.03; L-GHG=1.67; PHEP=1.23; No-Pest=0). Moreover, TFIothers was

237 significantly higher in the L-GHG system than in the other three systems (TFI_{others} values for the various systems:
238 L-GHG=1.01; PHEP=0.70; L-EN=0.35; No-Pest=0). Crop residues were not buried, and molluscicides were more
239 frequently required for slug control than in the other systems (0.5 treatments per year in the L-GHG system, versus
240 0.2 and 0.1 treatments per year in the PHEP and L-EN systems, respectively). The inclusion of winter oilseed rape
241 in the crop sequence resulted in higher levels of fungicide use: 0.3 treatments per year were applied in both the L-
242 GHG and PHEP systems, whereas no fungicide was applied in either the L-EN or the No-Pest system (details in
243 table 3). Overall, "TFI_{others}" values, which included data for fungicides, were low, due to climatic conditions
244 unfavorable for disease development over the 2009-2014 period (Agreste, 2014).

245

246 **3.1.2. Energy use**

247 **3.1.2.1. The energy constraint in the L-EN cropping system: comparison between the L-EN and PHEP** 248 **systems**

249 Mean total fossil energy consumption (direct and indirect energy) was $7755 \pm 711 \text{ MJ.ha}^{-1}.\text{year}^{-1}$ for the PHEP
250 system and $5201 \pm 502 \text{ MJ.ha}^{-1}.\text{year}^{-1}$ for the L-EN system; energy consumption was thus 33% lower for the L-
251 EN system (table 4). The energy constraint target (half the energy consumption of the PHEP system) was therefore
252 not met, although the decrease was nevertheless considerable. Indirect energy consumption, which accounted for
253 almost 50% of total energy consumption in both cropping systems, was 37% lower in the L-EN system ($2584 \pm$
254 $479 \text{ MJ.ha}^{-1}.\text{year}^{-1}$) than in the PHEP system ($4090 \pm 489 \text{ MJ.ha}^{-1}.\text{year}^{-1}$). The mean amounts of N fertilizer, the
255 largest contributor to indirect energy consumption, were $19 \text{ kgN.ha}^{-1}.\text{year}^{-1}$ for the L-EN system and 56
256 $\text{kgN.ha}^{-1}.\text{year}^{-1}$ for the PHEP system (table 3). Direct energy consumption, defined as energy used exclusively by
257 farm machinery (*i.e.* for plowing, tillage, sowing, fertilization, crop protection and harvest, table 3), was 29%
258 lower in the L-EN system ($2618 \pm 171 \text{ MJ.ha}^{-1}.\text{year}^{-1}$) than in the PHEP system ($3665 \pm 223 \text{ MJ.ha}^{-1}.\text{year}^{-1}$),
259 mostly due to direct drilling and the absence of tillage.

260

261 **3.1.2.2. Energy performance of the four innovative cropping systems**

262 Total energy consumption was not significantly different in the PHEP ($7755 \pm 711 \text{ MJ.ha}^{-1}.\text{year}^{-1}$), No-Pest (7604
263 $\pm 517 \text{ MJ.ha}^{-1}.\text{year}^{-1}$) and L-GHG ($7459 \pm 793 \text{ MJ.ha}^{-1}.\text{year}^{-1}$) systems and was significantly higher than that in
264 the L-EN system ($5201 \pm 502 \text{ MJ.ha}^{-1}.\text{year}^{-1}$, $p < 0.05$). A similar pattern was observed for both indirect and direct
265 energy consumption (*i.e.* lowest values for the L-EN system, $p < 0.05$, table 4). An analysis of energy components
266 revealed differences between systems. In the No-Pest system, direct energy consumption was significantly higher

267 (4417 ± 425 MJ.ha⁻¹.year⁻¹, *p*<0.05) than that in the other systems, due to the large number of plowings (four
268 plowings over the six-year crop sequence, table 3). The indirect energy consumption linked to fertilization (table
269 3) was significantly greater in the PHEP (4090 ± 489 MJ.ha⁻¹.year⁻¹, *p*<0.05) and L-GHG (4897 ± 568
270 MJ.ha⁻¹.year⁻¹, *p*<0.05) systems than in the other two systems (the No-Pest system: 3187 ± 99 MJ.ha⁻¹.year⁻¹, the
271 L-EN system: 2584 ± 479 MJ.ha⁻¹.year⁻¹, table 4).

272
273 The L-EN system generated significantly less energy than the other systems (70997 ± 9991 MJ.ha⁻¹.year⁻¹,
274 *p*<0.05, table 4). The high degree of variability of the energy output of this system was linked to the low winter
275 wheat yield in 2012 (yield of 0.75 t.ha⁻¹, replicate 3, table 5), due to the development of highly competitive white
276 clover. In the No-Pest system, despite low yields for most crops, energy output was high (103323 ± 3629
277 MJ.ha⁻¹.year⁻¹), due to the production of hemp (mean yield value of 11.23 t.ha⁻¹, table 5, with a calorific value of
278 1.65 MJ.t⁻¹). However, it was not significantly different from that calculated for the PHEP (95965 ± 8397
279 MJ.ha⁻¹.year⁻¹, *p*<0.05) and L-GHG (90229 ± 5572 MJ.ha⁻¹.year⁻¹, *p*<0.05) systems.

280
281 The higher energy use efficiency of the No-Pest system (13.61 ± 0.54, ns) than of the L-GHG system (12.14 ±
282 0.74, ns) resulted principally from its higher energy output, with no significant difference in the total energy
283 consumption of these two systems (table 4). The energy efficiency value of the L-EN system was high (13.71 ±
284 2.10), but not significantly different from the other systems, due to the high level of energy output variability for
285 the L-EN system (70997 ± 9991 MJ.ha⁻¹.year⁻¹, table 4).

286

287 **3.1.3. Carbon balance performance**

288 **3.1.3.1. The carbon balance constraint in the L-GHG cropping system: comparison between the L-GHG** 289 **and PHEP systems**

290 The carbon balances of the L-GHG (1202 ± 86 kgCO₂eq.ha⁻¹.year⁻¹) and PHEP (1188 ± 270 kgCO₂eq.ha⁻¹.year⁻¹)
291 systems were not significantly different (*p*<0.05, table 6). The carbon balance constraint (halving the emissions
292 relative to the PHEP system) was not, therefore, achieved. For both systems, total greenhouse gas emissions and
293 C sequestration accounted for nearly 90% and 10% of the carbon balance, respectively. There was no significant
294 difference between these two systems in terms of total, direct and indirect greenhouse gas emissions (*p*<0.05, table
295 6), resulting in similar ratios of direct and indirect greenhouse gas emissions for the two systems. The difference
296 in direct greenhouse gas emissions between the L-GHG (541 ± 102 kgCO₂eq.ha⁻¹.year⁻¹) and PHEP (622 ± 82

297 kgCO₂eq.ha⁻¹.year⁻¹) systems was linked to an absence of plowing and only a few shallow tillage operations in the
298 L-GHG system, whereas the plot was plowed once and subjected to numerous shallow tillage operations over the
299 course of the crop sequence in the PHEP system (table 3). In the L-GHG system, indirect greenhouse gas emissions
300 (511 ± 82 kgCO₂eq.ha⁻¹.year⁻¹) were higher due to the high seed requirement: (1) the number of seeds sown in no-
301 plow conditions was systematically greater than that sown in current systems, in accordance with technical
302 references, (2) emergence failure was observed for winter rapeseed in 2009 and 2014, and for maize and spring
303 field beans in 2011, leading to a second sowing, and (3) cover crops were sown systematically each year (table 3).

304
305 After the first crop sequence, C sequestration was -149 ± 117 kgCO₂eq.ha⁻¹.year⁻¹ for the L-GHG system and -
306 117 ± 150 kgCO₂eq.ha⁻¹.year⁻¹ for the PHEP system (negative values indicate a decrease in CO₂ relative to initial
307 C content, *i.e.* 13 g.kg⁻¹ dry matter) and this difference between these two systems was not significant. Cover crop
308 biomasses were lower than expected (data not shown) in the L-GHG system, due both to the high frequency of
309 very dry summers (in 2009 and 2012, total rainfall in August was 7 mm and 29 mm, respectively, whereas the 20-
310 year mean value for rainfall in August was 51 mm) and the high degree of competition with weeds (data not
311 shown). In addition, yields for spring field bean and winter oilseed rape (in 2014) were lower than expected (table
312 5, see explanations below). These crop residues did not, therefore, increase the C content of the soil.

