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1 **Crop diversification improves cropping system sustainability: an 8-year on-** 2 **farm experiment in south-western France**

3

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9

10 **Abstract**

11 **CONTEXT**

12 Conventional cropping systems in south-western France contribute greatly to the degradation
13 of environmental resources. Crop diversification is considered to be an effective mechanism
14 to increase the sustainability of cropping systems and promote their transition to agroecology.
15 To test this hypothesis, farmers, agricultural advisers and scientists developed a participative
16 co-design project.

17 **OBJECTIVE**

18 The main objective was to co-design cropping systems to reduce the use of inputs, experiment
19 with them on farms and assess their sustainability over several years.

20 **METHODS**

21 Eight diversified cropping systems were designed during multi-actor co-innovation
22 workshops. These systems were established and monitored for eight years (2010-2017) on
23 two fields on each of eight farms located in areas with different soil and climate conditions.
24 At the end of the eight-year study, the performance of these cropping systems was evaluated
25 using 15 economic, environmental and social indicators.

26 RESULTS AND CONCLUSIONS

27 Crop diversification improved most of the environmental indicators. Pesticide use decreased
28 by 20-64% in five of the eight systems but increased in the other three, due to production
29 contracts that required systematic applications or in order to control high levels of pest or
30 weed pressure. In parallel, mean energy consumption (-30%), greenhouse gas emissions
31 (-36%) and irrigation water consumption (-43%) decreased significantly after diversification,
32 which helped the systems mitigate and adapt to climate change. The economic performance,
33 however, was more contrasted, with four of the eight farms showing a decrease in semi-net
34 margin of 10-35% compared to those of the initial systems, but the other four showing an
35 increase of 5-190%. Production of food energy also generally decreased (by up to 40%) after
36 diversification, mainly due to a decrease in the amount of cereals produced (especially maize).
37 Thus, crop diversification usually improves the environmental sustainability of cropping
38 systems; however, for certain specialised high-value cropping systems, which often have high
39 environmental impacts, it tends to reduce their economic performances.

40

41 **Keywords:** multi-criteria evaluation; low-input cropping system; on farm-experiment; co-
42 design approach

43

44 **1. Introduction**

45 Food production in the second half of the 20th century has increased greatly due to
46 intensification of agriculture, but it has also led to many undesirable environmental impacts,
47 such as biodiversity loss; soil degradation; and soil, water, air, and food contamination by
48 pesticides (Foley *et al.*, 2005; MEA, 2005), which can have negative impacts on human health
49 (Mostafalou and Abdollahi, 2013; Carvalho, 2017; Kim *et al.*, 2017). To limit or reduce these
50 negative externalities, several directives and plans have been developed and implemented in

51 the European Union since the 1990s, especially through the Common Agricultural Policy (*e.g.*
52 Directive 2009/128/EC; European Green Deal). In France, the national Ecophyto plan (2008-
53 2025) aims to halve the amount of pesticides applied by developing and promoting alternative
54 pest management strategies, based mainly on integrated pest management principles
55 (Reganold *et al.*, 2001; Barzman *et al.*, 2015), while maintaining an overall level of
56 production compatible with food/feed demand or other industrial needs (*e.g.* energy, fibre)
57 (Debaeke *et al.*, 2009; Lechenet *et al.*, 2016; Lechenet *et al.*, 2017a). Attempting to meet such
58 potentially contradictory objectives simultaneously may be difficult and raise questions that
59 need to be addressed collectively by farmers and stakeholders in agricultural research and
60 development (Thornton and Herrero, 2001; Vasileiadis *et al.*, 2013; Richard *et al.*, 2020).

61 Among the possible strategies to reach these ambitious goals, redesigning cropping systems
62 (CS) using a diversity of agronomic mechanisms that are well-reasoned and interconnected
63 for maximum efficiency is probably one of the most promising to reduce the dependence of
64 agricultural systems on inputs (Attoumani-Ronceux *et al.*, 2011; Lechenet *et al.*, 2017b).

65 Redesigning of cropping systems can be combined with complementary strategies such as
66 substitution of inputs with more “environmentally friendly” practices. Many agricultural
67 research and development projects use this Efficiency-Substitution-Redesign strategy
68 (MacRae *et al.*, 1989; Hill and MacRae, 1995) to assess the degree of change between initial
69 and alternative systems and to develop methods to analyse and compare alternative systems
70 that have been developed to decrease the use of inputs (Giuliano *et al.*, 2016; Casagrande *et*
71 *al.*, 2017; Lechenet *et al.*, 2017b).

72 Many agronomists consider crop diversification in space and time as the most effective
73 strategy for decreasing input dependence because it can decrease pest pressure (*e.g.* break
74 biological cycles, reduce weed specialisation), and it is a central pillar of agroecology (Altieri
75 and Nicholls, 2005; Duru *et al.*, 2015). However, the specialisation of farming systems and

76 CS in France in the past 50 years has often decreased crop diversity (Duru *et al.*, 2015;
77 Meynard *et al.*, 2018), which has resulted in monocultures (mainly of maize and winter
78 cereals) in several regions. Currently, reintroducing crop diversity faces technical lock-ins,
79 such as a lack of agronomic knowledge about crop species (e.g. choice, management,
80 performance), a scarcity of references on how to use this diversity to build efficient crop
81 rotations (Meynard *et al.*, 2018) and organisational and economic lock-ins, with specialised
82 sectors (e.g. the maize production chain) that are unwilling to manage a wide range of crops
83 (Magrini *et al.*, 2016; Magrini *et al.*, 2019).

84 When designing CS prototypes, two main approaches can be used: model-based design or a
85 prototyping approach that involves different stakeholders/experts (Vereijken, 1997; Lançon *et*
86 *al.*, 2007; Lesur-Dumoulin *et al.*, 2018). By using knowledge from farmers, advisers (e.g.
87 from extension services, cooperatives) and scientists in a design step and then defining
88 objectives that the CS prototype needs to fulfil, this second approach can explore more
89 innovations than the former (Lesur-Dumoulin *et al.*, 2018).

90 In south-western France, especially in the Occitanie region, CS are highly specialised and not
91 very diversified. In alluvial valleys, on loamy soils with differing depths and degrees of stone
92 content, the CS are dominated by maize (mainly for grain), usually irrigated (> 70% of the
93 area) and planted in monoculture. Water consumption for irrigation is a major issue,
94 especially as effects of climate change become more severe. At the same time, although maize
95 requires few pesticide treatments, the active ingredients used, such as S-metolachlor, are
96 widely detected in the region's groundwater and surface water. In hillside areas of the region,
97 mainly on clay soils, the CS are based on a relatively short rotation of wheat (durum or soft)
98 and sunflower. Most of these CS include deep tillage (usually mouldboard ploughing) and
99 bare soil during the fallow period. These operations often cause significant erosion, loss of
100 soil fertility and high energy consumption.

101 The objective of this study was to test the hypothesis that crop diversification can improve
102 agronomic, economic, environmental and social performances of CS. One of its original
103 features was to conduct these experiments on farms over a long period (8 years). To this end,
104 CS were co-designed during workshops with groups of 6-8 farmers, advisers and scientists in
105 six territories of the Occitanie region. Following these co-design workshops, eight farmers (1-
106 2 per territory) committed themselves to implement the co-designed diversified CS with
107 support from their local adviser. The performance of these CS was monitored for eight years
108 using a variety of indicators to assess their sustainability.

109

110 **2. Materials and methods**

111 2.1. Territories of the study and main features of their initial CS

112 The study was conducted in the Occitanie region (Fig. 1), which has an oceanic climate with
113 Mediterranean influences, according to the Köppen climate classification. In 2009, six
114 agricultural territories that represented the main areas of cash-crop production of the
115 Occitanie region were chosen:

- 116 - three were located in alluvial corridors of the Garonne, Ariège and Adour Rivers (Fig.
117 1). Soil types there are mainly silty (55-60%, clay content 15-20%), with a relatively
118 low organic carbon content (mean < 1.0%) and sometimes stony (especially in the
119 Ariège corridor). The main CS is based on a grain maize (or maize seed) monoculture,
120 mostly irrigated and cultivated after deep tillage (mouldboard ploughing) in the spring.
- 121 - the other three were located on hillsides of the region (Lauragais, Tarn and Causses du
122 Lot) (Fig. 1). Soils there are mainly calcareous clay (clay content > 30%). The CS,
123 usually rainfed, are based mainly on a durum wheat-sunflower rotation, but are
124 sometimes more diverse, with rapeseed or barley as winter crops and sorghum as a

125 summer crop. Soil tillage is generally reduced for winter crops but deeper
126 (mouldboard ploughing or other deep tillage) for spring crops.

127 In each territory, a group of 6-8 farmers, all exclusively field-crop producers with no
128 livestock, was assembled according to local advisers' knowledge of their potential interest in
129 redesigning more sustainable CS. These farmers were involved in the co-design workshops,
130 which started at the end of 2009 or beginning of 2010.

