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1 **Ecological performance underlying ecosystem multifunctionality is promoted by organic**
2 **farming and hedgerows at the local scale but not at the landscape scale**

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16 **Abstract**

- 17 1. The relative contributions of agricultural intensity and semi-natural habitats to the
18 multifunctionality and sustainability of ecosystems at different spatial scales remain
19 largely under-investigated.
- 20 2. In this study, we assessed the multifunctionality of 40 winter cereal fields and 40
21 hedgerows based on ecological, agronomic and socio-economic performance using data
22 from field surveys and interviews with farmers. We specifically focused on the effects
23 of local farming systems (organic vs. conventional) and management (cereals
24 intercropped with legumes vs. monocrops), the effects of landscape heterogeneity
25 related to hedgerow density, and the spatial extent of semi-natural habitat and organic
26 farming.
- 27 3. Multifunctionality indices associated with increased values of proxies for biodiversity
28 conservation and pest control functions were higher for hedgerows than crop fields.
- 29 4. Agroecosystem multifunctionality was similar between organic and conventional
30 farming as a consequence of antagonistic responses of individual function proxies.
31 While organic farming promoted ecological performances of crops, conventional
32 farming resulted in higher agronomic performances (i.e. yield). Interestingly, lower
33 yields of organic crops were not systematically associated with reductions in socio-
34 economic performance in terms of farmer income and labour.
- 35 5. At the landscape scale, hedgerow density and the extent of semi-natural habitats and
36 organic farming had little influence on agroecosystem multifunctionality or individual
37 function proxies.
- 38 6. *Synthesis and applications.* Our results confirm the high value of hedgerows and organic
39 farming at the local scale for the ecological performance of ecosystems. Our study
40 suggests that, among existing agri-environment schemes in Europe, hedgerow planting

41 and organic farming are appropriate tools to optimise the ecological performance of
42 ecosystems at the local scale even if antagonistic effects with agronomic performance
43 should not be neglected.

44

45 **Keywords:** Above-ground biodiversity, hedgerows, landscape, organic farming, pollination,
46 pest control, socio-economic performance, yield

47

48 **Résumé (French)**

49 1. Les contributions relatives de l'intensité de l'agriculture et des habitats semi-
50 naturels à la multifonctionnalité et à la durabilité des écosystèmes à différentes échelles
51 spatiales restent largement sous-étudiées.

52 2. Dans cette étude, nous avons évalué la multifonctionnalité de 40 parcelles de
53 céréales d'hiver et de 40 haies sur la base de leurs performances écologiques,
54 agronomiques et socio-économiques, en utilisant des données provenant à la fois de
55 relevés de terrain et d'entretiens avec des agriculteurs. Nous nous sommes
56 spécifiquement concentrés sur les effets des systèmes agricoles locaux (biologiques ou
57 conventionnels) et de la gestion (céréales en association avec des légumineuses ou
58 monocultures), et les effets de l'hétérogénéité du paysage liée à la densité des haies, à
59 l'étendue spatiale des habitats semi-naturels et à l'étendue des surfaces en agriculture
60 biologique.

61 3. La multifonctionnalité, associée à des valeurs accrues d'indicateurs de
62 conservation de la biodiversité et de lutte contre les ravageurs des cultures, était plus
63 élevée pour les haies que pour les cultures.

64 4. La multifonctionnalité des parcelles cultivées ne variait pas entre agriculture
65 conventionnelle et agriculture biologique, du fait de réponses antagonistes entre
66 fonctions. Alors que l'agriculture biologique favorise les performances écologiques,
67 l'agriculture conventionnelle est associée à des performances agronomiques plus élevées
68 (i.e. le rendement). Il est intéressant de noter que les rendements inférieurs des parcelles
69 en agriculture biologique n'étaient pas systématiquement associés à des réductions des
70 performances socio-économiques en termes de revenu et de travail des agriculteurs.

71 5. À l'échelle du paysage, la densité des haies, l'étendue spatiale des habitats semi-
72 naturels et l'étendue spatiale de l'agriculture biologique avaient peu d'influence sur la
73 multifonctionnalité des parcelles ou sur les indicateurs de fonctions considérées
74 individuellement.