313

314 **3.1.3.2. Carbon balance of the four innovative cropping systems**

315 Carbon balance did not differ significantly between the four systems ($p < 0.05$, table 6). However, the similarities
316 in carbon balance resulted from very different combinations of the two components of this balance: total
317 greenhouse gas emissions and C sequestration. The proportions of the two components were almost identical for
318 the L-GHG and PHEP systems. In the L-EN system, total greenhouse gas emissions were significantly lower (554
319 ± 107 kgCO₂eq.ha⁻¹.year⁻¹, $p < 0.05$) than those of the L-GHG (1052 ± 183 kgCO₂eq.ha⁻¹.year⁻¹) and PHEP (1071
320 ± 145 kgCO₂eq.ha⁻¹.year⁻¹) systems, and were linked to significantly lower direct and indirect greenhouse gas
321 emissions than for the other two systems ($p < 0.05$, table 6). The significantly lower level of N fertilization in the
322 L-EN system (19 ± 6 kgN.ha⁻¹.year⁻¹, $p < 0.05$, table 3) than in the L-GHG (57 ± 13 kgN.ha⁻¹.year⁻¹) and PHEP
323 (56 ± 11 kgN.ha⁻¹.year⁻¹) systems led to low direct and indirect N₂O emissions (*i.e.* use over input manufacture).
324 However, the low yields in the L-EN system resulted in small amounts of crop residues (table 5), leading, in turn,
325 to a sharp decrease in C sequestration. The performance of the L-EN system was thus poorer than that of the L-
326 GHG and PHEP systems. The No-Pest system had intermediate total greenhouse emissions (844 ± 46 kgCO₂eq.ha⁻¹

327 ¹.year⁻¹ table 6). In this system, direct emission levels were high, due to four plowing and several tillage operations
328 during the six-year crop sequence (table 3), but indirect emissions were low, due to the low N fertilizer
329 requirements (low yield objectives close to those in organic systems, 4.7 t.ha⁻¹, table 5). In this system, intensive
330 plowing practices (table 3) and the small amounts of crop residues due to low yields (table 5) both resulted in much
331 lower levels of C sequestration (-560 ± 49 kgCO₂eq.ha⁻¹.year⁻¹).

332

333 **3.1.4. Other environmental performances**

334 The values obtained for the various qualitative indicators were lowest for crop diversity indicators (ranging from
335 6.8, for the PHEP system, to 7.8 for the L-EN system), whereas the other environmental indicators reached values
336 of at least 8.4 (table 7). The environmental targets may therefore be considered to have been achieved. These
337 findings varied little between replicates.

338 The PHEP system generated significantly less N₂O (8.69 ± 0.16 , $p < 0.05$) than the L-EN system (9.17 ± 0.06),
339 due to differences in the amounts of N fertilizer applied (see explanation above). The amount of nitrogen leached
340 was very small in all systems (less than 10 kgN.ha⁻¹.year⁻¹), due to the small amounts of N fertilizer applied (table
341 3). In the cropping system currently used in Ile-de-France, the mean amount of N fertilizer applied was about 110
342 kgN.ha⁻¹.year⁻¹, whereas the mean amount of fertilizer applied in the PHEP system was 56 ± 11 kgN.ha⁻¹.year⁻¹.
343 Furthermore, careful adjustment of N application dates according to plant N requirements (not shown in table 3)
344 and/or regular soil cover with plants or crop residues over time (*i.e.* catch or cover crops present most of the time
345 between main crops, resulting in only short periods of bare soil) could explain these results.

346

347 The values of all pesticide indicators were greater than 8. These results were generally consistent with the TFI
348 values obtained. However, it is difficult to explain the small differences between the innovative systems. The main
349 findings were the significantly higher scores for the No-Pest system ($p < 0.05$) and the low level of variability
350 between the replicates of each innovative system.

351

352 **3.2. Yield**

353 **3.2.1. The PHEP system**

354 Yield objectives (table 5) were regularly achieved, for all crops except winter faba bean (mean decrease in yield
355 of almost 50%: 1.45 ± 0.31 t.year⁻¹ versus 3.0 t.year⁻¹ expected), and were even higher than expected for winter
356 oilseed rape (higher yields than expected: 3.64 ± 0.29 t.year⁻¹ versus 2.8 t.year⁻¹ expected). During the first three

357 years of the field assessment, very long cold winter periods destroyed many legume plants and delayed growth in
358 the spring, thereby decreasing potential yield (*i.e.* in 2009, 2010 and 2011 10-day minimum temperatures from the
359 beginning of December to the end of February, were -7.23°C , -5.2°C and -2.4°C respectively, whereas the mean
360 10-day minimum temperature calculated over a 20-year period was systematically above 0°C . In 2009, 2010 and
361 2011, 10-day minimum temperatures below 0°C were observed from 1/12/2008 to 20/02/2009, from 10/12/2009
362 to 10/02/2010 and from 01/12/2010 to 30/01/2011). No-till practices may also decrease potential yield, consistent
363 with the results obtained for the L-EN system ($3.11 \pm 0.97 \text{ t}\cdot\text{year}^{-1}$). In this system, winter faba bean yields in
364 replicates 1 ($2.88 \text{ t}\cdot\text{year}^{-1}$) and 3 ($2.28 \text{ t}\cdot\text{year}^{-1}$) were much lower than those in replicate 2 ($4.16 \text{ t}\cdot\text{year}^{-1}$), in which
365 plowing took place (in 2009, all the plots of the L-EN system were plowed, to homogenize soil structure in the
366 trial).

367

368 **3.2.2. The No-Pest system**

369 Winter wheat yields were systematically higher than expected ($6.38 \pm 1.47 \text{ t}\cdot\text{year}^{-1}$ and $6.40 \pm 0.36 \text{ t}\cdot\text{year}^{-1}$ rather
370 than the $4.7 \text{ t}\cdot\text{year}^{-1}$ expected), due to the low pest pressure over this period as a result of specific climatic conditions
371 (*i.e.* very long cold winters in four of the six years and very dry conditions in spring in 2009 and 2011), resulting
372 in an absence of disease outbreaks in spring (<http://agriculture.gouv.fr/bulletins-de-sante-du-vegetal>). Hemp yields
373 were both very high and variable ($11.23 \pm 2.65 \text{ t}\cdot\text{year}^{-1}$ *versus* $8.0 \text{ t}\cdot\text{year}^{-1}$ expected), highlighting the
374 underestimation of the target to be attained in a region without relevant references, and improvements in crop
375 management over time.

376

377 **3.2.3. The L-EN system**

378 In the L-EN system, the yields of winter wheat, sown after winter faba bean, were higher than expected ($6.46 \pm$
379 $0.51 \text{ t}\cdot\text{year}^{-1}$ *versus* $5.4 \text{ t}\cdot\text{year}^{-1}$ expected), due to optimal use of the N provided by this legume (the objective yields
380 for faba bean were achieved, see above), in conditions in which small amounts of N fertilizer were applied. Yield
381 varied considerably between replicates for winter wheat following flax ($4.40 \pm 1.45 \text{ t}\cdot\text{year}^{-1}$). The lowest yield
382 obtained for winter wheat, sown after flax (yield of $0.8 \text{ t}\cdot\text{ha}^{-1}$ in replicate 3, table 5), resulted from high levels of
383 competition with white clover and weeds (data not shown). The high levels of herbicide use on both flax and winter
384 wheat (six and three applications on these two crops, respectively, table 3) reflect the high degree of weed
385 development.

386

387 **3.2.4. The L-GHG system**

388 Yield goals were not always reached, but the results obtained differed between crops. Winter wheat yields were
389 higher than expected (7.38 ± 0.15 t.year⁻¹ *versus* 6.7 t.year⁻¹ expected), whereas spring faba bean yields were much
390 lower than anticipated (*i.e.* 66% lower than the target yield on average, 1.36 ± 0.71 t.year⁻¹ *versus* 4.1 t.year⁻¹
391 expected). These low yields reflected severe black aphid attacks in 2011 (*i.e.* 0.61 t.ha⁻¹, replicate 3,
392 <http://agriculture.gouv.fr/bulletins-de-sante-du-vegetal>). Moreover, no-till practices are also known to reduce
393 yield. In the L-GHG and No-Pest systems (*i.e.* without and with plowing, respectively, table 3), spring faba bean
394 yields were 1.36 ± 0.71 t.year⁻¹ and 2.41 ± 1.98 t.ha⁻¹, respectively. Winter oilseed rape yields varied considerably
395 between years (2.43 ± 2.14 t.year⁻¹), with the lowest value obtained for 2014 (*i.e.* 0 t.ha⁻¹, replicate 1). In our trial
396 conditions, no-plow practices over a six-year period led to a gradual increase in the weed population (data not
397 shown), resulting in an increase in herbicide use (one, two, two, three, and four herbicides used per year in 2009
398 to 2014, respectively; table 3). In the face of such weed competition, winter rapeseed was cut at the flowering stage
399 in 2014.