131

132 2.2. Method to co-design, test and evaluate diversified CS

133 Co-designing of the CS was based on a participative prototyping approach that involved
134 farmers, advisers and scientists (Vereijken, 1997; Lançon *et al.*, 2007; Lesur-Dumoulin *et al.*,
135 2018). The farmers were identified by local advisers from the Chamber of Agriculture
136 according to (i) their farming systems, which had to be representative of the territory, and (ii)
137 their motivation for the project. Most of the farmers selected could be considered as “adviser
138 farmers” (Richard *et al.*, 2020): aware of the need to improve agricultural production methods
139 and with a high level of expertise and knowledge about agronomic mechanisms alternative to
140 the use of inputs. A two-day group workshop was then organised in each territory. The
141 workshop was divided into two main steps (Fig. 2), which aimed to (i) analyse advantages and
142 disadvantages of the initial CS and stakeholders in the territory in order to (ii) co-design and
143 evaluate CS prototypes.

144

145 2.2.1. Step 1 – Systems analysis and farmers' perceptions

146 The main objectives of step 1 were to identify the main issues of the territory in order to
147 improve the sustainability of farming systems and to analyse their existing CS by defining the
148 one that would serve as a reference. In most territories, farmers spontaneously mentioned
149 environmental problems, mainly degradation of water quality (surface or ground water) due to

150 the presence of nitrate and/or pesticides. In this first phase of step 1, the advisers and
151 scientists let the farmers express themselves so they could exchange practical knowledge and
152 suggestions. Next, the group analysed strengths, weaknesses, opportunities of and threats to
153 (SWOT) agronomic, economic, environmental and social aspects of the reference system. The
154 next phase aimed to have the group share and adhere to a systems approach to be able to co-
155 design the CS prototypes and then define and prioritise their main objectives.
156 During this phase, the advisers and scientists present identified 1-2 farmers who were likely to
157 experiment with, on their own farms, the CS outlined. Farmers were chosen by considering
158 their motivations, open-mindedness and ability to exchange with other farmers and the
159 advisers. Two farmers accepted doing so in two of the territories (Fig. 1), while one farmer
160 accepted doing so in the other four (Fig. 2).

161

162 2.2.2. Step 2 – Co-design and *ex-ante* assessment of the CS prototypes

163 An iterative method, based on that developed by the national network on innovative CS
164 (Attoumani-Ronceux *et al.*, 2011), was used to combine the participative co-design of CS
165 with multi-criteria *ex-ante* assessment of the CS prototypes designed (Fig. 2). For the co-
166 design phase, the objectives previously defined were used and supplemented by a variety of
167 constraints (e.g. keeping certain crops in the rotation, such as durum wheat or maize). The
168 objectives and constraints could vary among territories, but some of them were the same. In
169 particular, a common objective was to use less pesticides and fertilisers than in the initial CS,
170 using both crop diversification and other mechanisms of integrated crop protection.

171 The initial group of 6-8 farmers, 2-3 advisers and 1-2 scientists was divided into two equal-
172 sized subgroups, and a prototype version of the serious game “Mission Ecophyt’eau®”
173 (<https://www.civam.org/accompagner-le-changement/mission-ecophyteau/>) was used to
174 facilitate interactions and knowledge sharing in a playful atmosphere. The principle of this

175 collaborative game is to generate interactions between participants in order to co-design CS
176 that meet the objectives and constraints set. One of the scientists or advisers acted as the
177 “facilitator”, who was familiar with the CS co-design method. Maintaining a neutral position
178 during the workshop, the facilitator stimulated discussion and thoughts in the groups. The
179 participants first identified which cash crops to include in the CS and then discussed where
180 place these crops in the CS. These exchanges led them to reflect on how to manage fallow
181 periods, sometimes by adding multiservice cover crops or maintaining periods of bare soil
182 (e.g. “false sowing” for mechanical weed control). Once the CS was finalised, which usually
183 required many iterations, the group defined the technical operations and their associated
184 decision rules. These rules specified the reasoning behind management decisions, such as
185 tillage operations, destruction dates of multiservice cover crops and pest thresholds at which
186 pesticide treatments begin.

187 When 2-3 prototypes had been designed in each group, *ex-ante* assessment of their
188 performance was performed using the multi-criteria assessment method MASC 2.0® (Sadok
189 *et al.*, 2009) to verify whether the prototypes met the objectives set. If the performances
190 assessed using the selected indicators did not meet the farmers’ objectives and constraints
191 sufficiently well, adjustments could be made. At the end of this stage, the farmer(s) who were
192 going to experiment with the co-designed CS on their farm chose from among the prototypes
193 developed, depending on their specific objectives and constraints. Because the CS developed
194 were no longer prototypes after the farmers’ choice, we refer to them as "diversified CS".

195

196 2.2.3. Step 3: On-farm experimentation of diversified CS

197 Experiments with the diversified CS started with tillage for spring crops in 2010 and lasted
198 until harvest of spring crops in 2017. On each of the eight farms involved in the project (Fig.
199 1), at least two fields with a minimum area of 1 ha were used to experiment with the

200 diversified CS. The other fields on each farm continued to be managed according to the initial
201 CS, against which performances of the diversified CS could be compared. The duration of the
202 rotation of the diversified CS (Table 1), allowed for evaluation of one complete rotation of the
203 diversified CS on each of the two fields for Farm 8 and nearly three complete rotations of the
204 diversified CS on each field for the shortest CS (Farms 2 and 4).

205 Farmers and advisers recorded all the information needed to calculate the selected indicators
206 (section 2.3), such as technical operations, crop yields, weed pressure on fields, labour time
207 and grain quality at the field level. During the project, local advisers, scientists and farmers
208 met once per year to present results, describe the degree to which the objectives had been
209 achieved and collect farmers' feedback on the operational implementation of the CS tested.
210 Based on this feedback, the decision rules were sometimes modified slightly when necessary
211 (using a stepwise approach), to include specific characteristics not identified during the co-
212 design workshops, such as the presence of flora that are difficult to manage by mechanical
213 weeding alone.

214

215 2.2.4. Step 4: *ex-post* multi-criteria assessment of the diversified CS

216 After eight years of study, the sustainability of the initial and diversified CS was assessed
217 using multi-criteria evaluation based on 15 indicators, mainly from the MASC 2.0® and
218 SYSTERRE® (Toqué *et al.*, 2019) tools (Table 2). To provide input data for or calculate
219 these indicators, all technical operations used in the initial CS (maintained on most of the
220 farms) and the diversified CS (tested on two fields per farm), such as the equipment used and
221 labour times were collected regularly by the advisers involved in the project.

222

223 2.3. Description of the indicators

224 The 15 indicators selected to evaluate the overall performance of the CS were divided among
225 economic (4), environmental (8) and social (3) aspects (Table 2).

226

227 2.3.1. Economic indicators

228 **#1 Mean semi net-margin at the rotation level**

229 The semi-net margin (SNM, €/ha/year), an indicator of the economic profitability of the crop
230 or CS, was calculated as follows:

231 $SNM = (\text{Gross product} + \text{Subsidies} - \text{Operational costs} - \text{Mechanical costs}) / \text{Rotation}$
232 duration

233 with $\text{Operational costs} = \text{Seed costs} + \text{Pesticide costs} + \text{Fertiliser costs} + \text{Irrigation costs}$

$$\text{Mechanical costs} = \sum_{i=1}^n \text{Area}_i \times (\text{Tractor cost}_i + \text{Equipment cost}_i + \text{Fuel costs})$$

234 where n is the number of mechanical operations on a field, and Area_i is the area worked (in
235 ha) per operation. The costs of the tractor, equipment and fuel (in $\text{€} \cdot \text{ha}^{-1}$) per operation include
236 wear, maintenance and depreciation.

237 Irrigation costs include the irrigation equipment used (e.g. pivot, hose reel, sprinkler) and
238 associated costs (e.g. electricity or fuel for pumps). Mechanical costs are estimated using
239 reference values for technical operations based on the type of equipment, traction power and
240 working width used (Chambres d'agriculture de France, 2018).

241 Eight crop-price scenarios were chosen for the period 2007-2014 to test the robustness of the
242 SNM of the CS (Massot *et al.*, 2016) (Table 3). Economic performances of the initial CS and
243 diversified CS were compared.

244

245 **#2 Weed pressure in the field**

246 Weed pressure was considered an economic indicator because poor weed management can
247 have severe economic consequences for farmers due to primary harmfulness (competition) in
248 the short term or secondary harmfulness (seed bank) in the long term. Weed abundance and
249 phenological stage were determined using qualitative scales at the flowering stage of each
250 cash crop of the rotation. Measurements were based on counting weeds in 0.5 m² quadrats (5
251 per field) to estimate weed density (plants.m⁻²) and on crossing each field in a “W” shape (i.e.
252 four transects) to assess ca. 2000 m² per field. The scales used for monitoring were as follows:

- 253 - Seven classes for abundance, based on weed density (plants.m⁻²) (adapted from Barralis
254 (1976)): ε: less than 10 individual weeds in the entire area assessed; Class 0: < 0.1, Class
255 1: 0.1-1, Class 2: 1-3, Class 3: 4-20, Class 4: 21-50, Class 5: 51-500, Class 6: > 500
- 256 - Five classes for phenological stage: A: Cotyledons to 1-3 leaves (grasses: 1-3 leaves); B:
257 Young plant (4-6 leaves); C: Adult plant (grasses: tillering); D: Flowering; E: Seeds
258 disseminated, senescent plant.