75 6. Synthèse et applications. Nos résultats confirment la grande valeur des haies et
76 de l'agriculture biologique à l'échelle locale pour les performances écologiques des
77 écosystèmes. Notre étude suggère que, parmi les programmes agri-environnementaux
78 existants en Europe, la plantation de haies et l'agriculture biologique sont des outils
79 appropriés pour optimiser les performances écologiques des écosystèmes à l'échelle
80 locale même si des effets antagonistes avec les performances agronomiques existent et
81 ne doivent pas être négligés.

82 **1. Introduction**

83 Faced with global climate change and biodiversity crises, there is an urgent need to shift from
84 intensively managed landscapes toward landscapes comprising multifunctional ecosystems that
85 simultaneously provide multiple functions to support the goods and services needed by society
86 (Stürck & Verburg, 2017). Enhancing ecosystem multifunctionality in agricultural landscapes
87 presents significant challenges, given that it requires both a holistic view and practical tools to
88 reconcile the needs of agricultural production, biodiversity conservation, and ecosystem
89 functioning (Manning et al., 2018; Hölting et al., 2019).

90 In agricultural landscapes, ecosystem multifunctionality is generally investigated with
91 a focus on agroecosystems, based on consideration of their ecological, socio-economic and
92 agronomic performance. Whereas agronomic performance is largely centred on food
93 production, socio-economic performance takes into account the income and well-being of
94 farmers (Wittwer et al., 2021). With respect to ecological performance, it is accepted that
95 agroecosystems benefit from the multiple functions carried by biodiversity, including natural
96 pest control and pollination (Dainese et al., 2019). Conversely, there is growing interest in the
97 potential contribution of agriculture to biodiversity conservation (Tilman et al., 2014), even
98 where biodiversity may also be associated with negative externalities such as pest infestation
99 of crop fields (Zhang et al., 2007).

100 Gaining an understanding of the multiple drivers of ecosystem multifunctionality clearly
101 necessitates a consideration of different spatial scales (Wu & David, 2002). At the field or farm
102 scale, organic farming (OF) is considered a promising system for promoting multifunctionality
103 (Shennan et al., 2017; Smith et al., 2020; Wittwer et al., 2021). Many studies have revealed that
104 compared with conventional farming (CF), OF is beneficial for preserving farmland
105 biodiversity, including pollinator and predator communities (Tuck et al., 2014; Lichtenberg et
106 al., 2017). Although OF systems are often characterised by lower agronomic performance (i.e.,

107 crop productivity) (Shennan et al., 2017), they can be particularly profitable for farmers in terms
108 of income (underpinned by subsidies) and quality of life (Shennan et al., 2017; Smith et al.,
109 2020). However, if current organic subsidies are reduced or no longer applied, the economic
110 benefits of OF could be lower than those of CF (Crowder and Reganold, 2015). Alongside OF,
111 the conservation or implementation of semi-natural elements adjacent to crop fields, such as
112 hedgerows, provide another way to promote local biodiversity (Dainese et al., 2017; Baudry et
113 al., 2000) and associated ecosystem services such as natural pest control and pollination
114 (Montgomery et al., 2020). Indeed, hedgerows may act as a refuge and provide habitats and
115 overwintering sites for above-ground biodiversity (Sarhou et al., 2014; Garratt et al., 2017).
116 Hedgerows are thus thought to be more multifunctional than cultivated fields (Van Vooren et
117 al., 2018), despite potential negative externalities for agroecosystems, including the provision
118 of shelter for crop pests (Fusser et al., 2016).

119 Beside local drivers, there is growing evidence that a landscape perspective is essential
120 for promoting multifunctionality (Dainese et al., 2017; Botzas-Coluni et al., 2021). In this
121 regard, landscape heterogeneity, defined as the composition (i.e. diversity and amount) and
122 configuration (i.e. spatial arrangement) of landscape elements (Fahrig et al., 2011) is assumed
123 to play a key role for biodiversity and ecological processes (Benton et al., 2003; Tschardt et
124 al., 2012). Among studies investigating the effects of landscape heterogeneity on
125 multifunctionality, most have focused on few ecological functions, generally studied one-by-
126 one (Holzschuh et al., 2008; Chaplin-Kramer et al., 2011). Studies focusing on multi-diversity
127 (Sirami et al., 2019) or on simultaneous ecological and agronomic performance (Martin et al.,
128 2016; Martin et al., 2019; Smith et al. 2020; Botzas-Coluni et al., 2021) are particularly scarce.
129 These studies revealed that a large amount of semi-natural habitat (SNH) and application of OF
130 methods are beneficial for pollinators and natural pest enemies. They also showed that
131 increasing landscape configuration (by decreasing mean field size or increasing edge density)