400

401 **3.2.5. Impact of particular annual weather conditions and role of the crop preceding the trial**

402 Weather conditions explained some low yields in the innovative systems: in 2009. Low yields for maize in both
403 the No-Pest (replicate 1, 3.81 t.year⁻¹ *versus* 5.6 t.year⁻¹ expected) and L-GHG (replicate 3, 5.27 t.year⁻¹ *versus* 7.0
404 t.year⁻¹ expected) systems were linked to a very dry summer period (*i.e.* in July and August 2009, 44 mm of rainfall:
405 calculated during a period for which the 20-year mean was 114 mm; <https://donneespubliques.meteofrance.fr/>); in
406 2012, the lowest yield of flax (replicate 2, 0.86 t.year⁻¹ *versus* 1.6 t.year⁻¹ expected) resulted from a very cold period
407 in February (*i.e.* during the first 10 days of February 2012, the mean minimum temperature was -5.5°C ; the 20-
408 year mean minimum temperature for the corresponding period was 4.8°C) that required a second sowing (*i.e.* of
409 spring flax). In the L-EN system, the high spring oat yield in replicate 2 (6.06 t.year⁻¹ *versus* 3.2 t.year⁻¹ expected)
410 resulted from a combination of very good weather conditions, low pest pressure
411 (<http://agriculture.gouv.fr/bulletins-de-sante-du-vegetal>) and high nitrogen availability due to the earlier sowing
412 of a legume catch crop (*i.e.* data not shown). Variability may also be linked to features specific to the trial: the
413 sowing of winter barley as the prior crop in 2008 led to the development of winter wheat root disease (*i.e.*
414 *Gaeumannomyces graminis*, data not shown) in the No-Pest system, replicate 3 (6.38 ± 1.47 t.year⁻¹), in 2009.

415

416 **3.2.6. Variability over time**

417 Yields were fairly stable in the PHEP, L-EN and No-Pest systems. By contrast, in the L-GHG system, yields
418 reached expected levels in the first four years of the crop sequence, but were lower in the last two years (*e.g.* for
419 oilseed rape in replicate 1: 0.00 t.year⁻¹ *versus* 2.8 t.year⁻¹ expected). Both large increases in the weed population
420 and changes in soil structure (data not shown) due to an absence of plowing gradually reduced crop yields in our
421 field conditions.

422

423 **3.3. Economic results**

424 Gross margins were highest for the PHEP (757.0 ± 88.7 €·ha⁻¹·year⁻¹), No-Pest (701.4 ± 48.4 €·ha⁻¹·year⁻¹) and L-
425 GHG (619.6 ± 77.3 €·ha⁻¹·year⁻¹) systems (table 8). Furthermore, gross margins were significantly higher for the
426 PHEP system than for the L-EN system (606.4 ± 56.1 €·ha⁻¹·year⁻¹, *p* < 0.05). The similar results obtained for the
427 L-GHG and L-EN systems resulted from different combinations of gross outputs and total variable costs. In the L-
428 GHG system, high total variable costs (567.7 ± 29.7 €·ha⁻¹·year⁻¹) counteracted the high gross output (861.9 ±
429 84.0 €·ha⁻¹·year⁻¹). In the L-EN system, both gross output (696.0 ± 74.5 €·ha⁻¹·year⁻¹) and total variable costs (415.0
430 ± 46.7 €·ha⁻¹·year⁻¹) were lower than in any other system because (i) less N fertilizer was applied than in the PHEP
431 and L-GHG systems, (ii) the no-till practices resulted in lower levels of fuel consumption and machinery use than
432 for the No-Pest system, which was characterized by several plowing and tillage operations over the course of the
433 crop sequence (table 3). The gross margin of the No-Pest system was one of the highest (701.4 ± 48.4 €·ha⁻¹·year⁻¹
434 ¹), due to hemp and winter wheat yields both being higher than expected (table 5).

435

436 **3.4. Performance comparisons between the prototype systems and the field trial assessments**

437 For the four innovative systems, most environmental performance indicators (total GHG emissions, total energy
438 consumption, energy output, energy efficiency) and gross margins were close to the predictions of *ex ante*
439 assessments (figure 1). The specific environmental constraints of the No-Pest and L-EN systems were almost
440 satisfied. TFI, TFIH and "TFIothers" in the No-Pest system, and total energy consumption in the L-EN system
441 closely matched expectations. For the L-GHG system, total greenhouse gas emissions were as projected, whereas
442 C sequestration levels were much lower than expected.

443

444 A comparison of *ex ante* and *ex post* assessments showed large differences for TFI, TFIH and "TFIothers" (figure
445 1). In the L-GHG and L-EN systems, herbicide applications were underestimated in the prototype systems, and
446 TFIH was four times higher for the L-GHG, and two times higher for the L-EN in the field assessments than

447 estimated for the prototypes. TFIH was also higher than expected in the PHEP system, but to a lesser extent.
448 During the design process, "TFIothers" was systematically overestimated because it could not take into account
449 the specific low pest pressures occurring over the 2009-2014 period. For each innovative system, the energy output
450 results measured in field conditions were very close to the expected values.

451

452 **3.5. Performance comparisons between the innovative cropping systems subject to constraints and the** 453 **PHEP system, taken as the reference system**

454 The PHEP system performed particularly well, so the three constraint-limited systems performed poorly by
455 comparison (figure 2). In both the L-GHG and L-EN systems, TFI, TFIH and "TFIothers" were higher than those
456 calculated for the PHEP system (see the explanations above). However, these two systems under constraints
457 differed for other performances. Most environmental performances were similar for the L-GHG and PHEP
458 systems, whereas the L-EN system outperformed the reference system. In both the L-GHG and L-EN systems,
459 gross margins were lower than those in the PHEP system, due to lower yields (table 5). This was unexpected for
460 the L-GHG system, but was anticipated at the design step for the L-EN system (*i.e.* this system was designed with
461 a target yield 20% lower than that of the PHEP system, to satisfy the energy constraint; Colnenne-David and Doré,
462 2015a). For a similar gross margin, pesticide indicator performances in the No-Pest system were much better than
463 those in the PHEP system, but were associated with poor direct energy and C balance performances.

464

465 **3.6. Performance comparisons between the innovative systems implemented in the field trial and the current** 466 **system in the Ile-de-France region**

467 Comparison between the four innovative systems and the current system in the Ile-de-France region (figure 3)
468 demonstrated that all environmental performances were better in the innovative systems (*i.e.* all ratios below 1)
469 than in the current system. Moreover, despite the lower energy outputs of the new systems than of the current
470 system, gross margins were similar or slightly higher in the new systems than in the current Ile-de-France system.
471 However, in the L-EN and No-Pest systems, TFIH and direct energy consumption, respectively, were similar to
472 those for the current system (*i.e.* ratio values close to 1).

473

474 **4. Discussion**

475 **4.1. Achievement of a multiplicity of objectives**

476 We were able to design and implement the PHEP system, the environmental performances of which were better
477 than those of the current system in the region, with no decrease in gross margin. The absence of pesticide use in
478 the No-Pest system did not reduce gross margin either (the lower target yield resulted in an absence of impact on
479 yield performance in our trial), but improved environmental performance (low greenhouse gas emissions, high
480 energy use efficiency, low nitrate leaching). However, higher levels of direct energy consumption, linked to the
481 high frequency of tillage practices, resulted in lower levels of C sequestration. It was possible to decrease energy
482 consumption in the L-EN system only with a decrease in yield, resulting in a lower gross margin, and low levels
483 of C storage in the soil. However, with the exception of the herbicide indicator, most of the environmental
484 performances were fine. The management of agronomic strategies in the L-GHG system led to high yield
485 variability, with a low economic impact. All environmental performances were satisfactory, with the exception of
486 the herbicide use indicator, which was similar to that for the current system in the region.

487
488 As discussed in previous studies (Colnenne-David and Doré, 2015a), the various targets set for innovative systems
489 can be antagonistic. The imposition of strong environmental constraints modified the performances of the
490 constrained systems. Some performances deteriorated. In both the L-GHG and L-EN systems, no-plow practices
491 led to higher levels of herbicide use to destroy cover crops and weeds (high TFIH), as previously reported by
492 Zetner *et al.* (2004), Moreno *et al.* (2011), and Soane *et al.* (2012). In the L-EN system, lower levels of energy
493 consumption, due to both no-till practice and low levels of N fertilization, were associated with 20% lower yields.
494 In the No-Pest system, the absence of pesticide use had an adverse effect on SOM and yield. Decreases in the
495 frequency of tillage and target yields resulted in much lower levels of C sequestration. Conversely, some
496 environmental performances were significantly improved by the imposition of a severe environmental constraint.
497 In both the L-EN and No-Pest systems, gas balance and energy efficiency were as high as those in the reference
498 PHEP system. Economic comparisons with published findings were difficult, because the prices of both inputs
499 and outputs depend on the country concerned, the period analyzed and the cropping system used (organic farm
500 produce is sold at higher prices than the products of conventional agriculture). We then compared the gross margins
501 of the innovative systems and the current system in Ile-de-France, in one price context: gross margins were slightly
502 lower than those of the regional system for the L-GHG and L-EN systems, and slightly higher for the other new
503 systems. However, this initial assessment did not take into account the contribution of product quality to farm-gate
504 price, which is potentially higher for free-pesticide seeds, and the existence of specific markets for crops such as
505 hemp.

