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1 **Conservation agriculture as a promising trade-off between conventional and organic agriculture in**
2 **bundling ecosystem services**

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17 **Keywords**

18 Ecosystem service bundles; Conservation Agriculture; Organic Agriculture

19

20 **Abstract**

21 Agriculture is a human activity that receives the most direct benefits from ecosystem services (ES)
22 while it is one of the most influential on their sustainability and is also directly impacted by global
23 changes. One main challenge for future agroecological systems is thus to encourage the co-
24 occurrence of multiple services both *to* agriculture and *from* agriculture. In this article, we
25 questioned through a large-scale study, the ability of conservation agriculture to support not only
26 supporting services related to soils, as it was originally designed for, but also overall biotic potential
27 for multiservice agriculture. We assessed the expression levels of ES from and to agroecosystems
28 (input and output services respectively) within 5 crop management systems, comparing different
29 forms of conservation, organic and conventional agricultures. Fifty winter wheat and fava bean fields
30 in southwestern France were monitored for 17 ES: seven input services (either supporting or
31 regulating) and ten output services (either provisioning or out of direct agricultural income).
32 Observed co-variations and antagonisms between services occurred only for input services and were
33 related to services based on mobile agents or soil properties. Regarding pest regulations, opposite
34 responses were observed between aphids and bruchids, attributed to contrasted responses of the
35 pests to habitat diversity and especially notable in fields under conservation agriculture. As to soil
36 quality, conservation agriculture exhibited significantly higher levels of soil structure stability than
37 conventional and organic systems but slightly lower water infiltration. For output services, our results
38 showed that crop production was not jeopardized by conservation agriculture practices with, for
39 instance, no significant differences in levels of winter wheat yields between systems based on direct
40 seeding or plowing. Organic agriculture however improved crop health regarding diseases but
41 significantly decreased yields. However, high variability in level of expression of output services in
42 conservation agriculture was observed, with both highest and lowest rated fields observed under
43 direct seeding management for provisioning services. These variations can be attributed mainly to
44 system immaturity regarding both ecological processes and farmers' expertise. Finally, one

45 unexpected outcome of the study was that negative impacts of intensive agricultural practices
46 appeared to be mitigated by elements of production situation such as presence of livestock and
47 clayey soils. Overall, the study provides a detailed illustration of the potential for conservation
48 agriculture to address the apparent antagonism between productivity and environmental
49 performances.

50 **1. Introduction**

51 Agriculture implies risks and costs to ecosystems and the services they support. Modern agriculture
52 is defined by high crop and labor productivities that rely on systematic chemical inputs and ever-
53 improving machine technology (Hazell and Wood, 2008; Tilman et al., 2002). Agriculture that relies
54 solely on large amounts of industrial inputs, *in simplified landscapes*, to meet greater land and
55 human productivities threatens water quality and availability (Tilman et al., 2002), increases
56 greenhouse gas emissions (Martin and Willaume, 2016) and disturbs natural processes such as pest
57 control by natural enemies or pollination (Dainese et al., 2019; Deguines et al., 2014; Hendrickx et al.,
58 2007). Increasing food production remains a challenge due to population growth and the resulting
59 demand for food. Current food production is even more challenging in the context of increasingly
60 limited resources such as energy, phosphate, land and water (FAO, 2011), and future farming
61 systems must consider decreasing negative externalities to the environment as a priority to ensure
62 their sustainability (Garnett et al., 2013). Future production systems will encounter the challenging
63 task of evolving to systems that ensure productivity, decrease dependence on chemical inputs and
64 non-renewable resources, as well as maintain or improve the supply of ecosystem services (ES)
65 (Wezel et al., 2015). Integrating biological diversity and ecological principles in agronomy and
66 applying them to agriculture can achieve this agroecological intensification (Bommarco et al., 2013;
67 Wezel et al., 2015) and conserve ecosystem functions. Innovative agriculture primarily includes
68 ecological, spatial and temporal diversification as the core of crop management systems (Duru et al.,
69 2015; Kremen and Miles, 2012). Agroecological practices include increasing soil organic matter to

70 improve soil biota and its related nutrient cycling and natural regulation of diseases (Hobbs et al.,
71 2008; Lemanceau et al., 2015; Song et al., 2015) as well as soil structure and structural stability
72 improvement (Bronick and Lal, 2005; Kay et al., 1988), using legume crops to reduce chemical
73 fertilizer applications (Drinkwater and Snapp, 2007). They also include diversifying rotations and
74 conserving semi-natural habitats (SNH) to increase the diversity of pollinators and natural enemies of
75 pests (Crowder and Jabbour, 2014; Kremen et al., 2002; Landis et al., 2005; Rusch et al., 2016) to
76 encourage natural control of pests, diseases and weeds (Crowder et al., 2010; Veres et al., 2013;
77 Witmer et al., 2003).

78 A systemic approach to evaluate performances is required to assess the sustainability of these
79 agroecological cropping systems. This involves considering system multi-functionality that includes
80 economic, ecological and social aspects (Craheix et al., 2016; Garbach et al., 2016). Moreover, and
81 from a broader perspective, the study of ES “bundles” (*i.e.* groups) in agroecosystems under different
82 management practices and environmental conditions will help to assess the so-called “adaptation
83 services”, as defined by Lavorel et al. (2015). In their case, *i.e.* for the adaptation to climate change,
84 they defined them as “*the benefits to people from increased social ability to respond to change,*
85 *provided by the capacity of ecosystems to moderate and adapt to [...] change and variability*”.

86 Furthermore, the economic value of non-marketed ES, improved by agroecological practices, could
87 exceeds farm subsidy payments in Europe (Porter et al., 2009) or current global costs of pesticides
88 and fertilizer inputs (Sandhu et al., 2015). Thus, evaluating farming system through a multiservice
89 approach rather than focusing mainly on productivity, allow a more holistic valuation of farming
90 sustainability by including these non-marketed ES (Ghaley et al., 2014).

91 Among farming systems relying on agroecological practices, organic agriculture was one of the first
92 to address these sustainability challenges. Many studies have assessed organic agriculture and
93 demonstrated its ability to meet the environmental and productive aspects of the challenge (e.g.
94 Badgley et al., 2007; Reganold and Wachter, 2016; Rigby and Caceres, 2001; Sandhu et al., 2015,

95 2010). In particular, organic farming systems exhibit a much more balanced ES provisioning, even if
96 lightly less productive, than their intensive conventional counterpart (Reganold and Wachter, 2016),
97 crop yields being negatively correlated to many ES in agroecosystems (Röös et al., 2018; Syswerda
98 and Robertson, 2014). Aside from organic farming, another model of agroecological system that has
99 recently received more attention from stakeholders, is conservation agriculture (Farooq and
100 Siddique, 2015). It is based on three fundamental principles: reducing or eliminating tillage (hereafter
101 called “reduced tillage” and “direct seeding” respectively) to decrease soil disturbance ; lengthening
102 and diversifying crop rotations, often by including legume crops; and using crop residues and/or a
103 cover crop for permanent ground cover (Farooq and Siddique, 2015; FAO, 2008). Conservation
104 agriculture is receiving growing interest and support from the scientific community around the world
105 (Hobbs et al., 2008; Pisante et al., 2015; Pittelkow et al., 2015b), especially for its potential to
106 conserve or improve ES (Palm et al., 2014). Its practical adoption is expanding in South America,
107 North America and Australia, among other places (Kassam et al., 2015), but remains controversial
108 (Giller et al., 2009) and is limited in Africa and Western Europe (Kassam et al., 2015; Lahmar, 2010).
109 Unlike for organic farming, conservation agriculture received very few interest regarding its potential
110 to exhibit trade-offs or synergies among ES (Garbach et al., 2016; Palm et al., 2014; Sanderson et al.,
111 2013). More precisely, quantification of ES bundles from simultaneous field experiments, *i.e.* through
112 ‘bottom-up’ approach (Sandhu et al., 2013), as it is the case for organic farming (Sandhu et al., 2008),
113 are lacking for conservation agriculture. ‘Bottom-up’ approach of bundles of ES provides a great
114 opportunity to reinforce our knowledge about the state of ES in agroecosystems and their changes in
115 response to human management and field measurements from case studies are necessary to
116 validate current or future models.

117 The objective of the present study was thus to assess the bundling of ES within agroecological
118 farming systems, taking two contrasted agroecological approach, organic and conservation, and their
119 combination, compared to conventional farming. Seventeen services, either agricultural or

120 ecosystem, were studied. Following Le Roux et al. (2008) and Zhang et al. (2007) operational
121 classification of ES for agroecosystems, we differentiate in this paper input services (*i.e.* services to
122 agriculture) from output services (*i.e.* services from agriculture). These two categories are themselves
123 subdivided into regulating and supporting services for the former and into provisioning services and
124 services out of direct agricultural income (thereafter referred to as “non-marketed services”) for the
125 latter (see table 1 for correspondence to Common International Classification of Ecosystem Services
126 (CICES) v5.1; Haines-Young and Potschin, 2018). We studied four regulating services (pollination,
127 specific parasitism, specific and generalist predation of crop pests) and three supporting services
128 (structural stability of soil aggregates, soil water infiltration, root development); seven provisioning
129 services (yields – *i.e.* primary production – and yields stability in the face of diseases and three pests
130 for a cereal and a legume crop); and three non-marketed services (biodiversity conservation, habitat
131 conservation, greenhouse gas recycling).