259 The observer records the weed species identified and their minimum, maximum and dominant
260 phenological stages. To estimate overall weed pressure in the field, a score from 1-10 is then
261 attributed to each of the four transects according to the dominant class of abundance and
262 phenological stage of the weed community (without distinguishing species), and the four
263 scores are averaged for the field (Table 4). When designing this scoring system, the
264 agricultural advisers in the project considered that a mean score > 7 corresponds to well-
265 managed weeds, whereas a mean score > 8 corresponds to a low risk of increasing the weed
266 seed bank.

267

268 **#3 Economic efficiency of inputs**

269 This indicator represents the technical efficiency with which the CS transforms inputs and
270 indicates the degree to which the gross margin is increased per € of input used:

271 Economic efficiency of inputs = (Gross_Products – Operational_costs) / Operational_costs

272

273 #4 Food energy production

274 The amount of energy produced by the yield of a CS is considered as a proxy of its efficiency.

275 The energy-production indicator (EP, MJ/ha/year), which estimates the mean amount of
276 energy in the yields of a rotation at the CS level, was calculated as follows:

$$277 \quad EP = (\text{Yield}_1 \times K_1 + \text{Yield}_2 \times K_2 + \dots + \text{Yield}_n \times K_n) / n$$

278 where Yield_n = yield (kg/ha dry matter (DM)) of a crop in the CS, and K_n = energy content
279 (MJ/kg DM) in the crop and n = duration of the CS (years)

280

281 Nearly all of the energy contents came from ADEME (2011) – 15.8 MJ/kg DM for soft
282 wheat, 15.9 for durum wheat and barley, 16.2 for grain and maize seed, 16.4 for sorghum,
283 20.2 for soya bean, 16.0 for faba bean, 26.1 for sunflower and 25.2 for rapeseed – while that
284 for carrot seed (13.8) came from Wadhwa *et al.* (2013), for carrots grown as vegetables.

285

286 2.3.2. Environmental indicators

287 #5 Treatment Frequency Index

288 The Treatment Frequency Index (TFI) estimates the number of registered doses of a given
289 pesticide applied, per ha and per cropping season (OECD, 2001) and is calculated for each
290 pesticide application as follows:

$$\text{TFI} = \frac{\text{Application rate} \times \text{Application area}}{\text{Registered dose} \times \text{Field area}}$$

291 The application rate and registered dose are both expressed for a given commercial product
292 (which can contain several active ingredients). The recommended dose depends obviously on
293 the crop and the targeted pest. In this study, the registered dose was defined as the lowest dose
294 of a pesticide (including seed treatments) that is recommended for a given crop. The TFI for a
295 given cropping season equals the sum of the TFI for each pesticide application performed
296 during the cropping season. The TFI for a given CS equals the sum of the TFI of each crop of
297 the CS divided by the number of crops. Thus, the TFI describes pesticide use using a single
298 summary variable.

299 To compare the TFI of the diversified CS to CS that grew an equivalent number of crops,
300 regional reference TFIs for the crops in the diversified CS were used to calculate a regional
301 reference TFI for a CS (i.e. “regional CS”) with the same crop species.

302

303 **#6 I-PHY**

304 Environmental impacts of pesticides were estimated using the cumulative I-PHY index
305 (formerly IPEST), an expert system for calculating indicators that reflect potential
306 environmental impacts of applying a pesticide to a field crop (van der Werf and Zimmer,
307 1998; Lindahl and Bockstaller, 2012; Lechenet *et al.*, 2014). I-PHY estimates the risk of
308 pesticide application to three compartments of the environment: air, surface water and ground
309 water. I-PHY is calculated for each active ingredient application and ranges from 0 (high risk)
310 to 10 (no risk), with an acceptable risk defined at a score of 7. I-PHY is based on a field’s
311 inherent sensitivity to pesticide transfer toward these three compartments; characteristics of
312 the active ingredient (e.g. sorption properties, solubility, ecotoxicity, mobility, degradation
313 half-life); and characteristics of the application (e.g. number of active ingredients, canopy
314 cover at application) to calculate three impact factors, one for each compartment. I-PHY is

315 obtained using fuzzy decision trees that aggregate the three impact factors into one summary
316 indicator.

317

318 **#7 Nitrogen indicator**

319 The nitrogen indicator (NI) assesses the potential risk of technical operations on the quality of
320 (i) ground water, through NO_3^- leaching ($I_{\text{NO}_3^-}$), (ii) air, through N_2O ($I_{\text{N}_2\text{O}}$) emissions and (iii)
321 the soil and biodiversity, indirectly through the NH_3 volatilisation (I_{NH_3}), a source of
322 atmospheric deposition. For each of these processes, a risk indicator is calculated that ranges
323 from 0 (high risk) to 10 (no risk), with an acceptable risk defined at a score of 7. NI equals the
324 minimum value of $I_{\text{NO}_3^-}$, $I_{\text{N}_2\text{O}}$ and I_{NH_3} .

325

326 **#8 Irrigation amount**

327 The amount of irrigation water supplied to crops was recorded, and a mean per ha and per
328 year for each CS was calculated.

329

330 **#9 Organic matter indicator**

331 The organic matter indicator (OMI) was developed from the Henin-Dupuis model (Boiffin *et*
332 *al.*, 1986) to calculate the inputs necessary (recommended input, R_{input}) to maintain the soil at
333 a satisfactory equilibrium organic matter (OM) content in the long term. The OMI is a
334 function of the mean OM input over the past four years (OM_{input}) divided by R_{input} :

335
$$\text{OMI} = 7 \times \frac{\text{OM}_{\text{input}}}{R_{\text{input}}}$$
, with $\text{OMI} = 7$ as a satisfactory score. Weights are used to calculate OM_{input}

336 to consider soil tillage intensity (especially conservation tillage). See Bockstaller *et al.* (1997)

337 for details on calculating OMI.

338

339 **#10 Duration of bare soil**

340 This indicator calculates the percentage of the CS rotation with bare soil during the period of
341 risk for nitrate leaching and erosion. For nitrate leaching, bare soil corresponds to soil without
342 live plant cover during the drainage period (late autumn and winter), while for erosion, it
343 corresponds to soil without live plant cover or crop residues during periods of intense rainfall,
344 corresponding to spring (May-June) and autumn (October-November) in the study region. For
345 erosion, an area of tilled crops sown during the risk period or in juvenile development stage is
346 considered as bare soil, while an area under conservation or reduced tillage is considered to
347 have no erosion risk:

348 Bare soil duration = duration of bare soil during the risk period (for erosion and nitrate
349 leaching) / duration of the rotation \times 100

350

351 **#11 Energy consumption**

352 Energy consumption (MJ/ha/year) = (Mechanical energy use + Energy used to produce
353 fertilisers + Energy used to produce pesticides + Energy used to produce seeds) / duration of
354 the rotation

355 Values for mechanical energy use, energy used to produce fertilisers, energy used to produce
356 pesticides and energy used to produce seeds were collected from ADEME (2011).

357

358 **#12 Greenhouse gas emissions**

359 Greenhouse gas (GHG) emissions include direct CO₂ emissions from combustion of fossil
360 fuels on fields (e.g. tractors, harvesters) and N₂O emissions related to the nitrogen cycle (e.g.
361 nitrogen input, crop residues). Emissions are calculated in kg CO₂ eq./ha/year.

362

363 2.3.3. Social indicators

364 **#13 Labour time**

365 Labour time corresponds to the time spent in and outside the field. The farmers recorded the
366 operations performed in the CS and the time they spent on them (h/ha). They also estimated
367 the time spent observing crops to make decisions about pest management. This observation
368 time is often considered to become longer when CS are diversified and strategies besides
369 pesticide use are used.

370

371 **#14 Workload distribution**

372 Labour time was summed by month (h/ha/month) to estimate the distribution of the workload
373 throughout the year.

374

375 **#15 Number of human-toxic pesticide applications**

376 This indicator estimates the number of pesticides toxic to humans applied in the CS studied,
377 as follows:

$$\text{Toxicity to human health} = \sum_{i=1}^n \frac{\text{number of toxic pesticide applications during rotation}_i}{\text{duration of the rotation}}$$

378 The pesticides included are those classified as very toxic (class I in the European Union,
379 initially labelled as T+ (very toxic)) or as toxic (class II in the European Union, initially
380 labelled as T (toxic)).

381

382 2.4. Farmers' perception of CS performances

383

384 At the middle and end of the project, workshops with farmers who tested the diversified CS
385 allowed scientists and advisers to assess their perceptions of the performances obtained. As

386 expected, farmers' personal motivations influenced how they perceived a decrease in certain
387 performances or degrees of achieving objectives. This qualitative evaluation thus
388 supplemented the quantitative analysis based on the 15 indicators.

389

390 **3. Results**

391 3.1. Overall description of the co-designed diversified CS

392 During the co-design workshops, objectives common to all of the groups were defined. For all
393 of the CS designed, the first objective was to reduce the dependence on inputs, particularly
394 pesticides and nitrogen fertilisers, and to maintain or improve economic performances. The
395 objective for pesticide use was a decrease of 25% to 50%, the latter of which corresponds to
396 the goal of the French Ecophyto plan. In addition to these objectives, seven of the eight
397 farmers wanted to improve weed management.