506

507 It was difficult to meet the energy constraint in the L-EN system and environmental performances were less
508 satisfactory (specifically for herbicide use) than in the PHEP system. It was not possible to satisfy the greenhouse
509 gas constraint in the L-GHG system. For this system, during the design step, a clear hierarchy between the two
510 sub-objectives (*i.e.* to enhance carbon sequestration first and then to reduce N₂O emissions) were defined. In our
511 field conditions, this strategy was not effective. Biomass production was low (see the above comments for yields)
512 and resulted in lower levels of carbon storage than expected. Moreover, the amount of N fertilizer required to
513 produce the expected biomass did not differ between the L-GHG and PHEP systems (*i.e.* total greenhouse gas
514 emissions did not differ significantly between these two systems, table 6). After the first crop rotation, another
515 design step was required to improve the L-GHG system, and a new combination of agricultural practices is
516 currently being assessed in the field. The environmental results of the PHEP system were also very good, making
517 it difficult to achieve both the energy goal in the L-EN system and the greenhouse gas target in the L-GHG system.

518

519 **4.2. Difficulties implementing innovative systems with multiple goals in the field**

520 Overall, the predictive capacity of *ex ante* assessment was good. However, discrepancies between the estimated
521 performance of prototype systems and trial results, with some goals not achieved or the occurrence of unexpected
522 environmental conditions, highlighted the difficulties involved in managing such systems in the field. We
523 investigated the reasons for these differences, by analyzing agronomic practices, which we classified into four
524 groups. Group 1: the chosen agronomic strategies were unsuitable for achieving the goals set. For example, in the
525 L-GHG system, the absence of plowing did not lead to an increase in C sequestration. Group 2: some practices
526 were unable to satisfy multiple goals simultaneously. For example, in the No-Pest system, the restitution of small
527 amounts of organic matter, due to low yields, combined with regular plowing, which was required to manage weed
528 populations, had an adverse effect on C sequestration. Group 3: some of the planned practices may not have been
529 appropriate in field trial conditions. For example, despite the setting of TFI targets based on local experimental
530 results obtained over a 10-year period, the "TFIothers" and TFIH values obtained did not match expectations.
531 During the design process, pest occurrence rates were overestimated, resulting in higher levels of pesticide use
532 estimated for the prototypes than actually applied in the field, except for the No-Pest system
533 (<http://agriculture.gouv.fr/bulletins-de-sante-du-vegetal>, see the explanations above). Group 4: an unpredicted
534 change occurred in the agrosystem. For example, weed levels were higher after flax in the L-EN system, resulting
535 in higher levels of herbicide use than anticipated in several years (table 3). Similarly, weed populations increased

536 throughout the crop sequence in the L-GHG system, resulting in larger slug populations (data not shown). Despite
537 two molluscicide applications in 2014, oilseed rape was sown twice with no final yield (*i.e.* in 2014, yield was
538 0.00 t.ha⁻¹; in replicate 1, table 5). This classification highlighted the need for more time to eliminate technical
539 uncertainties and to improve the management of innovative systems, to prevent the technical problems observed
540 here (sowing failure, bad weed management in no-till systems). Moreover, the use of a broad range of tools should
541 make it possible to improve the predictive capacity of *ex ante* assessment.

542

543 **4.3. Comparison of performances with published results**

544 **4.3.1. Energy consumption**

545 The total energy consumption per hectare of the innovative systems was similar to that reported by Zentner *et al.*
546 (2004) for different winter wheat-based crop sequence plow practices, and by Planche *et al.* (2015) for different
547 cropping systems designed to meet specific environmental goals and assessed in France. As shown by Zentner *et*
548 *al.* (2004) and regularly confirmed by different authors (Dumaski *et al.*, 2006; Rothke *et al.*, 2007; Morano *et al.*,
549 2011), the reduction of energy consumption due to no-till practices was generally offset by an increase in herbicide
550 use. A similar pattern was observed when the energy performances of the PHEP and L-GHG systems were
551 compared. The contribution of N fertilization to the overall energy consumption of the new systems was similar
552 to that calculated for conventional, minimum tillage and no-till systems by Zentner *et al.* (2004), Rothke *et al.*
553 (2007) and Moreno *et al.* (2011). Nevertheless, the energy consumption of an "integrated" system, such as that
554 described by Nemecek *et al.* (2011b), with similar amounts of applied nitrogen to the PHEP system, was
555 significantly greater than that calculated for the PHEP system. However, more details of the practices used in the
556 Swiss "integrated" system, and of the references used for energy calculations, are required to analyze this
557 discrepancy. By contrast, the energy consumption of the No-Pest system due to chemical fertilization was greater
558 than that for organic systems using organic fertilizers (Morano *et al.*, 2011; Nemecek *et al.*, 2011a).

559

560 **4.3.2. GHG emissions**

561 Goglio *et al.* (2014) used a combination of LCA and ecosystem modeling to assess GHG emissions in innovative
562 systems. Over the 2009-2012 period, global warming potential (GWP) was 1.36 to 4.25 kgCO₂eq.ha⁻¹ in the PHEP
563 system. Brentrup *et al.* (2004b) reported GWP ranges of 0.29 to 4.10 kgCO₂eq.ha⁻¹ for wheat with different
564 amounts of N fertilizer, and Charles *et al.* (2006) reported a value of 2.42 kgCO₂eq.ha⁻¹ for the same crop. With a
565 range of 2.15 to 5.03 kgCO₂eq.ha⁻¹, the estimates for the Swiss "integrated" and organic systems involving cereals

566 (Nemecek *et al.*, 2011b) were slightly higher than those for the PHEP system. Despite the high variability of these
567 results, all the GWP results obtained were of the same order of magnitude. Since 2013, new cropping systems with
568 multiple goals, including lower levels of tillage, have been assessed in field trials (Planche *et al.*, 2015). The annual
569 GHG results calculated with the GES'TIM database (2010) ranged from 1340 to 2060 kgCO₂eq.ha⁻¹.year⁻¹. Despite
570 the use of different methodologies (calculation of GHG emissions at the crop sequence scale in the innovative
571 systems), the lowest value was close to that for the PHEP system (1071 kgCO₂eq.ha⁻¹.year⁻¹).

572
573 There is some debate about the degree to which no-till practices can increase soil organic carbon (SOC)
574 sequestration relative to conventional tillage. Conservation tillage practices, with an absence of tillage and
575 permanent soil cover, are adopted to limit the decline in SOC levels (Jonhson *et al.*, 2007; Smith *et al.*, 2008; Luo
576 *et al.*, 2010). However, Dimassi *et al.* (2014) and Virto *et al.* (2012) have shown that the C input from crop residues
577 is the major factor significantly correlated with differences in SOC levels between no-till and inversion tillage
578 systems. Moreover, the SOC initially present modifies the rate of mineralization of soil biogeochemical
579 components. Initial SOC content was 31 tC.ha⁻¹ in the trials managed by Li *et al.* (2005), 35 tC.ha⁻¹ in the study by
580 Andriulo *et al.* (1999) and 42-45 tC.ha⁻¹ in that by Dimassi *et al.* (2014). The C sequestration process was complex,
581 due to interaction between tillage practices and the amount of crop residue present. In the No-Pest system, low
582 levels of C sequestration may be linked to both the small amounts of crop residues left on the soil and intensive
583 plowing practices during the crop sequence (table 3), consistent with current scientific knowledge. However, in
584 the L-EN system, in which only small amounts of crop residues were present, the no-till practices did not prevent
585 C sequestration from being very low. Likewise, C sequestration did not differ significantly between the PHEP and
586 L-GHG systems, despite large differences in tillage practices (table 3). Moreover, in the other studies, assessments
587 were carried out over longer periods than this study. Dimassi *et al.* (2014) analyzed SOC evolution after 12 years
588 of no-till practice. Bremer *et al.* (2008) measured changes in SOC 12 years after the introduction of fallow. The
589 impacts of different tillage practices on C sequestration were assessed over 27- and 30-year periods by Liu *et al.*
590 (2009) and Ghangsen Li *et al.* (2005), respectively. However, our results, simulated with the Simeos® tool, require
591 validation with trial measurements. They were obtained after the first complete crop sequence (*i.e.* 5 to 6 years),
592 which may be too short for the analysis of C sequestration. At least another full crop sequence may be required for
593 a reliable analysis of changes in SOC. In organic systems, SOC content is generally reported to be higher than that
594 in conventional systems, due to the use of organic fertilizers (Clark *et al.*, 1998; Wells *et al.*, 2000; Azeez G., 2008;
595 Mancinelli *et al.*, 2010). The significant difference, by a factor of about five, between the No-Pest and PHEP

596 systems, may be explained by the many plowing operations and lower yields in the No-Pest system than in the
597 PHEP system, and by the removal of hemp straw.