132 We investigated the influence of de-intensification of practices and input use on multiple ES by
133 comparing 5 crop management systems (CM, including conventional, organic and conservation
134 agriculture practices) while taking into account their production situation (PS, *i.e.* landscape, soil
135 characteristics, types of production in the farm). To do so, we studied response profiles of ES for each
136 combination of CM and PS to address the following issues:

- 137 - How the four categories of ES are evolving in alternative CM systems compared to more
138 conventional systems?
- 139 - What are the occurring combinations and antagonisms of ES and their association to CM
140 systems?
- 141 - Do these combinations and their associations to CM systems vary according to production
142 situations?
- 143 - Beyond the CM system, does taking into account individual agricultural practices better explain
144 the expression level of ES?

145 **2. Materials and methods**

146 **2.1. Study site**

147 The study was conducted in crop fields under several crop management regimes (conventional,
148 organic and conservation agriculture) in southwestern France from September 2014 to April 2016.
149 Fifty winter wheat fields (1ha), 40 of which were paired with a fava bean field (0.5ha), were
150 distributed along a 200 km line intersecting Toulouse (Figure 1, see Chabert and Sarthou, 2017, for
151 further details). Except for crop cultivars and seed origin that was the same for all fields, all other
152 cropping practices were left to the farmer to decide and were monitored by surveys. To standardize
153 disease measurements, half of each winter wheat field did not receive fungicide treatment. All other
154 ES were measured in the treated half.

155 **2.2. Measurement of ecosystem services**

156 In order to study simultaneously 17 ES, we selected measurements simple and quick to implement.
157 Service expression level of each ES was expressed as a score normalized on a 0-5 scale. For all ES
158 except yields, the scale contained six classes (*i.e.* scores) of equal size within values from 0 to the
159 maximum observed value of the ES after removing outliers (*i.e.* values more than 1.5 times the
160 interquartile range from the nearest quartile). Mean regional yields were used to create classes for
161 yields. Fields with a yield over the mean received a score value of 5, and the five remaining classes
162 were set as equal-sized classes from 0 to the regional mean value. Except for biodiversity, root
163 development and **greenhouse gas** recycling, thorough description of all measurements used to
164 calculate ES scores in this study can be found in Chabert et al. (in press) and matching data are
165 available at <https://doi.org/10.15454/KEW1GK>.

166 Regulating services

167 We chose not to study biocontrol under one sole indicator considering the diversity of processes
168 involved, regarding the pest species, the regulating agents, their respective specialization. We thus
169 chose to limit our study to three examples of pest regulation processes: one specialized parasitism,

170 one specialized predation and one generalist predation. Four regulating services were thus assessed:
171 regulation of a wheat pest by a specific predator and a fava bean pest by a specific parasitoid,
172 generalist regulation by ground predators, and pollination. Pollination being also a key regulation
173 process in and for healthy ecosystems, we added an estimate for the potential of pollination around
174 fields in our set of measurements.

175 Grain aphid (*Sitobion avenae*) regulation by aerial predators was estimated based on an estimate of
176 the density of an aphidophagous hoverfly population (*Sphaerophoria scripta*, Diptera: Syrphidae) on
177 wheat ears just before harvest (Chabert and Sarthou, 2017).

178 Bruchid (*Bruchus rufimanus*) regulation by a specialized parasitoid was based on an estimation of the
179 percentage of bruchid parasitism by *Triaspis thoracicus* (Hymenoptera, Braconidea) after harvest.

180 Potential for generalist regulation was assessed by estimating activity density of opportunistic
181 ground predators, which include ground beetles (Coleoptera, Carabidae), spiders (Araneae) and rove
182 beetles (Coleoptera, Staphylinidae), using modified pitfall traps set in winter wheat fields for 36
183 hours, simultaneously with slugs' pressure measurements in mid-April. Species of genera *Zabrus* and
184 *Amara*, the only phytophagous genera of Carabid beetles harboring pest species for crops, were
185 excluded from counts.

186 Given that a positive correlation between pollinator diversity and pollination of plants has already
187 been demonstrated (e.g. Albrecht *et al.* 2012, Hoehn *et al.* 2008), potential for pollination was
188 assessed via the abundance of the main pollinators. Insects were sampled using interception "cornet
189 traps" (Sarthou, 2009). These traps are based on the Malaise trap principle but are (i) more resistant
190 to wind, to endure the two years of the study; (ii) lower, to limit trap effectiveness and save sorting
191 time, and (iii) unidirectional, to improve the orientation of traps. Four traps (two pairs of traps facing
192 opposite directions) were set, as much as possible, on two perpendicular edges of each winter wheat
193 field to capture along perpendicular directions in natural corridors. As far as possible, traps were set
194 in order to capture from each of the four cardinal directions. Insects were captured continuously for

195 50 days, in autumn (from mid-September to early November 2015). We considered only the main
196 pollinator groups that are Lepidoptera: Papilionoidea, Hymenoptera: Anthophila, and Diptera:
197 Syrphidae. We chose as indicator for the potential of pollination the mean number of pollinators in
198 the four traps.

199 Supporting services

200 Crop production supporting services included two measures of soil erodibility (structural stability of
201 soil aggregates and water infiltration rate) and a measure of root development. Water infiltration
202 rate was measured as the time needed for the soil to absorb water. Structural stability of soil
203 aggregates was assessed through turbidity of surface water, supposedly due to the detachment of
204 fine particles of soil from the impact of water drops. Root development was assessed for fava bean
205 taproots, which are influenced more by soil compaction than the shallower roots of winter wheat.
206 Five random plants were carefully uprooted, and total length of the taproot (the longest, if more
207 than one) and its apical diameter were measured. The indicator of root development for each field
208 was the mean value of length × diameter of the five taproots. All measurements were performed in
209 April 2016.

210 Provisioning services

211 The seven provisioning services were assessed focusing on crop yield and production stability, via
212 crop health and risk of pest damage.
213 Crop health was assessed by estimating fungal disease infection on leaves for both crops, within part
214 of the field that did not receive fungicide treatment (half of winter wheat field, whole field for fava
215 bean; see Chabert et al., in press). A standardized six-level scale was directly used to assess mean
216 diseases infection within studied fields. Pest risk was assessed as the density (hereafter referred to as
217 pressure) of a winter wheat pest, a fava bean pest and polyphagous pests (*i.e.* grain aphid *Sitobion*
218 *avenae*, bruchid *Bruchus rufimanus* and slugs *Deroceras reticulatum* and *Arion hortensis*,
219 respectively). For pest and disease pressures, observed values were ranked in a reversed scale so

220 that a score of 5 always represents high level of ES (*i.e.* no diseases or pest) and 0 the complete
221 absence of the ES (*i.e.* highest pressure observed).

222 Non-marketed services

223 Conservation of biodiversity was assessed using a Simpson diversity index applied to the entire
224 arthropod community captured in above-mentioned “cornet traps” sorted and counted by orders.

225 Conservation of SNH diversity was also assessed using a Simpson diversity index, which was applied
226 on the number of each SNH type and their relative area on the farm (% of the farm surface) to
227 prevent an overrating of big farms. Farmers identified SNH from photographs in their European
228 Union Common Agricultural Program forms.

229 Greenhouse gas recycling was estimated for each farm as an index that equaled the amount of
230 carbon sequestered in its soil divided by its greenhouse gas emissions for one year (2014). The index
231 was calculated using the DIALECTE environmental assessment (Solagro, 2000), whose method is
232 based on the computer tool AgriClimateChange (<http://www.agriclimatchange.eu/>). This indicator
233 includes greenhouse gas emissions from fuel, oil and natural gas consumed on the farm, all
234 greenhouse gas emissions from livestock enteric fermentation, and direct and indirect greenhouse
235 gas emissions from soils. Indirect emissions such as those due to electricity consumption, livestock
236 feed, chemical inputs, plastics and buildings are also included. For carbon sequestration, practices
237 such as no-till, cover crops and grass strips were considered, as were the surface areas of long-term
238 grassland, perennial crops and SNH (hedges, woods, etc.).

239 **2.3. Cropping system survey**

240 Information was recorded for tillage, chemical inputs, intercrop management, plant diversity, soils
241 and the landscape (see Chabert et al., in press). We distinguished information about PS (Aubertot
242 and Robin 2013), which are components and environment of a given field that farmers do not
243 manage directly, from that about CM, which are components directly related to farmers’ decisions
244 (Table 2).