398 Among other objectives, four farmers mentioned distributing work time better throughout the
399 year and, if possible, decreasing it. Two of these farmers wanted to develop new professional
400 activities: market gardening (Farm 3) or a second, non-farming activity (Farm 4). Several
401 farmers wanted to start or maintain reduced tillage (Farms 1, 5, 6, 7 and 8) or even go further
402 by engaging in conservation agriculture (Farms 2 and 4) by combining its three mechanisms:
403 crop diversification, maximizing the duration of soil cover with live plants or mulch, and
404 reducing or stopping tillage (Table 1). It was important to identify the farmers' individual
405 objectives, as they helped to understand their contrasting degrees of satisfaction with
406 performances after *ex-post* assessment.

407 As mentioned, one of the main mechanisms used during the co-design workshops to achieve
408 the objectives was to lengthen rotations and diversify crop production. This was used for all
409 eight co-designed CS, ranging from the introduction of one new crop (Farm 7, with an initial
410 rotation of three crops) to four new crops (Farm 1, with an initial monoculture CS). All CS
411 except for that on Farm 5 were also diversified by introducing multiservice cover crops (Table

412 1). Finally, the co-designed CS had a longer mean rotation duration than the initial CS ($4.9 \pm$
413 1.7 years vs. 1.9 ± 1.1 years, respectively). The initial CS grew crops from three botanical
414 families (80% from Poaceae (33% for maize alone), along with Asteraceae (sunflower) and
415 Brassicaceae (rapeseed)), whereas the diversified CS grew crops from five botanical families
416 (62% from Poaceae (only 15% for maize alone), along with 15% Fabaceae, introduced as
417 cash crops on five of the farms, and 15% Asteraceae). Fabaceae were also widely introduced
418 to diversified CS as cover crops, usually (14 of 18 cover crops) as faba bean and mainly in
419 pure stands (11 of 14 cover crops).

420 During the eight years of monitoring, the farmers applied the co-designed CS effectively,
421 except on Farm 5, which introduced carrot seed production, not considered initially but whose
422 economic potential prompted the farmer to introduce it into the initially defined rotation. Over
423 the eight years, crop yields of both initial and diversified CS were generally good (Table 1),
424 as they were slightly higher than the mean yields in the territories studied (Chambre
425 d'agriculture Occitanie, CERFRANCE, 2018). Nevertheless, on Farm 3, the soya bean yield
426 on one field in year 2 was extremely low (i.e. < 0.3 t DM/ha) due to flooding caused by a
427 dyke that failed after heavy rainfall. We considered that this event was not related to
428 performances of the diversified CS; consequently, when calculating indicators, its yield was
429 replaced by that obtained in the second season of soya beans (3.7 t DM/ha).

430

431 3.2. Performances of the diversified CS

432 3.2.1. Economic performances

433 Mean SNM of the initial and diversified CS were 589 ± 279 and 656 ± 261 €/ha/year,
434 respectively, with large differences among CS (Table 5). SNM decreased by 15-35% in four
435 of the eight diversified CS compared to that in the initial CS. Farmers' perceptions of these
436 changes varied. For example, despite a 10% decrease in SNM, the farmer of Farm 3

437 considered the economic performance of the diversified CS to be satisfactory (Table 5),
438 because it met his objective to decrease on-farm working time, which he had set during the
439 design workshops. According to the eight crop-price scenarios (Fig. 3), 27% of the diversified
440 CS generated a higher SNM (*ie* an increase > 10 % of the SNM of the initial CS), whereas
441 42% of the diversified CS generated a lower SNM (*ie* a decrease > 10 % of the SNM of the
442 initial CS). For some CS that were initially efficient economically (e.g. maize seed
443 monoculture on Farm 1, grain maize monoculture on Farm 3, rainfed CS with frequent
444 rapeseed crops in the rotation on Farm 7), no price scenario was favourable for the diversified
445 CS. On Farm 5, crop diversification, especially the introduction of a high value-added crop
446 under contract (carrot seed), always increased the SNM (by 20-80%, depending on the
447 scenario).

448 Weed pressure decreased in five of the eight diversified CS, but except on Farm 7, farmers
449 remained unsatisfied by it, perhaps reflecting over-representation of the ability of a longer
450 rotation to control weeds. On Farm 7, an abundance of herbicide-resistant ryegrass rendered
451 weed management difficult. Diversifying the initial CS of rainfed winter crops by introducing
452 sunflower and a cover crop improved management of the ryegrass greatly (weed pressure
453 indicator increased from 5.1 to 8.2) (Table 5), which the farmer considered satisfactory.
454 However, for three CS initially in maize monoculture, diversification did not improve weed
455 management. In addition, the weeds initially present were strongly related to maize
456 monoculture (e.g. *Echinochloa crus-galli*, *Polygonum persicaria*, *Polygonum aviculare*,
457 *Datura stramonium*), and crop diversification led to the appearance (or reappearance) of
458 species associated more with winter crops (e.g. significant increase in *Alopecurus*
459 *myosuroides*, *Vulpia bromoides* and *Lolium multiflorum*).

460 The economic efficiency of inputs ranged from 0.50-2.70 € for diversified CS and 0.10-2.60 €
461 for initial CS. Farmers' perception of these results varied, with some unsatisfied (Farm 1 and

462 7), but others satisfied (e.g. Farm 3) despite a relatively strong decrease (Table 5). Economic
463 efficiency of inputs increased most on Farms 2 and 4, which were initially maize
464 monocultures that adopted a similar strategy (although in different territories) by introducing
465 soya bean and a winter cereal and switching to conservation agriculture.
466 Food energy production of the CS varied from 63 000-190 000 MJ/ha, and CS with a high
467 percentage of maize (with high yields) produced the most. Thus, at best, diversified CS
468 maintained energy production (Farms 1, 6, 7) but usually decreased it slightly (\approx -10%, Farm
469 8) or strongly ($>$ -25%, Farms 2, 3, 4, 5).

470

471 3.2.2. Environmental performances

472 Pesticide use decreased greatly in four diversified CS compared to the initial CS, sometimes
473 by more than 50% (Table 5). TFI decreased most on Farm 2 (-64%), which was also managed
474 under conservation agriculture. This farm stopped all insecticide and fungicide applications,
475 maintaining only a few herbicide applications at low doses, notably glyphosate. This decrease
476 in pesticide use can be explained by (i) introducing low-TFI crops such as soya beans and (ii)
477 strong support from local advisers (involved in the project) when making decisions about
478 pesticide applications. On Farm 4, also under conservation agriculture, and Farm 5, under
479 reduced tillage, pesticide use increased significantly (+26 and +68%, respectively) (Table 5),
480 with the largest increase in herbicide use. On Farm 4, the increase was due mainly to
481 herbicide applications to kill cover crops, while on Farm 5, it was due to the carrot seed crop
482 on Farm 5 (which received 33% of the pesticide applications). Farm 3 decreased pesticide use
483 by nearly 20%, but the farmer was unsatisfied because his objective was a 50% decrease.
484 Comparing the TFI of the diversified CS to those of the regional CS (with the same crop
485 species), five CS had a relatively strong decrease in pesticide use (-27% for Farm 6 to -56%
486 for Farm 3) (Table 6). For Farm 5, the TFI of the diversified CS was much larger than that of

487 the initial CS (Table 5) but similar to that of the regional CS (Table 6). In contrast, for Farm
488 7, the TFI of the diversified was 10% larger than that of the initial CS, but 47% larger than
489 that of the regional CS, illustrating that the initial CS was not pesticide-efficient.

490 For all diversified CS except that on Farm 7, the I-PHY indicator improved (by 4-38%) and
491 had scores > 7, reflecting a low risk of transferring active ingredients into the environment.
492 For Farm 7, the lack of improvement is explained by the choice of active ingredients
493 considered to pose a risk to the air and ground water.

494 The duration of bare soil decreased in all diversified CS compared to that in the initial CS (by
495 8-40%), representing 5-12% and 6-14% of the year, respectively. This decrease was
496 associated with longer rotations and the introduction of cover crops into nearly all fallow
497 periods.

498 For the irrigated CS (Farms 1-5), the mean irrigation amount was $2\,121 \pm 884$ and $1\,034 \pm$
499 $387\text{ m}^3/\text{ha}/\text{year}$ in the initial CS and diversified CS, respectively. For most irrigated systems,
500 mainly in maize monoculture initially, diversification decreased irrigation amounts greatly (by
501 up to -72%). In parallel, energy consumption varied greatly among CS and was a mean of
502 30% lower in diversified CS than in initial CS ($4\,643 \pm 2\,947$ vs. $7\,747 \pm 5\,923\text{ MJ}/\text{ha}/\text{year}$,
503 respectively). For the irrigated CS, the decrease in irrigation explains most of that in energy
504 consumption (-10% to -40%) (Table 5). For Farm 4, the significant decrease (\approx -50%) in
505 energy consumption was also due to a strong decrease in nitrogen fertilisation (as illustrated
506 by the NI) and conversion to no-tillage for all crops. Total energy consumption and GHG
507 emissions were positively correlated ($r = 0.97$, $p < 0.01$). Mean GHG emissions decreased by
508 36% in the diversified CS compared to those in the initial CS, representing 352 ± 184 and 562
509 $\pm 327\text{ kg CO}_2\text{ eq.}/\text{ha}/\text{year}$, respectively (Table 5).