598

599 **4.3.3. Yield performances**

600 The target yields of the innovative systems were lower than those of conventional systems in the Ile-de-France
601 region, to make it possible to satisfy environmental targets. Yields in the PHEP system were 5% to 10% lower
602 than those of current systems, depending on the species considered, but gross margins were similar. Over the 2009-
603 2013 period, mean winter wheat yield was 9.77 t.ha⁻¹ for a conventional system (Colnenne-David *et al.*, 2015b)
604 assessed in a field trial located near Grignon (Debaeke *et al.*, 2009), whereas mean winter wheat yield was 8.56
605 t.ha⁻¹ in the PHEP system. The corresponding TFIs were 4.64 and 1.85 and the amount of N fertilizer applied was
606 147 kgN.ha⁻¹.year⁻¹ and 56 kgN.ha⁻¹.year⁻¹, respectively. The energy output of the innovative systems, with a range
607 of 71 to 103 GJ.ha⁻¹.year⁻¹ for the L-EN and No-Pest systems, respectively, was lower than that of conventional
608 systems in the Ile-de-France region (114 GJ.ha⁻¹.year⁻¹). Variable energy output results have been reported for
609 conventional and organic systems (Klimekova *et al.*, 2007; Moreno *et al.*, 2011) from different locations and with
610 different methodologies (different ways of taking straw energy into account). In all studies, energy output was
611 systematically higher in conventional than in organic systems, contrasting with the results for the PHEP and No-
612 Pest systems (96 and 103 GJ.ha⁻¹.year⁻¹, respectively). The high score of the No-Pest system resulted from both
613 high crop productivity, particularly for hemp, which had a mean yield of 11.23 t.ha⁻¹, and high calorific value.
614 Without hemp in the crop sequence, energy output would probably reach about 87 GJ.ha⁻¹.year⁻¹. The energy use
615 efficiency of the new systems ranged from 12.1 to 13.7, and was thus much higher than published values. The
616 EUE of the current Ile-de-France system was 7.75; those for conventional and organic systems were 6.55 and 6.41,
617 respectively, over an 11-year period in Bulgaria (Bochu *et al.*, 2008) and 7.77 and 10.57, respectively, over a six-
618 year period in Poland (Klimekova *et al.*, 2007). These high performances reflect a significant optimization of
619 agronomic practices, in terms of both plowing and N fertilizer management. Moreover, the specific climatic
620 conditions prevailing in the 2009-2014 period resulted in high yields with little or no pesticide application.

621

622 **5. Conclusion**

623 We show here that it is possible to design and implement innovative cropping systems with multiple goals
624 combining environment performance and economic results. However, some of these goals appear to be more easily
625 attainable than others. In our conditions, and during the first full crop sequence in the innovative systems, the

626 application of a constraint imposing an absence of pesticide use did not result in poorer environmental and
627 economic results that were obtained with the PHEP system, despite the strong performance of the PHEP system.
628 However, our efforts to halve GHG emissions failed, due to the use of an inadequate strategy, which was
629 nevertheless based on the knowledge available at the design stage. Increasing numbers of studies of the effects of
630 agricultural practices on L-GHG emissions and carbon storage are being published, and their findings should make
631 it possible to refine our strategy on the basis of cutting-edge knowledge. The L-EN system was moderately
632 successful. It performed well, but did not quite achieve the targets set, and environmental performances were
633 declining over time, suggesting a need for adaptation of the strategy. We are currently carrying out assessments
634 for the second complete crop sequence in the same field trial (1) to validate the preliminary results for the PHEP
635 and No-Pest systems, for which agricultural practices have been kept the same as in the first crop sequence, and
636 (2) to assess the performances of new prototypes of the L-EN and L-GHG systems, which have been modified to
637 decrease herbicide use, and to make it easier to satisfy the GHG constraint of the L-GHG system. We believe that
638 such agronomic studies, combining *in silico* loops with field trials, are important and will facilitate the design of
639 new innovative cropping systems to deal with the range of issues faced by agriculture.

640

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Figure 2. Multi-criteria assessment of the four innovative cropping systems. Comparisons between the three constraint-limited innovative systems and the PHEP system (the gray area corresponds to the constrained system/PHEP system ratio). Cropping systems: PHEP (productive with high environmental performance), L-GHG (low greenhouse gas emissions), L-EN (low energy use) and No-Pest (no pesticide use). Cg balance: carbon gas balance. Tot GHG: total greenhouse gas emissions. D GHG: direct greenhouse gas emissions. Ind GHG: indirect greenhouse gas emissions. Tot En: total energy consumption. D En: direct energy consumption. Ind En: indirect energy consumption. En op: energy output. EN eff: energy efficiency. TFI: treatment frequency index. TFIH: TFI for herbicides. TFIothers: TFI for all pesticides other than herbicides. G margin: gross margin. Dotted lines indicate a score of 1: constrained system = PHEP system.