245 CM systems were divided into five categories: plowing under conventional agriculture, plowing under
246 organic agriculture, reduced tillage under conventional agriculture, reduced tillage under organic
247 agriculture and direct seeding under conventional management. In all fields, the considered CM
248 system was applied for more than three consecutive years. Fields were considered under organic
249 agriculture when they were labeled with French Organic Certification.

250 To better understand the impact of practices underlying those CM, five indicators were used to study
251 effects of certain practices. Organic agriculture is based on banishment of the use of synthetic inputs
252 (pesticides and fertilizers). We thus used the (i) treatment frequency index (TFI) and (ii) total mineral
253 nitrogen input (Nmin), to study effects of reduced synthetic input use (from intensive use in some
254 conventional fields towards suppression of their use in organic fields, Table 3) on the ES studied.
255 Three parameter were used to consider each of the three principles of conservation agriculture
256 (Table 3): (iii) time since last plowing in years, *i.e.* time since conversion to these techniques
257 (Last_plow); (iv) rotation duration (Rotation) and (v) percentage of legume crop area at the farm
258 level (Legum).

259 **2.4. Production situations**

260 In order to compare CM systems in fields with similar agroecological contexts, we used a multiple
261 factorial analysis followed by a hierarchical ascendant classification to identify groups of similar PS.
262 PS were described with 12 variables (Table 2) drawn from Chabert et al. (in press). Six referred to the
263 landscape context and expressed as percentages of the area within a 1.5 km radius around the field
264 covered by woodlands, cultivated fields (crops or temporary grasslands), fallow lands (including
265 natural grasslands), human-modified areas, hedges and water (*e.g.* lakes, ponds, rivers). Five
266 variables described soil properties: soil pH and organic matter, clay, silt and sand contents. An
267 additional variable distinguished farms with or without livestock. Multiple factorial analysis allows to
268 group variables into weighted categories, thereby limiting the degree to which importance is
269 attributed to sets of variables related to the same feature (Escofier and Pagès, 1994). The first three

270 dimensions (28.12%, 15.43% and 15.20% of the observed variation respectively) distinguished
271 respectively: plots in farms without livestock ($\cos^2 = 0.82$), with more alkaline soils ($\cos^2 = 0.63$) and
272 higher clay contents ($\cos^2 = 0.35$, Figure 2a); plots with high percentage of human-modified areas in
273 their vicinity ($\cos^2 = 0.65$, Figure 2a); and plots with higher silt contents ($\cos^2 = 0.47$). Coordinates on
274 the first five dimensions (80.0% of observed variation) were retained to perform the hierarchical
275 ascendant classification, using Ward's method, to identify four homogeneous clusters of PS (Figure
276 2b). The first group (PS 1) consisted exclusively of the fields from farms without livestock. These
277 fields were mainly associated with clay-loam soils (mean clay content: $34 \pm 7\%$, mean pH: 8.07 ± 0.51).
278 Only two fields were loamy in PS 1 (clay content = 27.1% and 24.8%; pH = 7.06 and 6.8 respectively).
279 The second and third groups consisted of fields from farms with livestock and distinguished those
280 with acidic loamy soils (PS 2, mean clay content: $18 \pm 5\%$, mean pH: 6.47 ± 0.52) from clayey soils (PS 3,
281 mean clay content: $40 \pm 11\%$, mean pH: 7.97 ± 0.41). The fourth group (PS 4) contained only four fields
282 that differed from the others due to the urban neighborhood around three of them and a large lake
283 near the fourth. This fourth group was too small to be relevant, and after verifying whether the ES
284 scores of its four fields fell into the interquartile range of similar CM in other PS, we moved them to
285 the nearest PS. The two without livestock, clay content around 30% and alkaline pH were moved to
286 PS 1, while the two with high silt contents and presence of a livestock were moved to PS 2.

287 **2.5. Data analysis**

288 We first chose to select the CM "plowing under conventional agriculture" as the standard system in
289 our study area and determined whether each ES of the other four CM (considered as "alternative")
290 ranked higher than, equal to or less than that in the standard system. We performed ANOVA on
291 proportional odds models, an adaptation of cumulative link models to the study of scores (*i.e.* semi-
292 quantitative data) (Christensen and Brockhoff, 2013) for this comparison. Because significant
293 differences were rarely observed, we set the p-value threshold (α) at 0.10 to include slightly
294 significant trends. To study each ES category individually, we looked for changes in its mean score.

295 To study the co-occurrence or antagonism of ES, we performed principal component analysis (PCA)
296 of the 17 ES scores of the 50 fields. PCA is better adapted to studying ordered factors such as ranks
297 or scores than are factorial methods, in which the order of the factor's values is ignored (Meulman et
298 al., 2004; Vilela et al., 2015). CM and PS categories were added as supplementary factors to identify
299 corresponding fields in PCA output but were not used to construct PCA dimensions.

300 We then summarized the scores of the 17 ES with polar area diagrams to visualize co-occurrence of
301 ES among the groups of similar PS and the five CM types. Observed trends were then tested using
302 pairwise likelihood ratio tests on proportional odds models. The CM analysis was supplemented with
303 observations of effects of individual practices on each ES. Influential variables were selected using
304 forward-and-backward proportional odds models selection among the five practice indicators (TFI,
305 Nmin, Last_plow, Rotation, Legum) and the associated PS. We then verified whether the condition
306 number of the models' Hessian matrix was less than 10^4 (Christensen, 2015a); if not, the least
307 significant variable was removed. The most parsimonious model was maintained and analyzed with
308 type-II analysis-of-deviance (*i.e.* ANOVA with likelihood ratio tests). This method was not used to
309 study **greenhouse gas** recycling because it was the only ES that was estimated from surveys and not
310 from in-field measurements. Thus, by construction, it was correlated with most of the practices
311 studied. Finally, a study of the specific relationships between SNH diversity and mobile-agent based
312 ES was performed, also using ANOVA on proportional odds models.

313 All statistical analyses were performed with R v3.2.3 software (R Core Team, 2015) and the packages
314 *FactoMineR* 1.32 (F. Husson et al., 2016), *ordinal* (Christensen, 2015b), *car* (Fox and Weisberg, 2011),
315 *RVAideMemoire* (Hervé, 2016) and *lsmeans* (Lenth, 2016).

316 **3. Results**

317 **3.1. Comparison of ecosystem services under conventional plowing and alternative** 318 **systems**

319 Each of the four alternative CM systems had at least one regulating service whose score increased
320 compared to that under conventional plowing (Table 4), with both reduced-tillage systems having
321 two. The reduced tillage systems, however, also had two (conventional) to four (organic) provisioning
322 services that decreased, including yields. Organic plowing and direct seeding had two pest pressures
323 (aphids and bruchids) that increased, but their yields were the same as those of conventional
324 plowing, and crop health improved under organic plowing. For supporting services, organic plowing
325 ranked lower than conventional plowing for two ES, and organic reduced-tillage was the only system
326 that did not differ from conventional plowing. Reduced-tillage and direct-seeding systems increased
327 structural stability of soil aggregates, but water infiltration and root development were significantly
328 lower under direct seeding than under conventional plowing. Non-marketed services did not change
329 under organic plowing or reduced-tillage; however, biodiversity conservation increased under
330 organic reduced-tillage, and **greenhouse gas** recycling increased under direct seeding.

331 Mean scores per ES categories supported those observations (Figure 3). Mean scores of regulating
332 services increased in the four alternative systems. However, direct seeding exhibited large variability
333 and certain fields of this CM had regulating service scores as low as those of fields under
334 conventional management (Figure 3a). Opposite trends were observed for provisioning services.

335 Alternative CM generally had lower mean scores than conventional plowing, especially organic
336 reduced-tillage ($p = 0.04$). Direct seeding exhibited again a large variability and contained both the
337 lowest and the highest scores of provisioning services (Figure 3c). Conversely, for supporting services,
338 variability decreased from conventional plowing to direct seeding (n.s.). Alternative systems,
339 especially organic ones, had slightly lower mean scores than conventional plowing but similar
340 medians (Figure 3b). Non-marketed services increased in organic systems compared to their
341 conventional counterparts (n.s.), and direct seeding had significantly higher mean score compared to
342 both plowing and reduced tillage systems ($p = 0.01$ for both; Figure 3d).