510

511 3.2.3. Social performances

512 Labour time varied among the farms and the CS, ranging from 3.4-48.0 and 2.9-20.0
513 h/ha/year in the initial CS and diversified CS, respectively. Crop diversification usually led to
514 a decrease in labour time or small increase in initially low times (Farms 6 and 8) (Table 5).
515 Labour time decreased most for irrigated maize monocultures, with a 57% decrease for Farm
516 1, whose initial CS, a maize seed monoculture, required the most labour time per ha (mean of
517 48 h). All farmers were satisfied by these decreases, as well as the change in the distribution
518 of their workload in the diversified CS, which decreased the peak of intensive labour periods
519 (Table 5; Fig. 4).

520 For the number of human-toxic pesticides used, the general decrease in pesticide use and
521 decisions to use less toxic active ingredients in most of the diversified CS decreased the
522 number of human-toxic pesticides used and thus farmers' exposure to them. The decrease was
523 particularly large on Farm 1, whose maize seed monoculture led to the use of several human-
524 toxic pesticides per year (mean of 10), mainly insecticides. For Farm 3, however, the
525 diversified CS led to the use of human-toxic products (insecticides) that were not present in
526 the initial grain maize monoculture.

527

528 **4. Discussion**

529 4.1. Crop diversification as a mechanism to improve environmental performances

530 The degree to which the environmental performance of a CS can be improved depends on the
531 former's initial level and thus on the reference value used (Viguiet *et al.*, 2021). Nevertheless,
532 in this eight-year study, conducted with farmers who were ready to question their technical
533 operations, diversifying CS with cash crops and/or service plants improved most of the
534 environmental indicators selected. These results, obtained under "real" farming conditions and

535 not on research fields, are particularly original and encouraging and clearly highlight the
536 value of diversifying CS to reduce their environmental impacts.

537 Concerning pesticide use, a decrease of 50%, as targeted by the Ecophyto plan, appears to be
538 realistic and achievable, including in CS without livestock, but decreases differed greatly
539 among farmers. These differences were related mainly to (i) farmers' technical skills, in
540 particular their knowledge about the new species introduced into the CS (Meynard *et al.*,
541 2018); (ii) their freedom to make decisions about pesticide applications, as contracts for crops
542 usually require systematic applications and are thus less compatible with reduction of
543 pesticide use; (iii) initial pest and weed pressures in the CS and (iv) the number of
544 agroecological mechanisms that can be used to manage pest and weed pressures (Gaba *et al.*,
545 2014; Deguine *et al.*, 2021); for example, a lack of tillage in conservation agriculture systems
546 greatly complicates weed management without herbicides, especially glyphosate (Adeux *et*
547 *al.*, 2017). The decrease in pesticide use observed was also related to regular monitoring of
548 pest and weed pressures in fields by the local advisers in the project (12-14 days/year/farm),
549 in direct relation to the regional network for monitoring pest and weed pressures (Cros *et al.*,
550 2021). Along with the decrease in the amounts of pesticide used, decreasing the risk of
551 transfer to the environment seems possible, either directly because of this decreased use or
552 indirectly through a more appropriate choice of active ingredients applied or their formulation
553 (Li *et al.*, 2021).

554 In southern France, adapting CS to climate change requires, in particular, minimizing reliance
555 on irrigation water. Diversifying crops with species that consume less water (than maize, in
556 particular) has positive effects, in addition to decreasing the sensitivity of farms to climate
557 hazards (Lin, 2011; Roesch-McNally *et al.*, 2018; Hufnagel *et al.*, 2020). In addition,
558 increasing the duration of soil cover by plants (or mulch) can decrease negative effects of
559 extreme rainfall events (Baumhardt and Jones, 2002; Palm *et al.*, 2014), whose frequency is

560 increasing significantly. Here again, co-design of CS, their diversification, especially by
561 service plants, and better organisation of crop rotations can increase the duration of soil cover,
562 as highlighted during the on-farm monitoring. However, these effects are not always
563 sufficient to increase soil carbon sequestration (estimated here by the OMI) (Viguiet *et al.*,
564 2021), or in particular to return the amount of OM to the soil observed in irrigated maize
565 monocultures, even without soil cover during the fallow period. Achieving objectives of the
566 “4 per 1000” initiative is thus a major challenge for CS, which relies in particular on
567 increasing the OM returned to the soil, especially by service plants (Poeplau and Don, 2015;
568 Rumpel *et al.*, 2020; Rodrigues *et al.*, 2021). In this study, most of the cover crops planted
569 were faba bean, mostly as a pure crop, as it is inexpensive and easy to plant and establish, but
570 it does not fit well into all possible periods between two cash crops. To optimise carbon
571 sequestration, the species and varieties of cover crops and the composition of mixtures must
572 be chosen as a function of the CS and soil and climate conditions (Poeplau and Don, 2015;
573 Couëdel *et al.*, 2018; Bybee-Finley *et al.*, 2022).

574 In this study, crop diversification decreased energy consumption and GHG emissions, which
575 are strongly correlated, by nearly 40%; thus, CS diversification is an effective mechanism for
576 decreasing them, as highlighted in other studies (Pellerin *et al.*, 2013; Viguiet *et al.*, 2021).
577 The main items that consume energy are fertilisers, fuel and, if present, irrigation (Colnenne-
578 David and Dore, 2015; Pellerin *et al.*, 2017). Nevertheless, the CS studied appeared less
579 effective at mitigating effects of climate change through carbon sequestration, as only the CS
580 of Farm 4, under conservation agriculture, showed an increase in OMI. However, this
581 indicator remains relatively inaccurate and, as highlighted by other studies, should be
582 combined with measurements of soil carbon content after several rotations (Islam and Weil,
583 2000; Scopel *et al.*, 2013; Viguiet *et al.*, 2021). As mentioned, cover crops are important for
584 increasing soil carbon content in cereal CS significantly (Poeplau and Don, 2015). In south-

585 western France, one challenge is to successfully exploit the summer, during which potential
586 photosynthetic activity is highest but water to produce OM that will be returned to the soil is
587 scarce. By redesigning diversified CS whose cash crops use less water, some of the water
588 saved could be used to produce ecosystem services besides provisioning services, particularly
589 climate-regulation services; however, doing so requires a real paradigm shift in crop
590 production and potentially providing inputs (such as water) for supporting or regulating
591 ecosystem services, not only provisioning services.

592

593 4.2. Crop diversification as a mechanism to improve economic and social performances

594 The economic performance of the CS was assessed using four indicators, particularly the
595 SNM, which includes mechanisation costs. The eight-year monitoring of the eight farms
596 shows that crop diversification can increase the SNM significantly if the decrease in input
597 costs is combined with a strict control of mechanisation costs. Another important conclusion
598 is that crop diversification and input reduction do not always increase economic profitability,
599 despite good crop productivity. They can even lead, as for four of the farms in this study, to
600 lower economic performance, which is consistent with the economic performance of low-
601 input CS tested in experimental fields (Bonnet *et al.*, 2021; Viguier *et al.*, 2021). In initial CS
602 with high added value, such as the maize-seed monoculture studied, diversification always
603 decreased economic profitability. The farmers were satisfied by this improvement in
604 environmental performance, but it was not enough to compensate for the loss of more than
605 30% of SNM per ha. The reorientation of Common Agricultural Policy subsidies towards an
606 agroecological transition of systems is an incentive (Solazzo *et al.*, 2016; Scown *et al.*, 2020),
607 but it remains insufficient to make deep changes to these CS, which are oriented towards
608 economic optimisation, without any real consideration for the negative externalities
609 generated. In contrast, for irrigated grain-maize monocultures, introducing soya bean into the

610 rotation (as in four farms in this study) is a powerful mechanism for increasing SNM (Jouffret
611 *et al.*, 2015). Soya beans are relatively simple to grow, with few pest pressures, and are
612 suitable for low-input management (25% of soya bean area in France is in organic farming).
613 For two of the farms studied, initially irrigated maize monocultures, diversifying the CS
614 followed a similar strategy of introducing soya bean and a straw cereal. Nearly the same
615 rotation, tested at an experimental station to diversify a maize monoculture, showed
616 satisfactory economic performance and a large decrease in environmental impacts,
617 particularly pesticide transfers (Giuliano *et al.*, 2016; Giuliano *et al.*, 2021).
618 Finally, another positive effect of diversifying CS was better distribution of labour time
619 throughout the year, especially for CS that were initially specialised (e.g. monocultures). This
620 result must be tempered, however, because introduction of new crops into the CS was
621 accompanied by regular technical monitoring by advisers in the project, rather than by the
622 farmers themselves.

623

624 4.3. Limits and perspectives of the on-farm study

625 The multi-criteria analysis highlights that, to date, one or more CS cannot be identified that
626 simultaneously satisfy all the sustainability objectives targeted and that trade-offs must
627 therefore be accepted, for example according to the priorities of a territory. This observation
628 is similar to that made by other studies based on long-term experiments on CS at experimental
629 stations or based on monitoring of farmers' fields (Giuliano *et al.*, 2016; Angevin *et al.*, 2017;
630 Colnenne-David *et al.*, 2017; Viguier *et al.*, 2021). Furthermore, the diversity of stakeholders
631 in the co-design workshops of this study was probably too low, which did not allow for a
632 wide range of diversification strategies to be explored. Ultimately, despite strong
633 diversification of the initial CS, participants chose mainly crops that were already common in
634 the territories concerned, probably because organised value chains with a guaranteed a market

635 already existed, but also perhaps due to farmers' and advisers' fears and lack of technical
636 knowledge about less common crops (Meynard *et al.*, 2018). A recommendation for a future
637 study would therefore be to broaden the panel of stakeholders involved in co-design
638 workshops to (i) collectively choose and prioritise diversification objectives and strategies
639 that support the agroecological transition of territories and (ii) allow for a wide range of
640 possibilities that could, in some cases, favour the emergence of new value chains.