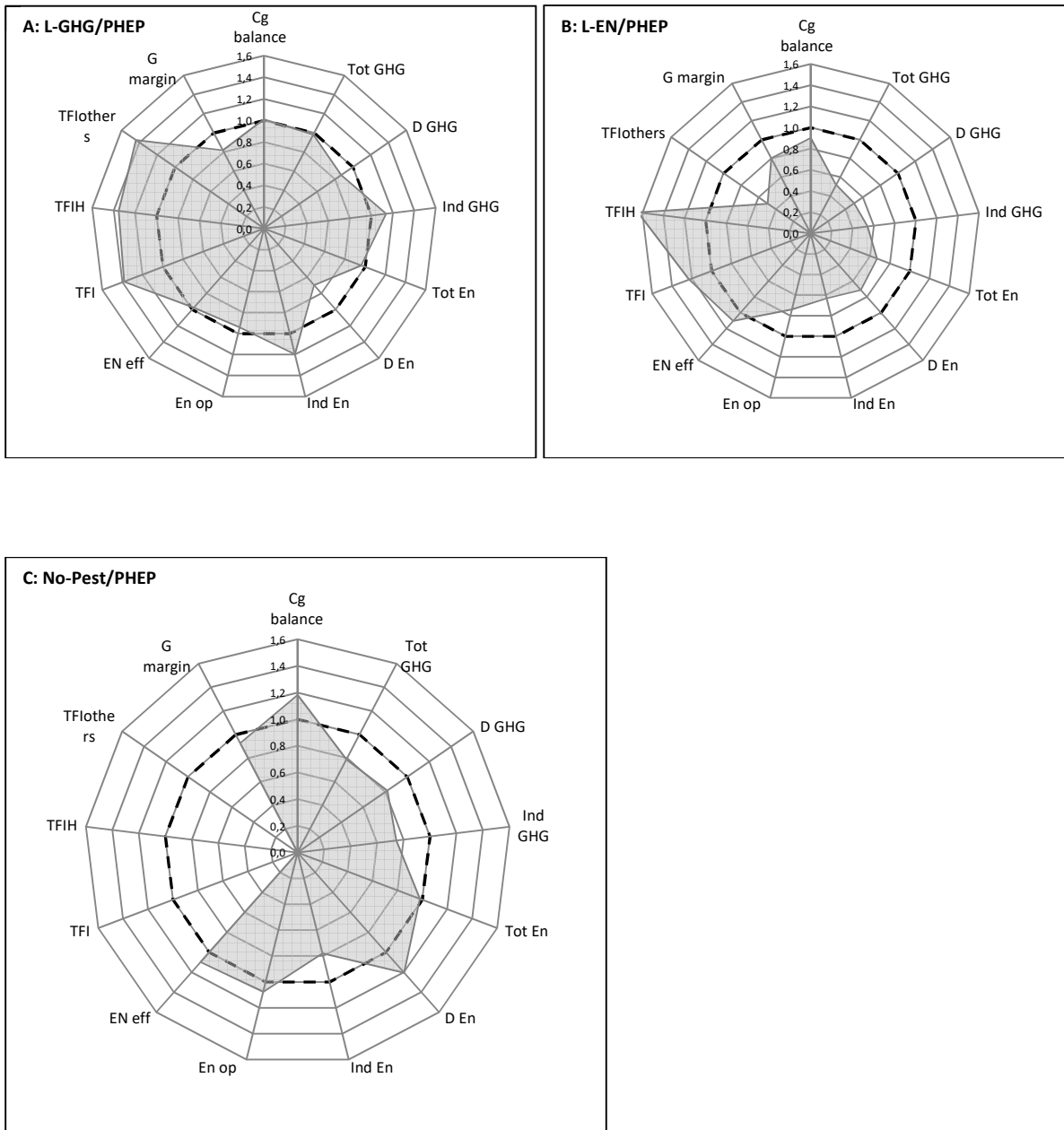


Figure 3. Multi-criteria assessment of the four innovative cropping systems. Comparisons between the four innovative systems and the current system in the Ile-de-France region (the gray area corresponds to the innovative system/current Ile-de-France system ratio). Cropping systems: A: PHEP (productive with high environmental performance), B: L-GHG (low greenhouse gas emissions), C: L-EN (low energy use) and D: No-Pest (no pesticide use). Cg balance: carbon gas balance. Tot GHG: total greenhouse gas emissions. D GHG: direct greenhouse gas emissions. Ind GHG: indirect greenhouse gas emissions. Tot En: total energy consumption. D En: direct energy consumption. Ind En: indirect energy consumption. EN op: energy output. TFI: treatment frequency index. TFIH: TFI for herbicides. TFIothers: TFI for all pesticides other than herbicides. G margin: gross margin. Dotted lines indicate a score of 1: innovative system = current Ile-de-France system.

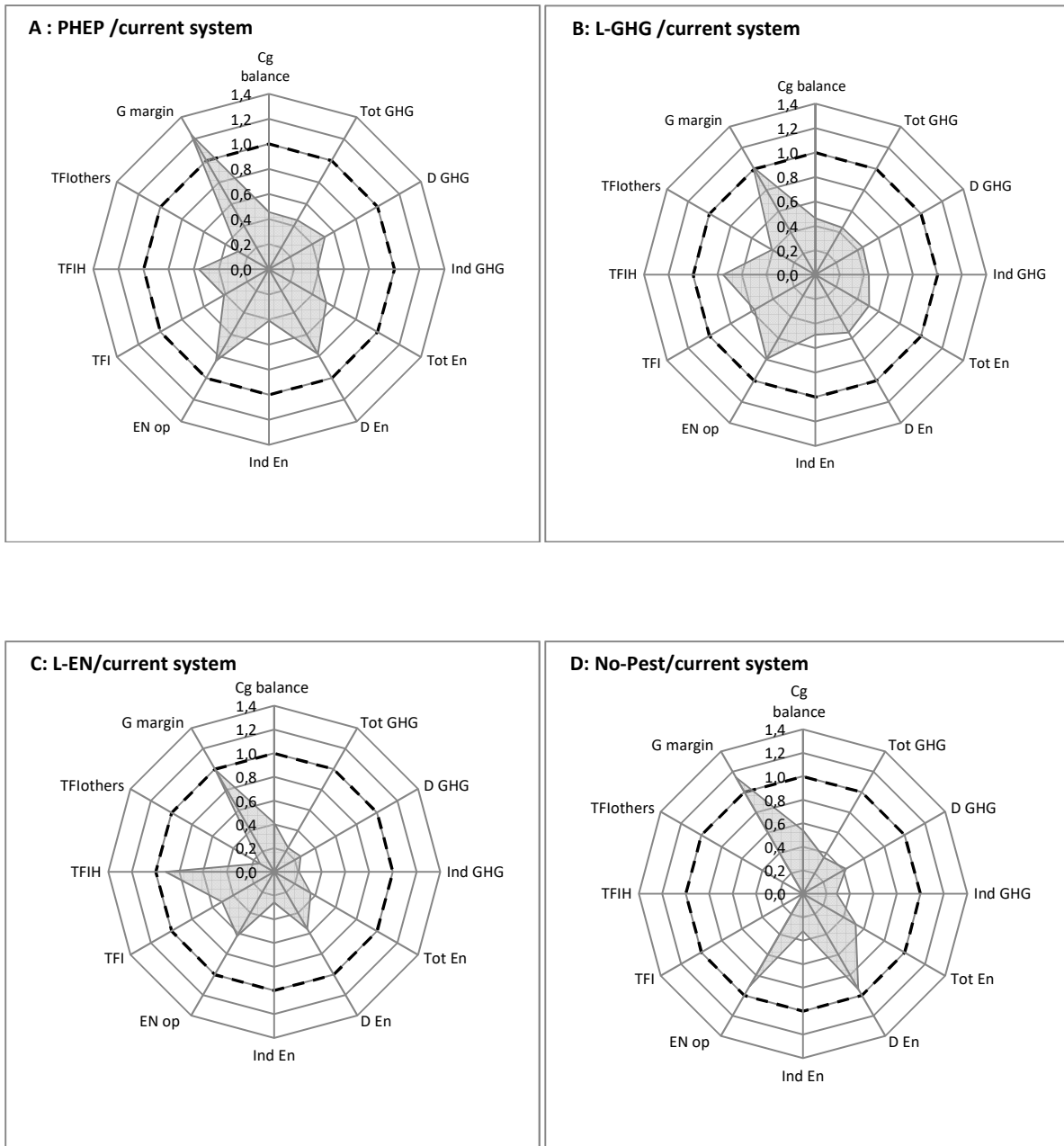


Table 1. Main crop management strategies used in the four cropping systems to meet constraints and environmental objectives. Cropping systems: PHEP (productive with high environmental performance), L-GHG (low greenhouse gas emissions), L-EN (low energy use), No-Pest (no pesticide use). In bold: constraints set for the innovative systems.

Cropping systems	Constraints and objectives of the systems	Specific agronomic practices managed in the innovative systems to reach the combination of targets specific to the system	Common agronomic practices managed in the four systems
PHEP	<ul style="list-style-type: none"> - No constraint - Environmental objectives - High yield 	<p>Earlier sowing of oilseed rape to maximize competition against weeds, and use of stale seed-bed techniques to increase weed emergence before sowing and to reduce herbicide use</p> <p>Shallow plowing to maintain beneficial insects such as carabids (slug predators) and to reduce molluscicide use</p> <p>One plowing permitted during the five-year crop sequence, to reduce energy consumption</p> <p>Target yield: similar to that of low-input cropping systems in the Ile-de France region</p>	<p>Lengthening of the crop sequence (five or six years) and sowing a wide range of crops to enhance crop diversity and to reduce the impact of pests on crops</p>
No-Pest	<ul style="list-style-type: none"> - No pesticide use - Environmental objectives - High yield 	<p>Alternate sowing of host and non-host plants or of spring and winter crops, to decrease pest pressure</p> <p>Sowing winter wheat later to reduce insect impact during autumn (aphids)</p> <p>Sowing species with rapid shoot growth, such as hemp and triticale, to increase competitiveness</p> <p>Using stale seed-bed techniques to increase weed emergence before sowing</p> <p>Shallow plowing to maintain beneficial insects such as carabids (slug predators)</p> <p>Use of <i>Trichogramma</i> parasitoid wasps against <i>Ostrinia nubilalis</i> on maize</p> <p>Mechanical weeding</p> <p>Lowering target yield and levels of N fertilizer to decrease pest impact</p> <p>Target yield: lower than for the PHEP system, higher than those achieved in organic systems because chemical fertilizers were allowed</p>	<p>Sowing of highly resistant varieties or variety mixtures to reduce the impact of diseases on crops</p> <p>Lower sowing density and levels of N fertilization to decrease shoot biomass and disease developments</p> <p>Sowing of a legume to reduce N fertilization needs (<i>i.e.</i> to</p>

L-EN	- To halve energy consumption relative to the PHEP system	Prohibition of plowing and use of a direct drilling system to reduce direct energy consumption Inclusion of legumes and high N use efficiency species in the crop sequence to reduce N fertilization requirements (<i>i.e.</i> indirect energy consumption)	reduce indirect energy consumption) Sowing catch crops before
	- Environmental objectives	Target yield: 20% lower than for the PHEP system, to reduce N fertilization (<i>i.e.</i> indirect energy consumption)	spring crops, oilseed rape after legumes and prohibition of N fertilization during the autumn
	- High yield		
L-GHG	- To halve greenhouse gas emissions relative to the PHEP system	Sowing of many cereals and maintenance of continuous soil cover (with a cover crop), to generate large amounts of residues to increase soil organic matter content Prohibition of plowing and use of a direct drilling system to reduce carbon mineralization	and winter, to decrease nitrogen leaching during these seasons.
	- Environmental objectives	Sowing of legumes to reduce N fertilization (<i>i.e.</i> N ₂ O emissions) Systematic sowing of cover crop to reduce NO ₃ ⁻ availability and N ₂ O emissions	Non-removal of crop residues, to stabilize soil organic matter levels
	- High yield	Sowing of species with taproots to reduce soil compaction Target yield: similar to that of the PHEP system	

Table 2. Mean annual treatment frequency indices (TFI: all pesticides; TFIH: herbicides; TFI others: pesticides than herbicides) for the four cropping systems, calculated at the crop sequence scale. Cropping systems: PHEP (productive with high environmental performance), L-GHG (low greenhouse gas emissions), L-EN (low energy use), No-Pest (no pesticide use). The values in brackets are the confidence intervals ($p < 0.05$) for the three replicates. For the No-Pest system, all values are zero.