343 **3.2. Ecosystem service bundles**

344 As to co-occurrence or antagonism among ES on the same plot, the **principal component analysis** of
345 ES scores highlighted several major trends, with **45.32%** of the observed variation explained in the
346 first three dimensions (**19.67%**, **13.74%** and **11.91%**, respectively). The first dimension indicated that
347 less aphid pressure often co-occurred in plots with better fava bean health and, **to a lesser extent,**
348 **more ground predator activity, less slug pressure and** more bruchid regulation, but displayed
349 antagonism with SNH conservation and aphid regulation **and, to a lesser extent, with biodiversity**
350 **conservation and potential for pollination** (Table 5). In addition, CM and PS types were correlated
351 with this first dimension (Table 6). Thus, conventional plowed fields or fields with livestock and silty
352 soils (PS 2) were often associated with low aphid pressure and low fava bean disease, but also low
353 SNH conservation **and aphid regulation**, while organic reduced-tillage or fields without livestock were
354 associated with the opposite effects on these ES (Table 6; Figure 4).

355 On the second dimension, plots that ranked highest for fava bean root development were opposed
356 to those with high structural stability of soil aggregates. PS or CM types were not significantly
357 correlated with the second dimension, but the CM type “direct seeding” was negatively associated to
358 it (Table 6), *i.e.* more stable soil aggregates but less root development.

359 The third dimension opposed fields with high fava bean yields, adequate **greenhouse gas** recycling
360 and low wheat disease to fields with low water infiltration rate. This third bundle was observed in
361 plowed fields (Table 6) but did not sufficiently explain the overall variation among CM or PS types.
362 Organic plowed fields were not significantly associated with a dimension, but were mainly
363 distributed in a neutral position in relation to the first bundle, with positive values on the second
364 dimension (Figure 4), *i.e.* adequate root development but low structural stability. Fields under
365 conventional reduced-tillage were homogeneously distributed along the first two dimensions, which
366 precluded generalizing whether these CM types were associated with specific bundles.

367 **3.3. Effects of crop management types on ecosystem services within production**
368 **situations**

369 Effects of production situation

370 Belonging to a specific PS appeared as a significant variable for five ES: SNH diversity conservation (p
371 = 0.004), ground predator abundance (p = 0.009), winter wheat health (p = 0.016), aphid pressure (p
372 = 0.020) and to a lesser extent biodiversity conservation (p = 0.064). In PS 1, *i.e.* fields on farms
373 without livestock and with clayey soils, higher diversity scores for both SNH conservation and
374 biodiversity were observed regardless of the CM considered (Figure 5a); organic fields had
375 significantly more **activity density of** ground dwelling predators (p-value of the interaction PS:CM =
376 0.042) and no difference among CM were observed in aphid pressure. In both PS with livestock (PS 2
377 and 3, Figure 5b and c), wheat health was better in conventional fields, whether plowed or not, than
378 their organic equivalent.

379 Effects of tillage

380 Supporting and non-marketed services exhibited the most significant trends regarding tillage (Figure
381 5). The two soil erodibility parameters had opposite responses. Structural stability of soil aggregates
382 was high under direct seeding in all PS (median score = 5, 4 and 3 for direct seeding, reduced tillage
383 and plowing, respectively; p = 0.003), while water infiltration was slightly higher in tilled fields,
384 whether plowed (PS 2) or not (PS 1 and PS 3) (median score = 1, 2 and 2.5 for direct seeding, reduced
385 tillage and plowing, respectively; p = 0.053). As to non-marketed services, farms practicing direct
386 seeding recycled a much greater proportion of **greenhouse gas** than any other CM system (median
387 score = 3, 0.5 and 0 for direct seeding, reduced tillage and plowing, respectively, p < 0.001) and SNH
388 diversity was **marginally** higher under reduced tillage and direct seeding (**median score = 4**)
389 **compared to plowing (median score = 3, p = 0.090 and p = 0.084 respectively).**

390 Concerning provisioning services, direct seeding and conventional plowing had similar winter wheat
391 yields (p = 0.786) while a non-significant decrease was observed under reduced tillage. Reduced-
392 tillage fields had the highest bruchid pressures (p = 0.028) and aphids were slightly more abundant
393 under direct seeding (p = 0.065), except in PS 1. Overall, variability in aphid and slug pressures

394 increased under reduced tillage and direct seeding. As to regulating services, despite variability
395 among PS, reduced tillage fields had the highest potential for pollination ($p = 0.028$), especially
396 organic reduced-tillage in PS3. Opposite trends were observed for aphid and bruchid regulation
397 under direct seeding (higher and lower than other CM respectively, n.s.).

398 Effects of organic management

399 Organic management was associated with significant negative trends for provisioning services and
400 some positive trends for non-marketed and regulating services. Organic fields, whether plowed or
401 not, produced less winter wheat than conventional fields ($p < 0.001$). A slight trend for improved
402 wheat health was observed in organic fields ($p = 0.054$), especially in the absence of livestock (Figure
403 5a). However, both crops' health was improved in conventional fields in PS 3, *i.e.* when livestock was
404 present on the farm and soils were clayey (p -values of the interaction = 0.015 and 0.002 for wheat
405 and fava bean respectively). For all three pest pressures, conventional plowing had lower pressures
406 in PS 2 and PS 3 (Figure 5b and c), and organic fields, whether plowed or not, generally had higher
407 pressures ($p = 0.017, 0.132$ and 0.071 for slugs, aphids and bruchids respectively). As to non-
408 marketed services, SNH diversity was higher in organic fields, whether plowed or not ($p = 0.006$), and
409 organic farms recycled a slightly greater proportion of their **greenhouse gas** than their conventional
410 equivalents (n.s., $p = 0.181$). The differences were greater in PS 1, *i.e.* farms producing only crops. All
411 regulating services were greatly variable among PS. For **activity density of** generalist predators,
412 conventional fields (plowed or not) ranked lower than organic in PS 1 ($p = 0.044$), aphid regulation
413 was slightly higher in organic than conventional fields, whether plowed or not (n.s., clayey fields in PS
414 1 and PS 3) and, at the opposite, bruchid regulation was generally higher in conventional fields,
415 provided that livestock were present (n.s., Figure 5b and c). Finally, structural stability of soil
416 aggregates was slightly higher in conventional fields than organic fields (median score = 4.5 and 3,
417 respectively; $p = 0.051$), regardless of PS and tillage management type.

418 **3.4. Effects of SNH diversity and individual crop management practices of**

419 **conservation and organic agriculture on ecosystem services**

420 SNH diversity scores were positively correlated with flying-pest pressure ($p = 0.016$ and <0.001 for
421 bruchids and aphids, respectively) and with the associated aphid regulation ($p = 0.004$) but were
422 negatively correlated with bruchid regulation ($p = 0.009$). For ground pests (slugs) and predators,
423 SNH diversity was associated with a slight increase of slug abundance ($p = 0.053$) and had no effect
424 on **activity density of** ground-dwelling predators. SNH diversity also had a slight positive correlation
425 with pollinator abundance ($p = 0.076$).

426 For conservation agriculture practices, extended rotation duration had significant positive effects on
427 bruchid regulation and fava bean yields, while the time since last plowing had negative effects on
428 these ES (Tables 7 and 8). It also had negative effects on water infiltration and root development and
429 a slight negative effect on fava bean health, but had a significant positive effect on soil structural
430 stability (Table 7). Slug pressure slightly decreased in fields with longer rotations but increased as the
431 percentage of legume crop area increased (Table 8). **Positive correlation was also observed between**
432 **SNH conservation and percentage of legume crop area (Table 8).**

433 For organic practices, **treatment frequency index** was negatively correlated with wheat health, yet
434 not correlated with wheat yield, and slightly correlated with fava bean yield (Table 8). For mineral
435 fertilizer, only slight trends in lesser soil structural stability and aphid pressure were observed with
436 decreasing nitrogen use (Table 7).

437 Studied practices had no significant effect on pollination, aphid and bruchid regulation and wheat
438 yield.

439 **4. Discussion**

440 Our findings overall supported those of Garbach et al. (2016), whose meta-analysis demonstrated
441 that conservation agriculture generally improved pest control, conservation of biodiversity and
442 habitats, carbon sequestration, control of erosion and water runoff, and water purification. While

443 organic systems improved pollination, biodiversity and habitat diversity, and control of erosion and
444 water runoff, control of pests and weeds was similar to that in the conventional system (Garbach et
445 al., 2016).

446 High variability of output services response to conservation agriculture practices

447 One finding that merits greater focus in future studies is the variability in results observed for
448 conservation agriculture systems. For provisioning services in particular, direct seeding and, to a
449 lesser extent, reduced tillage had high variability in yields, winter wheat health and abundance of
450 pests such as aphids and slugs. Particularly, the highest and the lowest scores of the same ES were
451 often found under direct seeding. Similar variability was found for most non-marketed services.
452 However, this was not observed for supporting services (Figure 3), whose variation under direct
453 seeding differed little when compared to plowing. The CM types we chose to study thus
454 encompassed a range of practices with variable agroecological performances. No-plowing systems
455 were found to be more economically productive and beneficial to soil quality when associated with
456 agroecological rather than industrial practices (Virginia et al., 2018). As stressed out by Bender et al.
457 (2016), to fully benefit from natural processes, agroecological systems need to integrate soil
458 ecological engineering, which requires high understanding of soil processes. Yet, farmers involved in
459 conservation agriculture suffer from a lack of specific knowledge and technical support to adapt their
460 technics to local conditions. Furthermore, as evidenced in this study by the significant effect of time
461 since last plowing on several ES, conservation agriculture systems need maturity to express their
462 potential for ES provision, due to gain of farmers' experience, soil evolutions and ecological
463 equilibrium, which may take a few years (Scopel et al., 2013).