641 On this point, contracting within certain value chains is often proposed as a mechanism for
642 economic stability and as a way to encourage diversification of production (Huh and Lall,
643 2013; de Roest *et al.*, 2018). However, the study shows that some contracts, particularly those
644 for seed production (e.g. maize and carrots), restrict technical operations and input levels.
645 This limits the ability to implement alternative strategies, particularly pesticide applications,
646 and farmers lose some of their decision-making capacity.

647 Finally, as mentioned, the results of this on-farm study are encouraging and suggest effective
648 strategies for decreasing environmental impacts of farming activities. Although performing
649 research directly on farms is increasingly encouraged to promote interactions and facilitate
650 transitions (Lacoste *et al.*, 2021), few on-farm studies that evaluate the performance of
651 innovative CS have been published, and in this respect the results of this study are original. In
652 this study, supporting the farms required a large amount of time of the agricultural advisers,
653 up to 15 days/year/farm. One of the initially unidentified benefits of this investment was that
654 it increased the local advisers' skill with systemic agronomy approaches, which they were
655 able to use later, particularly with the farm networks of the national Ecophyto plan. However,
656 this degree of human investment suggests that it will be difficult to disseminate equivalent
657 approaches to a larger scale if the same level of support is provided. Despite this large
658 investment in monitoring and accompanying farmers, it was not possible to have all crops of a
659 CS present on each farm each year, which is recommended to identify effects of annual

660 weather conditions on crop performance (Bonnet *et al.*, 2021). Moreover, this kind of
661 approach cannot specifically assess conflicts between technical operations, which remain
662 manageable when only two fields are involved but could become problematic if the entire
663 farm is involved. Nevertheless, to partially overcome this limitation, the results were
664 analysed, discussed and compared to those of other farmers in each territory at each annual
665 review.

666

667 **5. Conclusion**

668 This study summarised eight years of monitoring and data collection from initial and
669 diversified CS on eight farms in south-western France. The initial hypothesis was that crop
670 diversification was an important mechanism for improving the overall sustainability of CS.
671 The multi-criteria analysis performed, using a variety of indicators, indicates that crop
672 diversification improves the environmental sustainability of CS and some aspects of the social
673 dimension. Several farms were able to meet objectives for reducing inputs, particularly
674 pesticides and nitrogen fertilisers. Diversified CS were generally more climate-friendly as
675 they consumed less energy and emitted less GHGs. In irrigated CS, which were often
676 monocultures, diversification also decreased the amount of irrigation water greatly. Compared
677 to the initial CS, the diversification strategies used reduced farmers' workload and distributed
678 it better throughout the year. However, the economic performance of the diversified CS
679 varied, with no guarantee of increasing or even maintaining farmers' income. Promoting the
680 agroecological transition of CS and, more broadly, of food systems, thus implies providing
681 economic support to “virtuous” systems that help restore ecosystem functions and services.

682

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691

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Fig.1. Location of the six territories and eight farms of the study in the Occitanie Region (south-western France)

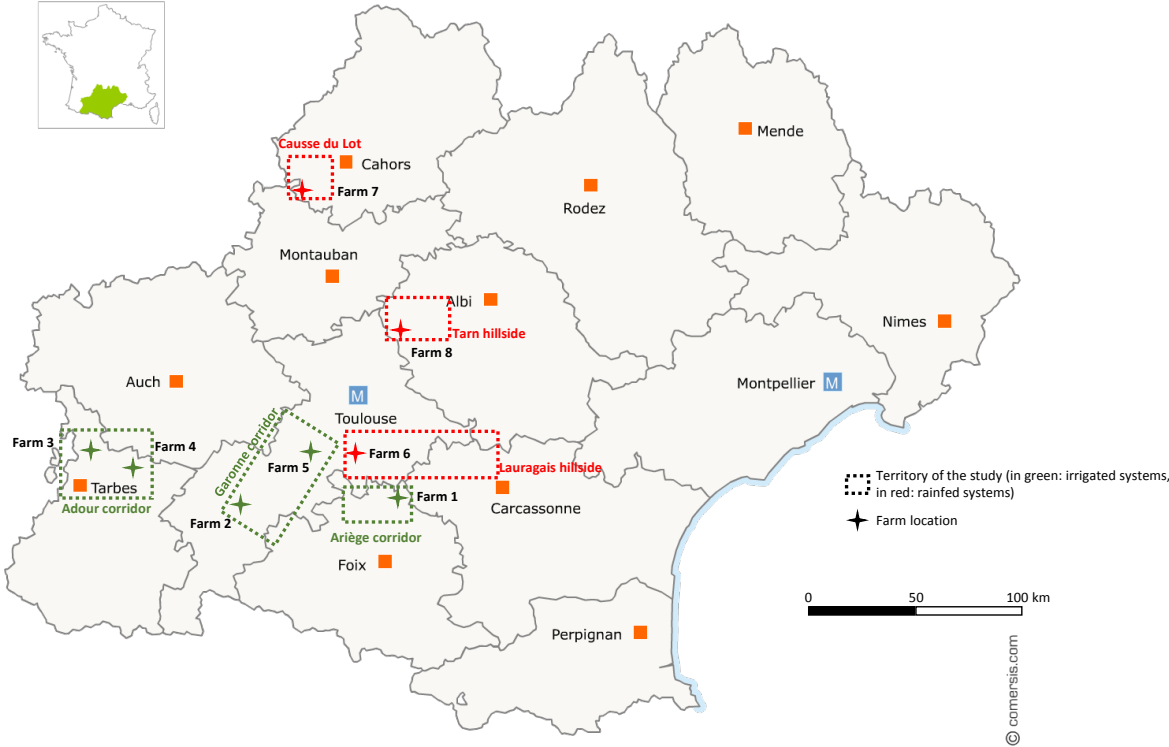


Fig. 2. Description of the participatory approach used to co-design and experiment with cropping systems (CS) in a farm network in south-western France.

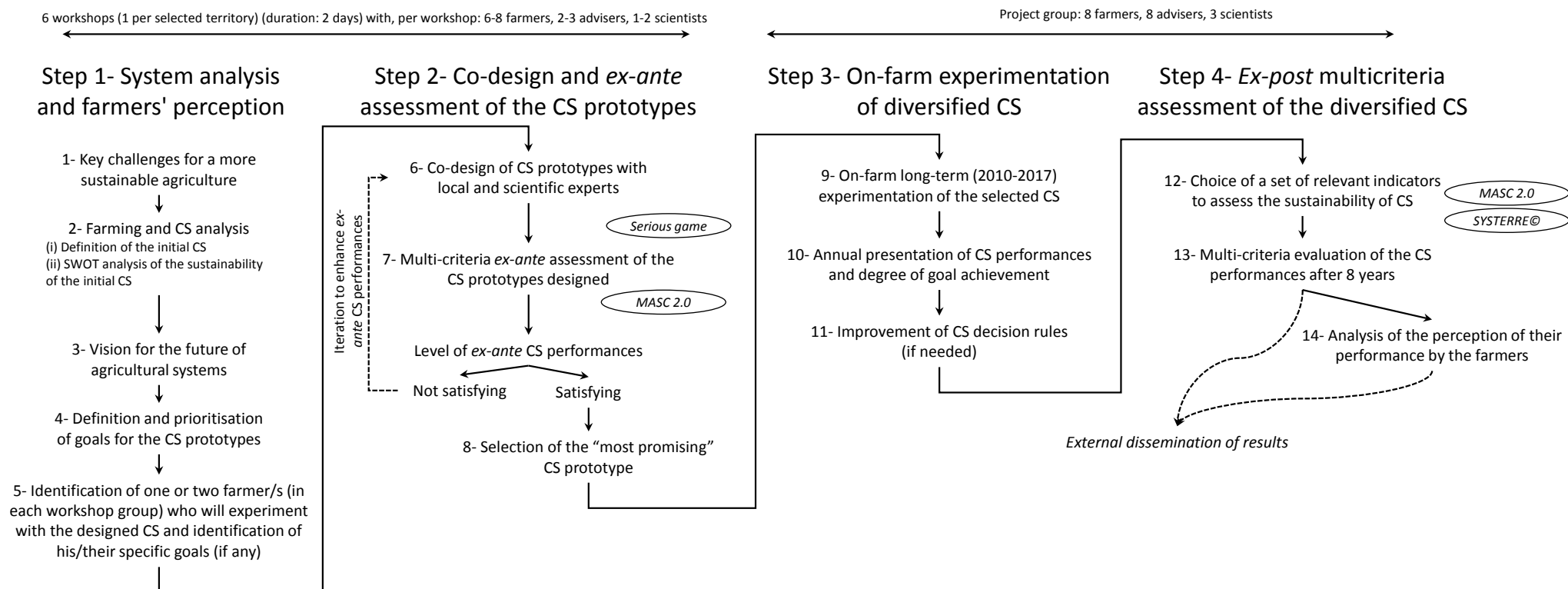


Fig. 3. Semi-net margin (SNM, €/ha/year) of the initial and diversified cropping systems (CS) for the eight scenarios of crop prices (see Table 3 for details).