Performances	PHEP	L-GHG	L-EN	No-Pest
TFI (ha ⁻¹ .year ⁻¹)	[1.73 ; 2.15]	[2.56 ; 2.81]	[1.83 ; 2.93]	0.00
TFIH (ha ⁻¹ .year ⁻¹)	[1.06 ; 1.41]	[1.49 ; 1.85]	[1.71 ; 2.36]	0.00
TFIothers (ha ⁻¹ .year ⁻¹)	[0.47 ; 0.94]	[0.78 ; 1.25]	[0.03 ; 0.67]	0.00

Table 3. Main agronomic practices of the four cropping systems, for each replicate and each crop. Bold characters correspond to the crops sown in 2009, *i.e.* the first crop of the crop sequence sown in each replicate. Rep = replicate. Nb = number. Catch or cover crops were systematically sown before main crops. W and S are winter and spring crops, respectively. MWheat or MBarley = mixture of varieties for wheat and barley, respectively. 2Oilseed rape or 2Maize = two sowings of oilseed rape or maize, respectively, due to plant emergence failure. Flax(W)+Flax(S) = sowing of spring flax after winter flax was destroyed by frost. None = no cover or catch crop. Bmustard and Wmustard correspond to brown and white mustard, respectively. Wclover = white clover. IntWheat = intercropped winter wheat and white clover. Cropping systems: PHEP (productive with high environmental performance), L-GHG (low greenhouse gas emissions), L-EN (low energy use), No-Pest (no pesticide use).

Cropping systems Replication Crop sequence	Crop	Nb of plowings (P) and tillage(T)	Sowing density (kg seed.ha ⁻¹)	Mineral nitrogen rate (kg.ha ⁻¹)	Species of cover/catch crops before each crop or associated crop in intercropping	Nb of herbicides (H), fungicides (F), insecticides (I), and molluscicides (M)	Nb of mechanical weedings
PHEP	Barley(S)	1P+1T	154	40	Bmustard	1H	None
Rep1: Barley(S) -Faba bean(W)-Wheat(W)- Rape(W)- MWheat(W)	Faba bean(W) Wheat(W) Rape(W) MWheat(W)	1T 3T 2T 1T	162 110 2 99	0 90 115 90	None None None None	None 1H 2H+1F+2I+1M 3H	None None None None
PHEP	Wheat(W)	1T	122	40	None	1H	None
Rep2: Wheat(W) - Barley(S)-Faba bean(W)-Wheat(W)- Rape(W)	Barley(S) Faba bean(W) Wheat(W) Rape(W)	1T 1P 4T 2T	112 212 109 3	70 0 70 100	Wmustard None None None	1H 3H 2H 2H+1F+1I°1M	None None None None
PHEP	2Rape(W)	1T	2+3	50	None	1H+1F+2I+1M	None
Rep3: 2Rape(W) - Wheat(W)-Barley(S)- Faba bean(W)- Wheat(W)	Wheat(W) Barley(S) Faba bean(W) Wheat(W)	2T 1P+1T None 2T	100 127 342 104	120 60 0 0	None Wmustard Buckwheat None	2H 2H 2H 2H+2F	None None None None
L-GHG	Wheat(W)	1T	122	40	None	1H	None
Rep1	Barley(W) Wheat(W) - 2Maize	None 1T	127 190	80 80	Peas Clover+Oat	1H 2H+1M	None None
Barley(W)-2Maize - Triticale-Faba bean(S)-2Rape(W)	Triticale Faba bean(S) 2Rape(W)	None None None	205 220 3+4	0 0 50	None Wmustard None	2H+1F 3H 4H+2M	None None None
L-GHG	2Rape(W)	1T	2+3	50	None	1H+1F+2I+1M	None
Rep2: 2Rape(W) - Wheat(W)- Barley(W)-Maize- Triticale-Faba bean(S)	Wheat(W) Barley(W) Maize Triticale Faba bean(S)	None None 1T None None	137 184 190 165 248	80 80 110 90 0	Peas Peas Clover+Oat No Lentil+Oat+Wmustard	2H 4H 3H+1M 1H 1H+1F+1M	None None None None None
L-GHG	Maize	1T	190	130	Bmustard	1H+1I	None
Rep3: Maize - Triticale-2Faba bean(S)-Rape (W)- Wheat(W)- MBarley(W)	Triticale 2Faba bean(S) Rape (W) Wheat(W) MBarley(W)	None None None None None	100 220+73 9 112 145	0 0 40 100 90	None None None Fenugreek Buckwheat	1H 3H+1I+1M 2H+1F+1I+1M 4H+2H+1M 3H	None None None None None
L-EN	Flax(W)	1T	33	0	None	1H	None
Rep1: Flax(W) - IntWheat(W)-Oat(W)- Faba bean(W)- Wheat(W)	IntWheat(W) Oat(W) Faba bean(W) Wheat(W)	None None None None	125 117 342 126	40 0 0 30	Wclover Wclover None None	1H 3H 4H 3H+1M	None None None None
L-EN	Oat(S)	1T	114	0	Wclover	1H	None
Rep2: Oat(S) -Faba bean(W)-Wheat(W)- Flax(W)+Flax(S)- IntWheat(W)	Faba bean(W) Wheat(W) Flax(W)+Flax(S) IntWheat(W)	None None None None	159 142 35+60 124	0 40 0 90	None None None Wclover	None 4H 5H 4H+1M	None None None None
L-EN	Faba bean(W)	1T	131	0	None	None	None
Rep3: Faba bean(W) -Wheat(W)- Flax(W)- IntWheat(W)-Oat(S)	Wheat(W) Flax(W) IntWheat(W) Oat(S)	None None None None	125 40 173 150	0 0 80 0	None None Wclover Wclover	2H 6H 3H 2H	None None None None
No-Pest	Maize	1P+2T	190	80	Bmustard	None	2
Rep1: Maize - MWheat(W)-Faba bean(S)-MWheat(W)- Hemp-Triticale	MWheat(W) Faba bean(S) MWheat(W) Hemp Triticale	None 1P+1T 3T 1P 1P+1T	235 220 160 57 141	70 0 0 30 30	None Wmustard+Oat None Vetch None	None None None None None	1 1 1 0 1
No-Pest	Faba bean(S)	1P+2T	189	0	None	None	0
Rep2: Faba bean(S) - MWheat(W)-Hemp-	MWheat(W) Hemp Triticale	1T 1P+2T 3T	156 55 160	0 0 40	Barley volunteers Clover+Mustard None	None None None	1 0 0

Triticale-Maize- MWheat(W)	Maize MWheat(W)	1P+1T 1P	190 160	90 70	Wmustard+Lentil None	None None	2 1
No-Pest	Wheat(W)	2T	174	0	None	None	0
Rep3: Wheat(W) - Faba bean(S)-	Faba bean(S) MWheat(W)	1P+2T 3T	196 160	0 0	Buckwheat None	None None	1 1
MWheat(W)-Hemp- Triticale-2Maize	Hemp Triticale 2Maize	1P+3T 1T 1P+3T	55 150- 220+220	0 0 110	Peas None Mustard+Lentil	None None None	0 1 5

Table 4. Energy (total, direct and indirect) consumption (MJ.ha⁻¹.year⁻¹), energy output (MJ.ha⁻¹.year⁻¹) and energy use efficiency of the four cropping systems. Cropping systems: PHEP (productive with high environmental performance), L-GHG (low greenhouse gas emissions), L-EN (low energy use), No-Pest (no pesticide use). The values shown are the means and the standard deviations for the three replicates. The same letters indicate homogeneous groups according to the Tukey test, $p < 0.05$ (ns: not significant).