464 Co-variation and antagonisms between ecosystem services mostly related to mobile agents or soil 465 properties

466 Several ES that rely on mobile agents and are greatly influenced by field surroundings appeared to
467 display co-occurrence or antagonism in fields. Interestingly, systems combining organic and

468 conservation practices displayed the highest diversity of SNH and associated services, proving that
469 farmers transitioning to agroecological practices seem to extend their management strategies
470 outside the productive zones of their farm. Our observations that both pest pressure and regulation
471 by a given natural enemy increased with habitat diversity and general biodiversity for aphids, was
472 expected (Roschewitz et al., 2005) and the opposite effects on bruchid parasitism concur with recent
473 findings that non-crop habitat diversity does not consistently support higher pest regulation (Karp et
474 al., 2018). Furthermore, for organic agriculture as much as conservation tillage, bruchids and aphids
475 were more abundant compared to conventional plowing, which contradicts results of previous
476 studies (see meta-analysis of Bengtsson et al. 2005). Yet, recent studies support that more complex
477 food web structure in organic farming do not consistently implies an improved pest control
478 (Macfadyen et al., 2009a, 2009b). Despite higher biodiversity (Hole et al., 2005) and richness of
479 potential biocontrol agents (Bengtsson et al., 2005), no differences are sometimes observed in pest
480 damages (Fusaro et al., 2016) or parasitism (Macfadyen et al., 2009b) and as-yet-unknown effects of
481 organic practices on pests and their enemies remain (Lohaus et al., 2013). **For instance, it can be
482 supposed that Hymenopteran parasitoids of bruchid larvae are hindered in localizing their host and
483 laying their egg when host plants are mixed with other cultivated plant species or weeds, or are
484 embedded in botanically complex surroundings.**

485 The other ES bundles observed were related to the soil and its sensitivity to erosion. Particularly,
486 both erodibility parameters, water infiltration rate and structural stability, appeared in two
487 orthogonal bundles. These two properties are thus expressed independently in a given field and are
488 not always negatively correlated. Contrary to Garbach et al. (2016) and Reganold and Wachter (2016)
489 meta-analyses, organic agriculture did not improve control of erosion and water run-off. Soil stability
490 was even lower under organic than conventional practices. But our findings confirmed the potential
491 for direct seeding (Bronick and Lal, 2005; D'Haene et al., 2008) to significantly decrease soil loss
492 thanks to more stable soil surface aggregates, which is one of the main advantages of no-till practices

493 (Puustinen et al., 2005; Soane et al., 2012; Ulén et al., 2010). However, we were unable to confirm
494 the decrease in runoff due to conservation tillage as stated by Soane et al. (2012). Infiltration rate is
495 usually assumed to be higher in conservation agriculture thanks to protection from raindrops and
496 their destructuring 'splash effect' by residues, the greater macropore conductivity, the continuity
497 between soil layers, and the vertically-orientated macroporosity (Sharratt et al., 2006; Soane et al.,
498 2012). Yet, no-till practices are also known to increase soil compaction, especially in the first few
499 years after conversion (Soane et al., 2012) which may hinder the permeability of the first few
500 centimeters **or even millimeters** of soil. This has been revealed by a decrease in fava bean root
501 development in conservation agriculture because of soil compaction. Furthermore, measurements
502 were performed soon after winter, when the biological activity that could have restored porosity still
503 remains low.

504 Crop production not jeopardized by conservation agriculture practices and crop health improved in
505 organic agriculture

506 Worldwide, all crops combined and from experimental plots (what is criticized by some farmers),
507 conservation agriculture is estimated to have yields 2.5% lower than those of conventional plowing
508 (Pittelkow et al., 2015a). Under conservation agriculture, yields are less affected by water stress
509 (Pittelkow et al., 2015a) and are estimated to increase by 20-120% compared to those of
510 conventional plowing in arid countries (Basch et al., 2015; Kesavan and Malarvannan, 2010). No
511 empirical evidence for the overall performance of conservation agriculture exists for France (Lahmar,
512 2010), but Basch et al. (2015) estimated that yields in Southern Europe (including France) would
513 increase by 13% under conservation agriculture. Yields in our study did not differ significantly
514 between conventional plowing and conservation tillage, including that of direct seeding. Except for
515 reduced tillage in organic systems, crop health was also unchanged by CM type. These findings
516 contradict certain scientific beliefs about conservation agriculture. Indeed, models based on expert
517 knowledge tend to predict an increase in diseases and pests when the soil remains undisturbed and

518 is covered with crop residues (Craheix et al., 2016). Several studies support this, but as mentioned by
519 Scopel et al. (2013), this is observed mainly in young, not-yet-mastered systems, in which the
520 principles of conservation agriculture are not completely **or well** applied. A large-scale European
521 survey of farmers adopting conservation agriculture revealed that, from their viewpoint, the
522 prevalence of diseases and pests did not change when they changed their practices (Veroz-González
523 et al., 2008). Our study tends to support their claim for diseases, with no trend of deteriorating crop
524 health under direct seeding. Yet, organic reduced-tillage was the CM with the strongest pressure of
525 pathogenic fungi, which indicates that obstacles remain for the development of conservation
526 agriculture in organic systems. As to risk of pests, if aphids and bruchids appeared greater in both
527 alternative agricultures, slugs however significantly increased only under organic agriculture
528 practices. Slugs are considered a major issue hindering the development of conservation agriculture
529 (Basch et al., 2015) but in the winter crops we studied, their abundance was highly variable in fields
530 under reduced tillage or direct seeding, leading to no significant effect of tillage. Thus, our results on
531 pests contradict previous studies showing an improved pest control in conservation agriculture
532 (Basch et al., 2015; Garbach et al., 2016; Kesavan and Malarvannan, 2010), except for regulation of
533 slugs which was poor in conservation agriculture. The differences observed in pest abundance were
534 due more to specific practices and habitat availability in field surroundings rather than CM type (*cf.*
535 below).

536 Yields and crop health differed greatly between organic and conventional systems. Consequent
537 decrease in wheat yields, but not for fava bean, was expected (Reganold and Wachter, 2016; Seufert
538 et al., 2012), indicating that it was mainly due to lack of mineral nitrogen. As to crop health, the
539 negative correlation between **treatment frequency index** and crop health proved that organic
540 systems tended to improve wheat health, a trend even greater in the absence of livestock. However,
541 **treatment frequency index** was not correlated with higher yields, indicating that treatments only
542 allowed fields affected by diseases to have yields similar to those of healthy fields.

543 Negative impacts of agricultural practices mitigated by elements of production situation such as
544 presence of livestock and clayey soils

545 We found that presence of a livestock was a major component of production situation and influence
546 several ES responses. Overall, when livestock was present, we observed lower negative effects of
547 conventional practices on several ES, such as soil aggregate stability, crop health, yields, activity
548 density of soil predators and abundance of pests. Presence of livestock on the farm implies
549 availability of organic matter for fertilization, resulting in higher organic matter content in the soils
550 (Figure 2) and potentially more grasslands and longer crop rotations. It seemed that soil quality
551 (physical, chemical and biological) improved in the presence of livestock and mitigated decreases in
552 ES caused by other practices. However, except for fava bean yields, rotation duration was not an
553 explanatory factor for these ES. Livestock presence was negatively correlated with SNH diversity
554 because although it was associated with larger area of grassland (and thus of SNH), grassland
555 dominated the types of SNH, resulting in low SNH diversity at the farm level. In the opposite,
556 livestock presence was logically related to higher greenhouse gas emissions (Gerber et al., 2013). An
557 exception was found for fields under direct seeding which greatly mitigated the impact of livestock
558 on greenhouse gas emissions by sequestering carbon in the soil. Greenhouse gas emissions were not
559 field measured in the present study but estimated and further studies are needed. Yet, our results
560 suggest a high potential for direct seeding to support such a crucial ES by beneficially balancing
561 energy consumption and agroecological practices.