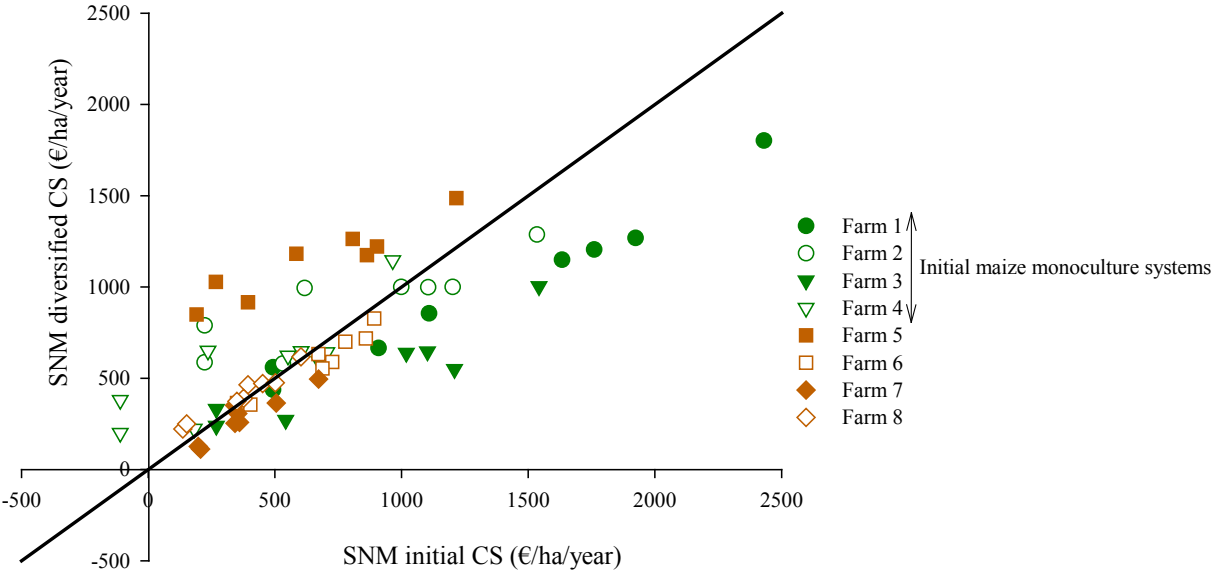


Fig. 4. Distribution of labour time throughout the year for the initial and diversified cropping systems (CS).

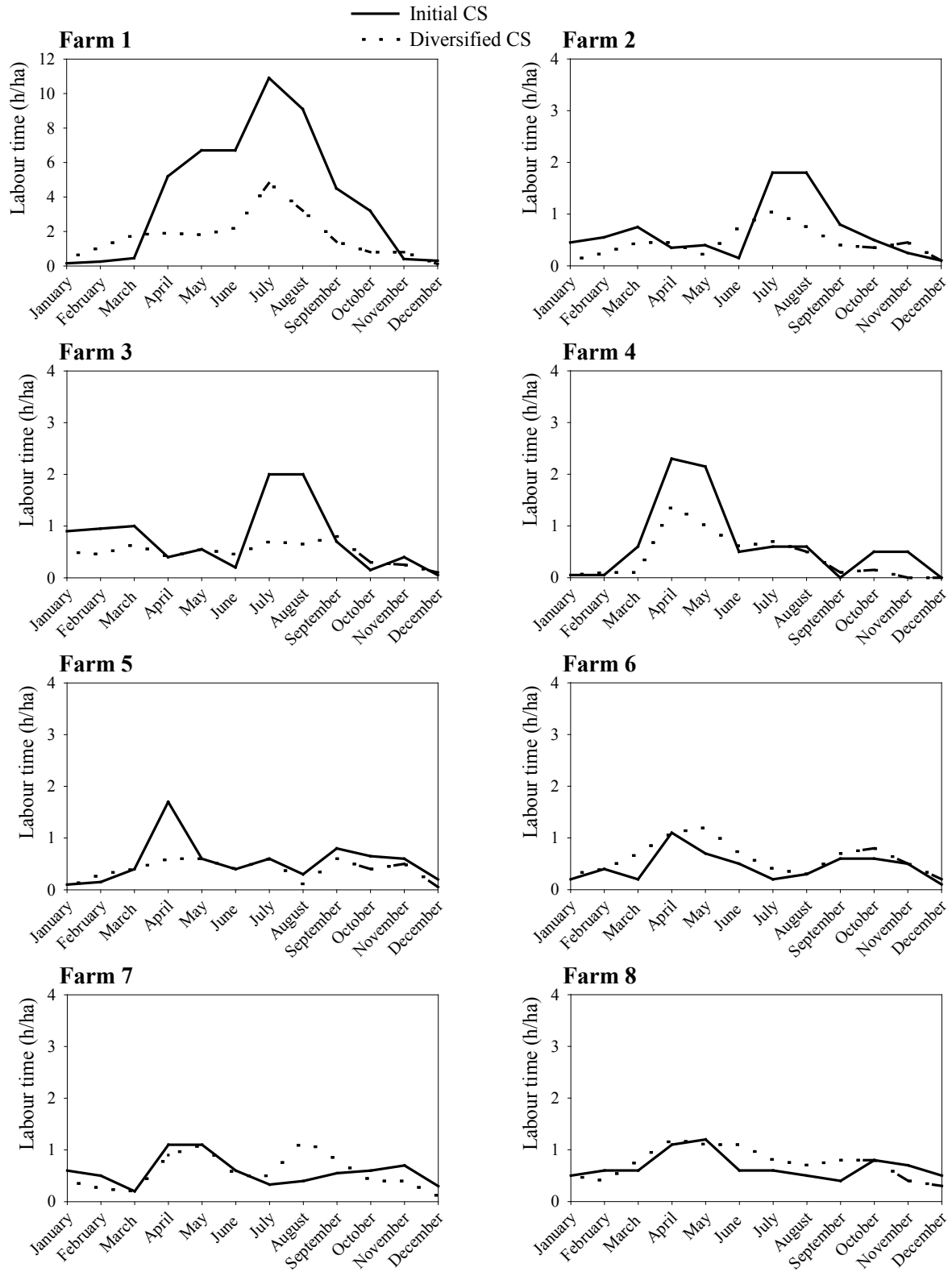


Table 1. Main characteristics of the eight farms in the study and main features of the initial and diversified cropping systems (CS).

B: barley; CS: carrot seed; DW: durum wheat; FB: faba bean; M: grain maize; MS: maize seed; RS: rapeseed; SB: soya bean; SG: sorghum; SF: sunflower; SW: soft wheat. The species in brackets and in italics correspond to cover crops during fallow period. Values indicate mean yields (t dry matter/ha).

Site	Main soil type (soil type)	Initial CS				Diversified CS															
Farm 1	Silt – Clay silt (Gleyic Luvisol)	MS monoculture			Conventional tillage (mouldboard plough, 25 cm deep)	2010-2014-2016	(FB)	2011-2015-2017	(Oat)	2012-2016	2010-2012-2016	(Vetch+ oat)	2012-2014	2012-2014	(FB)	Irrigated	Reduced tillage (≈ 10 cm deep)				
		3.9				MS*		MS		SF	SW		SB	SW		2.9	3.1	2.5	5.9	3.2	5.5
Farm 2	Silty with coarse elements, hydromorphic (Luvisol)	M monoculture			Reduced tillage (≈ 10 cm deep)	2010-2012-2013-2015-2016	2009-2010-2012-2013-2015-2016	(FB)	2011-2012-2014-2015-2017	(FB)						Irrigated	Conservation agriculture (no-tillage)				
		11.8				M	SW	SB								11.4	5.8	3.3			
Farm 3	Silt with coarse elements (Luvisol)	M monoculture			Conventional tillage (mouldboard plough, 25 cm deep)	2010-2014-2015	(FB+ phacelia)	2011-2015-2016	2010-2011-2015-2016	(FB+ phacelia)	2012-2013-2017	2012-2013	(FB+ phacelia)			Irrigated	Conventional tillage (mouldboard plough, 25 cm deep)				
		11.7				M		SF	SW		SB	SW				11.6	2.6	7.0	3.7	6.8	
Farm 4	Silt with coarse elements (Luvisol)	M monoculture			Reduced tillage (≈ 10 cm deep)	2010-2012-2013-2015-2016	(FB)	2011-2013-2014-2016-2017	2010-2011-2013-2014-2016	(FB)						Irrigated	Conservation agriculture (no-tillage)				
		9.8				M		SB	SW							10.2	3.8	7.1			
Farm 5	Silt with coarse elements, hydromorphic (Luvisol)	M	SW		Reduced tillage (≈ 10 cm deep)	2010-2014-2016	2010-2014-2016	2011-2015	2010-2012-2016	2011-2013	2012-2014					Irrigated	Reduced tillage (≈ 15 cm deep)				
		12.4	7.0			M	SW	CS	SW	RS	SW					11.2	7.1	0.4	6.9	3.2	6.4
Farm 6	Calcareous clay on hillsides (Cambic Calcisol)	DW	SF		Reduced tillage (≈ 15 cm deep)	2010-2012-2014-2016	(FB)	2012-2014-2016	2010-2012-2014-2016	(FB)	2012-2014-2016					Rainfed	Reduced tillage (≈ 15 cm deep)				
		6.2	2.7			DW		SF	SW		SG					5.7	2.5	5.7			5.2
Farm 7	Calcareous clay on hillsides (Calcisol)	RS	SW	B	Reduced tillage (≈ 15 cm deep)	2010-2011-2014-2015	2011-2012-2015-2016	(FB)	2010-2013-2014-2017	2010-2013-2014						Rainfed	Reduced tillage (≈ 15 cm deep)				
		3.2	4.7	4.5		RS	SW		SF	B						3.3	4.8	2.4	4.8		
Farm 8	Calcareous clay on hillsides (Cambic Calcisol)	DW	SF	SW	SF	Reduced tillage (≈ 15 cm deep)	2009-2013	(FB)	2011-2015	(FB)	2012-2016	2012-2016	(Vetch+ oat)	2010-2014	2010-2014	2011-2015	(Vetch+ oat)	2013-2017	Rainfed	Reduced tillage (≈ 15 cm deep)	
		5.3	3.2	5.5	2.0		DW		SG		SB	SW		SF	FB	SW		SF			1.9