Performance	PHEP	L-GHG	L-EN	No-Pest
Total energy consumption (MJ.ha ⁻¹ .year ⁻¹)	7755 ± 711 a	7459 ± 793 a	5201 ± 502 b	7604 ± 517 a
Direct energy consumption (MJ.ha ⁻¹ .year ⁻¹)	3665 ± 223 b	2562 ± 235 c	2618 ± 171 c	4417 ± 425 a
Indirect energy consumption (MJ.ha ⁻¹ .year ⁻¹)	4090 ± 489 ab	4897 ± 568 a	2584 ± 479 c	3187 ± 99 bc
Ratio: Indirect energy consumption/ Total energy consumption	52.7%	65.7%	49.7%	41.9%
Energy output (MJ.ha ⁻¹ .year ⁻¹)	95965 ± 8397 a	90229 ± 5572 a	70997 ± 9991 b	103323 ± 3629 a
Energy use efficiency	12.41 ± 1.07 (ns)	12.14 ± 0.74(ns)	13.71 ± 2.10 (ns)	13.61 ± 0.54 (ns)

Table 5. Annual yield (t.ha⁻¹) values (0% humidity) from 2009 to 2014, for each crop of the four cropping systems. Results in bold characters correspond to the crops sown in 2009 (i.e. the first crop of the crop sequence sown in each replicate). W and S are winter and spring crops, respectively. Cropping systems: PHEP (productive with high environmental performance), L-GHG (low greenhouse gas emissions), L-EN (low energy use), No-Pest (no pesticide use).

Cropping system	Successive crops in the crop sequence					
Replication						
PHEP: species	S barley	W faba bean	W wheat	W rape	W wheat	
calorific value (MJ.t ⁻¹)	14.5	14.4	14.5	24.6	14.5	
PHEP: target yield	5.3	3.0	6.7	2.8	6.7	
PHEP: Replicate 1	6.81	1.80	8.13	3.49	7.78	
PHEP: Replicate 2	5.32	1.38	6.65	3.48	6.13	
PHEP: Replicate 3	4.78	1.18	6.73	3.96	8.17	
PHEP: mean yield value and standard deviation	5.64 ± 1.04	1.45 ± 0.31	7.17 ± 0.81	3.64 ± 0.29	7.36 ± 1.12	
L-GHG: species	W wheat	W barley	Maize	Triticale	S faba bean	W rape
calorific value (MJ.t ⁻¹)	14.5	14.5	14.5	14.6	14.4	24.6
L-GHG: target yield	6.7	6.1	7.0	6.0	4.1	2.8
L-GHG: Replicate 1	7.40	6.15	7.64	5.82	1.95	0.00
L-GHG: Replicate 2	7.51	4.94	7.46	5.53	1.53	4.04
L-GHG: Replicate 3	7.24	4.96	5.27	6.99	0.61	3.26
L-GHG: mean yield value and standard deviation	7.38 ± 0.15	5.35 ± 0.72	6.79 ± 1.30	6.11 ± 0.79	1.36 ± 0.71	2.43 ± 2.14
L-EN: species	S oat	W faba bean	W wheat	W flax	W wheat	
calorific value (MJ.t ⁻¹)	15.8	14.4	14.5	21.2	14.5	
L-EN: target yield	3.2	3.0	5.4	1.6	5.4	
L-EN: Replicate 1	3.69	2.88	6.07	1.72	6.00	
L-EN: Replicate 2	6.06	2.28	6.33	0.86	6.51	
L-EN: Replicate 3	3.46	4.16	6.98	1.29	0.75	

L-EN: mean yield

value and standard

deviation 4.40 ± 1.45 3.11 ± 0.97 6.46 ± 0.51 1.29 ± 0.40 4.42 ± 3.16

No-Pest: species	Maize	W wheat	S faba bean	W wheat	Hemp	Triticale
calorific value (MJ.t ⁻¹)	14.5	14.5	14.4	14.5	16.5	14.6
No-Pest: target yield	5.6	4.7	3.1	4.7	8.0	4.3
No-Pest: Replicate 1	3.81	7.99	0.28	6.25	13.10	3.38
No-Pest: Replicate 2	5.24	6.09	4.19	6.82	8.20	4.97
No-Pest: Replicate 3	5.83	5.07	2.76	6.14	12.40	5.03

No-Pest: mean yield

value and standard

deviation 4.96 ± 1.03 6.38 ± 1.47 2.41 ± 1.98 6.40 ± 0.36 11.23 ± 2.65 4.46 ± 0.92

Table 6. Carbon balance, C sequestration and greenhouse gas emissions (total, direct and indirect) of the four cropping systems, calculated over a 50-year period (C content of the soil = 13 g.kg⁻¹ dry matter). Cropping systems: PHEP (productive with high environmental performance), L-GHG (low greenhouse gas emissions), L-EN (low energy use), No-Pest (no pesticide use). The values shown are the means and standard deviations for the three replicates. Identical letters indicate homogeneous groups according to the Tukey test, $p < 0.05$ (ns: not significant).

Performances	PHEP	L-GHG	L-EN	No-Pest
Carbon balance (kgCO ₂ eq.ha ⁻¹ .year ⁻¹)	1188 ± 270 ns	1202 ± 86 ns	1072 ± 29 ns	1404 ± 90 ns
C sequestration (kgCO ₂ eq.ha ⁻¹ .year ⁻¹)	-117 ± 150 a	-149 ± 117 a	-518 ± 92 b	-560 ± 49 b
Total greenhouse gas emissions (kgCO ₂ eq.ha ⁻¹ .year ⁻¹)	1071 ± 145 a	1052 ± 183 a	554 ± 107 b	844 ± 46 ab
Direct greenhouse gas emissions (kgCO ₂ eq.ha ⁻¹ .year ⁻¹)	622 ± 82 a	541 ± 102 a	311 ± 40 b	509 ± 26 a
Indirect greenhouse gas emissions (kgCO ₂ eq.ha ⁻¹ .year ⁻¹)	449 ± 64 ab	511 ± 82 a	243 ± 67 c	335 ± 20 bc

Table 7. Environmental performances of the various innovative cropping systems calculated with the Criter® tool, at the crop sequence scale. Cropping systems: PHEP (productive with high environmental performance), L-GHG (low greenhouse gas emissions), L-EN (low energy use), No-Pest (no pesticide use). For the NH₃ volatilization, N₂O emissions and NO₃⁻ leaching indicators, the values shown are the means and standard deviations for the three replicates. Identical letters indicate homogeneous groups according to the Tukey test, $p < 0.05$ (ns: not significant). The Pesticide volatilization, Pesticide leaching, and Pesticide runoff indicators, all take a value of 10 for the No-Pest system. We therefore show confidence intervals in italic brackets ($p < 0.05$). For the Crop diversity indicator, no standard deviations were calculated because the three replicates of each system had the same crop sequence.

Indicators	PHEP	L-GHG	L-EN	No-Pest
Qualitative indicators				
NH ₃ volatilization	9.84 ± 0.03 b	9.85 ± 0.04 b	9.94 ± 0.02 a	9.91 ± 0.01 ab
N ₂ O emissions	8.69 ± 0.16 b	8.80 ± 0.14 ab	9.17 ± 0.06 a	9.10 ± 0.13 ab
<i>Pesticide volatilization</i>	<i>[8.52 ; 9.72]</i>	<i>[8.22 ; 8.78]</i>	<i>[8.39 ; 9.37]</i>	<i>10.00</i>
<i>Pesticide leaching</i>	<i>[8.37 ; 8.43]</i>	<i>[8.74 ; 8.78]</i>	<i>[8.38 ; 8.76]</i>	<i>10.00</i>
<i>Pesticide runoff</i>	<i>[8.59 ; 9.10]</i>	<i>[8.69 ; 8.90]</i>	<i>[8.72 ; 9.02]</i>	<i>10.00</i>
Crop diversity	6.8	7	7.8	7.5
Quantitative indicator				
NO ₃ ⁻ leaching (kg NO ₃ ⁻ ·ha ⁻¹ ·year ⁻¹)	8.93 ± 2.24 a	4.53 ± 0.56 b	6.25 ± 0.67 ab	7.83 ± 0.80 ab

Table 8. Economic results (gross margin, gross output and total variable costs, all expressed in $\text{€}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$) for the various innovative cropping systems. CAP = Common Agricultural Policy. Cropping systems: PHEP (productive with high environmental performance), L-GHG (low greenhouse gas emissions), L-EN (low energy use), No-Pest (no pesticide use). The values shown are the means and standard deviations for the three replicates. Identical letters indicate homogeneous groups according to the Tukey test, $p < 0.05$.

Performances	PHEP	L-GHG	L-EN	No-Pest
Gross margin ($\text{€}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$)	757.0 ± 88.7 a	619.6 ± 77.3 ab	606.4 ± 56.1 b	701.4 ± 48.4 ab
Gross output ($\text{€}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$)	929.1 ± 71.6 a	861.9 ± 84.0 a	696.0 ± 74.5 b	879.0 ± 48.9 a
Total variable costs ($\text{€}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$)	497.5 ± 43.8 ab	567.7 ± 29.7 a	415.0 ± 46.7 b	503.0 ± 54.6 ab
CAP subsidies ($\text{€}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$)	325	325	325	325