562 We distinguished two groups of farms with livestock that differed mainly in soil type, *i.e.* loamy or
563 clayey soils, leading to distinct ES responses to CM type. In particular, direct seeding had the highest
564 yields on loamy soils, and plowing had the highest yields on clayey soils. The amount of clay in soils
565 might act as a buffer of prejudicial practices. For instance, practices of reduced tillage often
566 encompass shallow mechanical weed control to limit or supplant herbicide use, especially for organic
567 fields. This repeated shallow disturbance produces fine soil particles that obstruct the biologically-

568 created porosity connection between surface and deeper soil layers. As we observed for water
569 infiltration, low infiltration occurred on silty soils and/or soils with low organic matter contents, and
570 both conservation and organic agriculture practices were less detrimental on clayey soils.
571 Additionally, clay in soils buffers the alteration of soil redox potential by mechanical soil
572 management. Loamy soils are indeed more sensitive to oxidation due to soil disturbance or chemical
573 inputs (O. Husson et al., 2016), which provide non-optimal conditions for crops and indirectly
574 decrease the amount of photosynthates directed to grain (Husson, 2013), resulting in lower yields.
575 Soil type **in relation to oxidation level** might also influence other ES in unexpected ways. Indeed,
576 Chabert and Sarthou (2017) showed that *S. scripta* regulation of aphids might also be influenced by
577 soil and subsequent plant redox **potential** due to sensitivity of these organisms to **electromagnetic**
578 **fields**, as demonstrated for other pollinators (Clarke et al., 2013). **It could also be the result of a lesser**
579 **emission of HIPV (Herbivore Induced Plant Volatiles, molecules used by some natural enemies to find**
580 **their prey/hosts) by plants (Dicke et al., 2009), eventually because of their high oxidation level.**
581 Ecosystem services better explained by individual practices than categorization by crop management
582 type
583 Several authors indicate that a set of practices must be considered rather than only one aspect such
584 as soil tillage, especially for conservation agriculture. For example, Craheix et al. (2016) showed that
585 direct seeding with a short rotation was the system favoring the less ES and that conservation
586 agriculture, when completely applied and mastered, resulted in good supply of non-marketed
587 services. Many farmers adopt conservation agriculture practices only partially due to their
588 convictions, objectives or local conditions (Scopel et al., 2013), which greatly undermines the long-
589 term sustainability of their systems. In contrast, some systems based on conventional plowing can
590 have good supply of non-marketed services (Craheix et al., 2016) when, for example, they have long
591 and diversified rotations, reasoned SNH management and moderate pesticide use. Our study was
592 meant to somehow remedy to the lack of case studies that examine multiple ES in agroecosystems at

593 the same time. But because many ES were studied simultaneously, parameters for PS and CM were
594 kept simple to not overweigh the study and we only briefly reviewed several main practices related
595 to conservation and organic agriculture to refine the results. Overall, the assessment of main
596 practices confirmed observations of CM types and provided insight into effects of practices on
597 certain ES that did not significantly differ among CM types. Thus, we confirmed effect of
598 conservation agriculture on soil aggregate stability and water infiltration as an effect long-time non-
599 inverting soil management. The non-significant decrease in bruchid regulation observed in
600 conservation agriculture resulted from an opposite response to time since last plowing, which tends
601 to decrease regulation, and to rotation duration. The opposite effects of these two conservation
602 agriculture principles thus resulted in no definite effects of our CM types because they included fields
603 where the three conservation agriculture principles were not equally applied. Slugs pressure, which
604 varied greatly under conservation agriculture without significant trend, tended to be more important
605 when the percentage of legume crop area and the diversity of SNH on the farm were high, but they
606 were less abundant in fields with a more diversified crop rotation. As to fava bean yields, which were
607 similar among CM types, they were also influenced by time since conversion and rotation duration,
608 as well as pesticide use, which tends to confirm that yields were due mainly to the effectiveness of
609 bruchid control, whether natural or chemical. Despite those examples, only a few cases of prevalence
610 of individual practices over CM or PS categorization appeared in the current study. Indeed, as shown
611 in a previous study in the same dataset (Chabert and Sarthou, 2017), when finer parameters and raw
612 measurement of ES rather than scores are studied, it is possible to show that nitrogen input and time
613 since conversion to conservation agriculture explained aphid regulation more than classification as
614 “organic” or “conservation” agriculture. The relatively coarse assessment of effects of specific
615 practices observed in this study thus initiate future service-specific studies.

616 **5. Conclusion**

617 Overall, this study showed a good performance of conventional agriculture for the expression of
618 provisioning and supporting services but it generally had lower levels of regulating and non-marketed
619 services compared to organic agriculture, which conversely, often had the lowest performance for
620 provisioning and supporting services. In contrast, conservation agriculture showed good potential to
621 sustain agroecological transition in southwestern France. Unlike for organic agriculture, provisioning
622 services did not generally decrease, even though pest risk was sometimes higher. In addition,
623 conservation agriculture can help reduce soil loss by decreasing particle removal caused by water
624 runoff.

625 Questioning the co-occurrence or antagonisms of ES revealed that the relationship between pests,
626 their natural enemies and habitat diversity was not as straightforward as previously believed.
627 Bruchids for example, did not respond to habitat diversity as expected, and their response was
628 opposite to that of aphids. Drawing general conclusions about multiple pest pressures and
629 regulations for a given type of agriculture system is thus misleading due to high response variability
630 from one species to another.

631 Interestingly, with this case study, we emphasize the importance of production situation parameters
632 such as inclusion in a livestock-crop farm or soil type on the expression of multiple ES, even if
633 focusing on non-forage crop or non-soil related ecosystem services. Even if determinants remain
634 unclear, livestock on the farm seemed to mitigate negative effects of conventional agriculture,
635 increasing scores of ES such as potential predation by ground-dwelling predators and soil aggregate
636 stability. Similarly, higher soil clay content buffered beneficial effects of alternative systems on soils.

637 Contrary to some authors claim, conservation agriculture did not show increased yields compared to
638 conventional plowing in this study; however, fields on loamy soils had higher yields under
639 conservation agriculture, indicating its potential and the undervalued effect of soil texture on
640 agroecological performances of conservation agriculture. Potential improvements in soil chemical
641 properties under organic or conservation agriculture are understudied and, from our viewpoint, this

642 includes soil redox potential (here again interfering with soil clay content), along with pH and organic
643 matter content.
644 Finally, a main conclusion of this study concerns the high variability in ES expression under
645 conservation agriculture. Direct seeding had the most variable results, especially for provisioning
646 services, for which it had the highest (higher than conventional systems) and the lowest (lower than
647 organic reduced-tillage) rated fields in the study. Furthermore, time since conversion to these
648 techniques, was often an influential parameter, either because ecological equilibrium was not reach
649 or because of a lack of farmer experience in mastering the required techniques. This study
650 emphasizes that knowledge on how to adapt systems to local conditions and to respond to climate
651 events, remains incomplete and is not easily available to farmers.

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Table 1. List of the studied ecosystem services and correspondence with Common International Classification of Ecosystem Services

Input services (to agriculture)			Output services (from agriculture)		
	CICES 5.1 group	CICES 5.1 section		CICES 5.1 group	CICES 5.1 section
Regulating Services			Provisioning Services		
Potential for pollination	Lifecycle maintenance, habitat and gene pool protection	Regulation & Maintenance	Crop yields (winter wheat, fava bean)	Cultivated terrestrial plants for nutrition, materials or energy	Provisioning
Pest regulation (aphids, bruchids)	Pest and disease control	Regulation & Maintenance	Crop health (winter wheat, fava bean)	Cultivated terrestrial plants for nutrition, materials or energy *	Provisioning
Potential for generalist predation	Lifecycle maintenance, habitat and gene pool protection *	Regulation & Maintenance	Pests pressure (aphids, bruchids, slugs)	Cultivated terrestrial plants for nutrition, materials or energy *	Provisioning
Supporting Services			Services out of direct agricultural income = Non-Marketed Services		
Soil aggregate stability	Regulation of soil quality	Regulation & Maintenance	Biodiversity conservation	Lifecycle maintenance, habitat and gene pool protection **	Regulation & Maintenance
Water infiltration rate	Regulation of soil quality	Regulation & Maintenance	Semi-natural habitat conservation	Lifecycle maintenance, habitat and gene pool protection **	Regulation & Maintenance

Root development	Regulation of soil quality	Regulation & Maintenance	Soil greenhouse gas recycling	Atmospheric composition and conditions	Regulation & Maintenance
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* can also be classified as 'Regulation & Maintenance' : 'Pest and disease control'

** can also be classified as 'Cultural' : 'Other biotic characteristics that have a non-use value'

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971 **Table 2. Description of the variables used in the multiple factor analysis (production situation) and the proportional odds models selection (crop**
 972 **management).**