*in bold: crops cultivated in year 1 of the project (2010) on two fields on each farm. The years in blue and green correspond to the rotations on the two fields that received the diversified CS.

Table 2. Indicators selected to assess cropping system performances.

Indicator number	Sustainability dimension	Criterion	Indicator (unit)
1	Economic	Profitability	Mean semi-net margin (€/ha/year)
2	Economic	Weed management	Indicator of weed pressure in the field
3	Economic	Dependence on external inputs	Economic efficiency of inputs
4	Economic	Productivity	Food energy production (MJ/ha/year)
5	Environmental	Water quality (pesticide)	Treatment Frequency Index
6	Environmental	Water quality (pesticide)	I-PHY
7	Environmental	Water quality (nitrate)	Nitrogen indicator (NI/year)
8	Environmental	Water quantity	Irrigation amount (m ³ /ha/year)
9	Environmental	Soil quality	Organic matter indicator
10	Environmental	Soil quality	Duration of bare soil (% of the period of nitrate-leaching and erosion risk)
11	Environmental	Fossil energy	Energy consumption (MJ/ha/year)
12	Environmental	Climate change mitigation	Greenhouse gas emissions (kg CO ₂ eq./ha/year)
13	Social	Farmer's quality of life	Labour time (h/ha/year)
14	Social	Farmer's quality of life	Workload distribution (h/ha/month)
15	Social	Famer and public health	Number of human-toxic pesticide applications

Table 3. Crop prices in the scenarios used to test the robustness of the semi-net margin of the initial and diversified cropping systems. The prices were collected during the 2007-2014 period (Massot et al., 2016).

Crop	Prices (€/t)							
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
Barley	159	157	183	160	157	155	107	94
Carrot seed	3500	3500	3500	3500	3500	3500	3500	3500
Durum wheat	207	225	211	238	233	227	150	162
Faba bean	225	148	188	252	263	310	245	156
Maize	131	167	204	160	176	97	120	97
Maize seed	999	1274	1556	1220	1342	740	915	740
Rapeseed	359	264	444	389	345	342	232	246
Soya bean	419	298	483	319	305	328	187	262
Sorghum	133	159	190	141	99	85	104	88
Sunflower	313	349	452	378	299	285	209	221
Soft wheat	171	166	196	166	149	147	117	107

Table 4. Score of the indicator of weed pressure as a function of weed abundance (plants.m⁻²) and phenological stage.

Class	Abundance	Phenological stage				
		A: Cotyledons	B: Young plant	C: Adult plant	D: Flowering	E: Seeds disseminated
0	< 0.1	10	10	9	8	7
1	0.1-1	10	10	9	7	7
2	1-3	10	10	8	7	5
3	4-20	10	9	8	6	3
4	21-50	9	9	7	5	1
5	51-500	9	8	6	4	1
6	> 500	9	8	5	2	1

Table 5. Indicators of economic, environmental and social performances of the initial and diversified cropping systems (CS) implemented on the eight farms in the study. Colours indicate the degree of farmer satisfaction according to his/her specific objectives: green: highly satisfied; orange: poorly satisfied; red: not satisfied.

Indicator	Farm 1			Farm 2			Farm 3			Farm 4			Farm 5			Farm 6			Farm 7			Farm 8			
	Initial CS	Diversified CS	Δ (%)	Initial CS	Diversified CS	Δ (%)	Initial CS	Diversified CS	Δ (%)	Initial CS	Diversified CS	Δ (%)	Initial CS	Diversified CS	Δ (%)	Initial CS	Diversified CS	Δ (%)	Initial CS	Diversified CS	Δ (%)	Initial CS	Diversified CS	Δ (%)	
ECONOMY	Mean semi-net margin (€/ha/year)	1 130	740	-34.5	628	918	+46.2	632	570	-9.8	218	632	+190	641	1105	+72.4	714	578	-19.0	365	308	-15.6	381	400	+5.0
	Weed pressure indicator	7.3	6.9	-5.5	8.1	7.2	-11.4	7.2	6.5	-9.7	6.1	6.7	+9.3	5.7	7.2	+27.1	6.3	7.2	+14.3	5.1	8.2	+60.8	6.3	7.2	+13.7
	Economic efficiency of inputs	2.6	1.6	-38.5	0.7	2.2	+214	2.6	1.8	-30.8	0.1	0.5	+400	2.3	2.7	+17.4	2.0	2.1	+5.0	1.0	0.8	-20.0	1.3	1.6	+23.1
	Food energy production (MJ/ha/year)	63 518	68 345	+7.6	190 566	113 841	-40.3	188 989	109 839	-41.9	159 300	118 606	-25.5	156 326	98 671	-36.9	84 576	83 072	-1.8	75 219	74 896	-0.4	70 388	63 342	-10.0
ENVIRONMENTAL	Treatment Frequency Index	3.7	2.2	-40.5	4.7	1.7	-63.8	1.6	1.3	-18.8	2.7	3.4	+25.9	2.5	4.2	+68.0	4.7	2.4	-48.9	4.9	5.4	+10.2	3.4	1.9	-44.1
	I-PHY	6.4	7.1	+10.9	6.6	7.5	+13.6	5.9	7.0	+18.6	6.9	7.5	+8.7	6.2	7.8	+25.8	5.2	7.2	+38.5	6.0	4.6	-23.3	8.3	8.6	+3.6
	Nitrogen indicator	5.8	8.3	+43.1	9.2	9.1	-1.1	7.9	8.1	+2.5	3.1	7.9	+155	8.4	9.6	+14.3	5.3	7.0	+32.1	6.8	8.5	+25.0	5.8	8.6	+48.3
	Irrigation amount (m ³ /ha/year)	3250	1580	-51.4	2670	750	-71.9	2080	1070	-48.6	980	1180	+20.4	1625	590	-63.7	-	-	-	-	-	-	-	-	-
ENVIRONMENTAL	Organic matter indicator	6.8	5.7	-16.2	7.0	6.2	-11.4	7.4	6.4	-13.5	7.1	8.5	+19.7	6.9	6.7	-2.9	8.1	8.3	+2.5	4.0	4.3	+7.5	5.1	4.9	-3.9
	Duration of bare soil period (%/year)	12	9	-28.9	10	6	-39.5	12	10	-9.5	10	6	-37.1	10	10	-7.9	14	12	-19.2	6	5	-13.0	14	12	-12.0
	Energy consumption (MJ/ha/year)	9 438	4 948	-47.6	14 439	8 813	-39.0	8 050	4 762	-40.8	17 706	9 040	-48.9	5 652	3 245	-42.6	2 250	2 300	+2.2	3 427	3 197	-6.7	1 013	843	-16.8
SOCIAL	Greenhouse gas emissions (kg CO ₂ eq./ha/year)	617	338	-45.2	937	640	-31.8	499	346	-30.6	1 146	603	-47.4	415	225	-45.8	322	252	-22.0	383	310	-19.0	180	102	-43.6
	Labour time (h/ha/year)	47.9	20.3	-57.6	7.9	5.3	-32.9	9.3	5.8	-37.6	7.9	4.7	-40.1	6.5	4.6	-29.2	5.4	7.3	+35.2	7.0	6.8	-3.3	8.1	8.9	+9.9
SOCIAL	Number of human-toxic pesticide applications	10	2.1	-	1	1	-	0	1.5	-	2	1	-	1.5	0.75	-	3	1.8	-	1	1	-	2	0.3	-

Table 6. Treatment Frequency Index (TFI) of the diversified cropping systems (CS) and the regional CS based on regional TFI values of each crop in the CS.

Farm number	TFI of the diversified CS	TFI of the regional CS	Δ (%)
Farm 1	2.2	3.7	-40.7
Farm 2	1.7	2.9	-40.8
Farm 3	1.3	3.0	-56.4
Farm 4	3.4	2.9	18.4
Farm 5	4.2	4.3	-1.6
Farm 6	2.4	3.3	-26.9
Farm 7	5.4	3.7	46.6
Farm 8	1.9	3.2	-41.4