	Subcategory	Variable	Description
Production Situation	Landscape	Wood	% of woodland area within a 1.5 km radius
		Cult	% of cultivated area within a 1.5 km radius
		Fall	% of fallow land area within a 1.5 km radius
		Water	% of water area within a 1.5 km radius
		Hedg	% of hedge area within a 1.5 km radius
		Human	% of human-modified area within a 1.5 km radius
	Soil properties	pH	Soil pH
		OrgMat	Organic matter content
		Clay	% of clay content
		Silt	% of silt content
		Sand	% of sand content
	Farm context	Livestock	Presence or absence of a livestock on the farm
Crop Management	Tillage	Last_plow	Time since last plowing (years)
		Inputs	TFI
	Crop diversity	Nmin	Quantity of mineral nitrogen fertilizer applied
		Legum_area	% of area covered by legume crops at farm level
		Rotation	Mean rotation duration at farm level (years)

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974 **Table 3. Mean values (\pm standard deviation) of CM variables for each CM type studied. Between brackets number of fields concerned.**

		Last_plow	Legum_area	Rotation	TFI	Nmin
Conventional agriculture	Plowing (13)	0,54 \pm 0,88	13,03 \pm 11,83	3,54 \pm 1,09	2,05 \pm 1,25	66,90 \pm 68,74
	Reduced Tillage (14)	8,36 \pm 5,26	24,51 \pm 23,31	3,84 \pm 1,25	2,18 \pm 0,79	149,2 \pm 62,20
	Direct Seeding (10)	15,6 \pm 6,47	45,55 \pm 23,15	4,40 \pm 1,24	2,08 \pm 1,18	154,7 \pm 56,54
Organic agriculture	Plowing (5)	0,80 \pm 0,84	21,67 \pm 12,62	3,90 \pm 0,74	0,00 \pm 0,00	0,00 \pm 0,00
	Reduced Tillage (8)	7,88 \pm 6,24	43,97 \pm 22,47	4,75 \pm 1,36	0,00 \pm 0,00	0,00 \pm 0,00

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976 **Table 4.** Number of services improved (dark gray), unchanged (light gray) or decreased (no shading) by each crop management practice compared to
 977 conventional plowing. Differences are considered significant at $p < 0.10$.

	Organic Plowing			Reduced Tillage			Organic Red. Till.			Direct Seeding		
	↑	↔	↓	↑	↔	↓	↑	↔	↓	↑	↔	↓
Regulating	1	3		2	2		2	2		1	3	
Supporting		1	2	1	2			3		1		2
Provisioning	2	3	2		5	2		3	4		5	2
Non-marketed		3			3		2	1		1	2	

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980 **Table 5.** Significant correlations of the 17 ecosystem services studied with the first three **principal component analysis** dimensions.

	Variable	Corr.	p-value
Dim 1	Aphid pressure	0.74	8.96E-10
	Fava health	0.51	1.68E-04
	Ground predators activity	0.49	2.69E-04
	Slug pressure	0.49	2.98E-04
	Weevil regulation	0.49	3.09E-04
	Fava yield	0.38	6.09E-03
	Weevil pressure	0.37	7.75E-03
	Wheat health	0.36	1.11E-02
	Greenhouse gas recycl.	-0.34	1.71E-02
	Pollination	-0.46	6.93E-04
	Biodiversity	-0.47	6.40E-04
	Aphid regulation	-0.59	7.37E-06
	SNH diversity	-0.69	4.05E-08
Dim 2	Root development	0.81	1.60E-12
	Weevil regulation	0.46	7.20E-04
	Fava health	0.41	3.12E-03
	Weevil pressure	0.33	2.09E-02
	Water infiltration rate	0.32	2.56E-02
	Aphid regulation	0.30	3.52E-02
	Aphid pressure	-0.40	3.72E-03
	Ground predators activity	-0.42	2.27E-03
	Soil aggregate stab.	-0.77	7.59E-11
Dim 3	Fava yield	0.63	8.35E-07
	Greenhouse gas recycl.	0.52	9.25E-05
	Wheat health	0.49	2.90E-04
	Aphid regulation	0.45	1.15E-03

Water infiltration rate	-0.71	8.97E-09
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984 **Table 6.** Significant correlations between crop management (CM) type, production situation (PS) group and **principal component analysis** dimensions.

	Variable	R2	p-value		Estimate	p-value
Dim 1	CM	0.201	3.50E-02	P	1.12	1.57E-02
				RO	-1.20	3.21E-02
	PS	0.295	4.13E-04	PS 2	0.96	2.53E-03
				PS 1	-1.28	8.89E-05
Dim 2	-	-	-	D	-1.05	2.50E-02
Dim 3	-	-	-	P	-0.87	3.30E-02

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987 **Table 7.** Signs of the estimates of the most parsimonious Proportional Odds Models of crop management practices on regulating and supporting services
 988 and p-values of likelihood ratio tests.

	Pollination		Aphid reg.		Weevil reg.		Ground pred.		Soil ag. stability		Water inf.		Root dev.	
	estim.	p-v	estim.	p-v	estim.	p-v	estim.	p-v	estim.	p-v	estim.	p-v	estim.	p-v
Rotation					+	< 0.001 ***					-	0.092 .		
Last plow			+	0.186	-	0.027 *			+	0.004 **	-	0.043 *	-	0.003 **
Legume crop													+	0.066 .
TFI							-	0.168						
mineral N	+	0.164					-	0.404	+	0.074 .			+	0.192

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992 **Table 8.** Signs of the estimates of the most parsimonious Proportional Odds Models of crop management practices on provisioning and non-marketed
 993 services and p-values of likelihood ratio tests.

	Wheat yield		Fava yield		Wheat health		Fava health		Slug pres.		Aphid pres.		Weevil pres.		Biodiversity		SNH diversity		
	estim.	p-v	estim.	p-v	estim.	p-v	estim.	p-v	estim.	p-v	estim.	p-v	estim.	p-v	estim.	p-v	estim.	p-v	
Rotation	-	0.251	+	0.017 *					+	0.062 .									
Last plow			-	0.023 *			-	0.077 .							+	0.368			
Legume crop									-	0.073 .								+	0.017 *
Treat. Freq. Index	+	0.128	+	0.067 .	-	0.006 **	-	0.970						+	0.174				
Mineral N	+	0.322										-	0.067 .						

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996 **Figures**

997 **Figure 1.** Map showing the location of the 50 fields studied.

998 **Figure 2.** Result plots of the first two dimensions of multiple factor analysis of production situation

999 variables: (a) Correlation circle, with distinction between landscape (lighter labels) and soil

1000 parameters (black labels), and (b) individual factor maps with distinction of the four production

1001 situation (PS) classified by hierarchical ascendant classification. Black symbols are farms with crops

1002 and livestock, while grey symbols are farms with crops only. See Table 2 for abbreviations of

1003 variables.

1004 **Figure 3.** Boxplots by crop management type (P: Plowing, PO: Organic Plowing, R: Reduced tillage,

1005 RO: Organic Reduced tillage, D: Direct seeding) of mean ecosystem service (ES) scores for each ES

1006 category: (a) regulating services, (b) supporting services, (c) provisioning services and (d) non-

1007 marketed services. Solid black lines represent medians, white diamonds represent means, box

1008 borders are quartiles and end of whiskers are extremum values. Asterisks identify CM types with

1009 means significantly different from that of conventional plowing (P).

1010 **Figure 4.** Individual factor map from the principal component analysis of the 17 ecosystem services,

1011 grouped by crop management. Circles are plowing systems, squares reduced tillage and triangles

1012 direct seeding. Empty symbols are conventional agriculture and full ones, organic agriculture. Only

1013 groups centroids and confidence ellipses are shown.

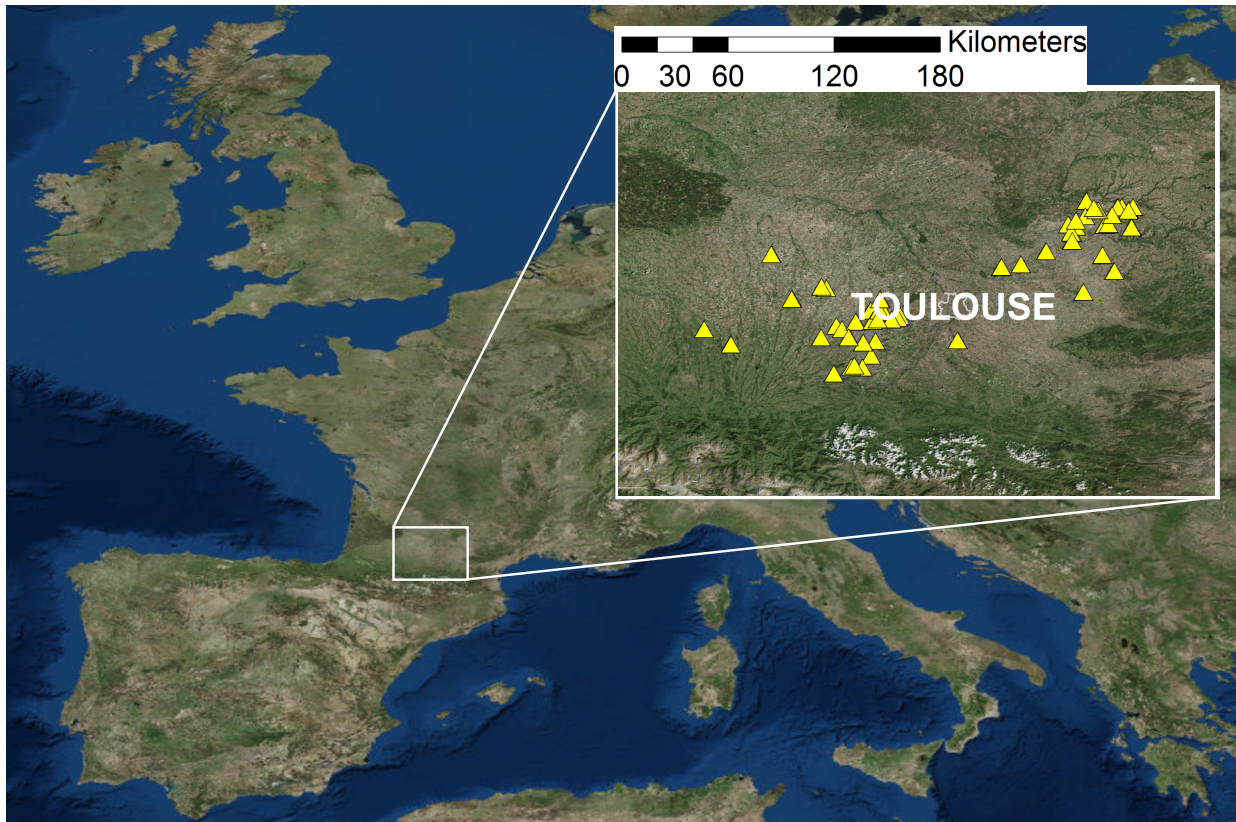
1014 **Figure 5.** Polar area diagrams of mean scores (range = 0-5) of 17 ecosystem services for each type of

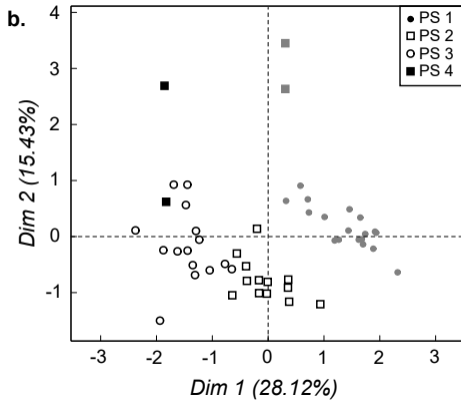
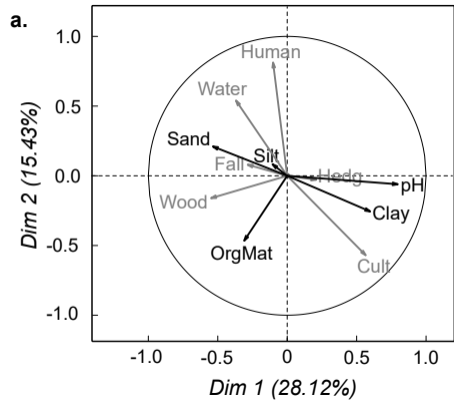
1015 crop management in each production situation group (PS): PS1, PS2 and PS3. Services are grouped by

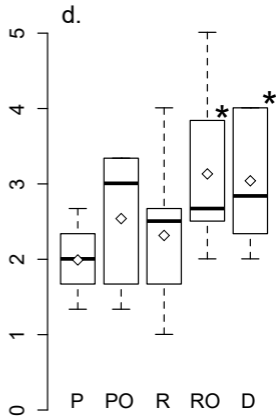
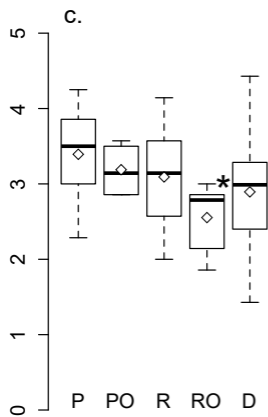
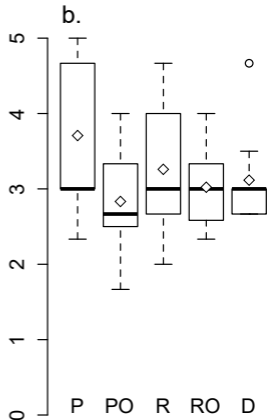
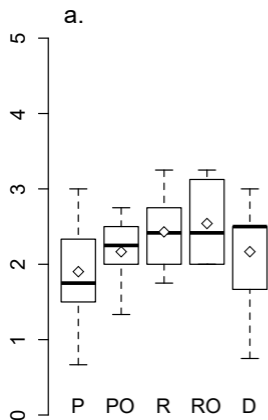
1016 color within the four ES categories. Areas with lighter coloring represent standard deviations,

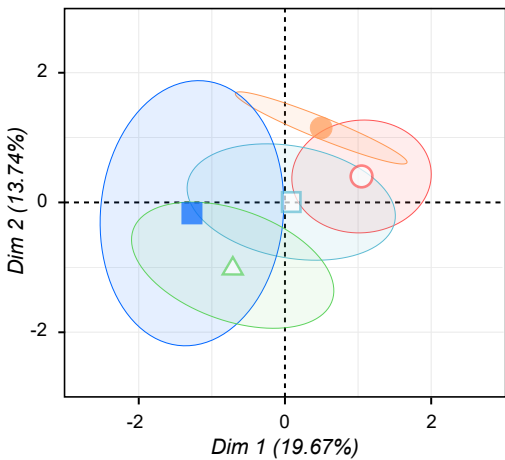
1017 hatched areas indicate unavailable data.

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Plowing

Reduced Tillage

Direct Seeding

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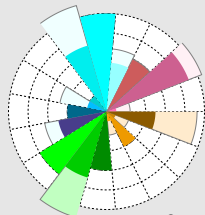
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Conv.

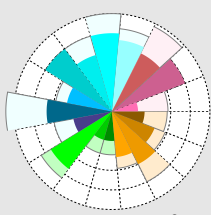
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a.

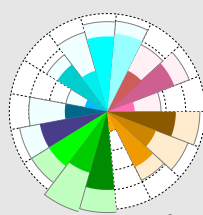
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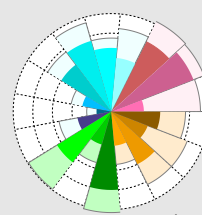
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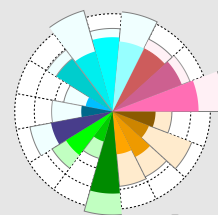
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n:6



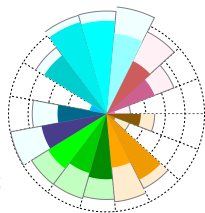
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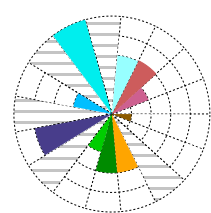
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b.

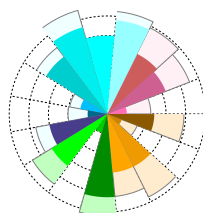
PS 2



n:8



n:1



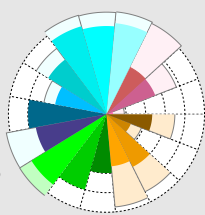
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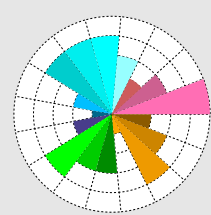
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c.

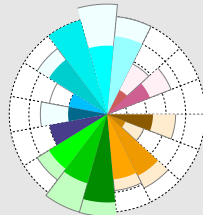
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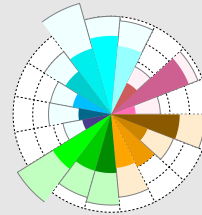
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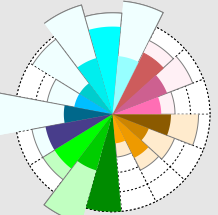
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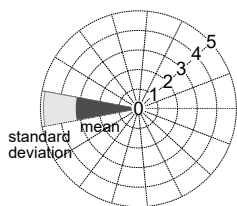
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Provisioning Services

1. Winter wheat yields
2. Fava bean yields
3. Winter wheat health
4. Fava bean health
5. Aphid pressure
6. Bruchid pressure
7. Slug pressure

Supporting Services

1. Soil aggregate stability
2. Water infiltration rate
3. Root development

Non-Marketed Services

1. Biodiversity conservation
2. SNH conservation
3. Soil GHG recycling

Regulating Services

1. Potential for pollination
2. Aphid regulation
3. Bruchid regulation
4. Ground-dwelling predators