132 benefited multitrophic diversity (Sirami et al. 2019) as well as pollination and pest regulation
133 (Martin et al., 2019; Botzas-Coluni et al., 2021). Conflicting results about the effect of
134 landscape configuration on agronomic performance (mainly crop yield) have been reported;
135 increasing mean field size benefited crop yield (Botzas-Coluni et al., 2021), and arable-
136 dominated landscapes with high edge densities achieved high yields (Martin et al., 2016; Martin
137 et al., 2019). Smith et al. (2020) showed that yield gaps between organic and conventional farms
138 increased and profitability benefits of OF decreased as crop field size increased in the
139 landscape. Despite these studies, there remains relatively little information available regarding
140 the influence of landscape heterogeneity on agroecosystem multifunctionality.

141 In the present study, we investigated the effects of OF and hedgerows on the
142 multifunctionality of ecosystems in agricultural landscapes at different spatial scales.
143 Specifically, we focused on (i) ecological performance associated with above-ground
144 biodiversity (conservation, pollination, pest control and pest infestation), (ii) socio-economic
145 performance (income and indicators of farmer labour), and (iii) agronomic performance (yield).
146 At the local scale, we expected higher multifunctionality correlated with ecological
147 performance in hedgerows than in crop fields. We also expected agroecosystem
148 multifunctionality to be higher in OF fields compared with CF fields. Lastly, we expected
149 higher agroecosystem multifunctionality in heterogeneous landscapes (i.e. those with a higher
150 proportion of SNH and OF and/or higher hedgerow density).

151 **2. Materials and methods**

152 **2.1. Study site**

153 The study was conducted in the Zone Atelier Armorique (47°55'N, 1°38'W), north-western
154 France (European LTER Network; osur.univ-rennes1.fr/za-armorique/). This area is
155 characterised by a dense hedgerow network (bocage), mixed dairy farming and cereal

156 production. The cultivated area is dominated by winter cereals and maize, along with grassland,
157 and is interspersed with semi-natural elements (i.e. woodlots and hedgerows).

158 We selected 40 winter cereal fields (20 fields under OF and 20 under CF), distributed
159 along two independent landscape gradients (Spearman correlation, $\rho = 0.19$) based on (i) the
160 varying extent (percentage cover) of OF (from 0% to 82% in 500 m radius circles centred on
161 studied fields), and (ii) the varying density (length) of hedgerows (from 1368 m to 5953 m, in
162 500 m radius circles; Fig. 1). The average distance between selected fields was $1361.12 \pm$
163 253.32 m and the minimum distance was 222.10 m. Cereal fields were under monoculture of
164 winter cereals such as wheat (*Triticum* spp.), triticale (*Triticosecale* spp.) or oat (*Avena sativa*
165 L.), hereafter referred to as ‘Cereal crops’ (10 OF and 20 CF fields), or winter cereals
166 intercropped with legumes, namely faba bean (*Vicia faba* L.) or pea (*Pisum sativum* L.), without
167 distinct row arrangement, hereafter referred to as ‘Mixed crops’ (10 OF fields; see Table S1 in
168 Supporting Information). This design reflects the practices of farmers in the study area, namely
169 frequent cultivation of ‘Mixed crops’ on OF farms, and a predominance of ‘Cereal crops’ on
170 CF farms. Field size was comparable between CF, OF Cereal crops and OF Mixed crops. In
171 addition, there were no significant differences in management practices (number of
172 interventions, fertiliser input and ploughing) between OF Cereal crops and OF Mixed crops
173 (Fig. S1). Surveys were conducted both in the centre of focal fields and in their adjacent
174 hedgerows. Hedgerows were all characterised by the simultaneous presence of herbaceous,
175 shrub, and tree layers. All farmers gave us permission for fieldwork. The study did not require
176 ethical approval.

177 **2.2. Ecological, agronomic, and socio-economic performance**

178 Multifunctionality was assessed based on (i) four ecological functions (biodiversity
179 conservation, pollination, pest control and pest infestation) based upon abundance or richness
180 of taxa as proxies of ecological performance; (ii) two functions (labour and semi-net margin)

181 as proxies of socio-economic performance; and (iii) one function (crop yield) as a proxy of
182 agronomic performance (Fig. 1).

183 **2.2.1 Proxies of ecological functions**

184 To assess ecological functions, we conducted field sampling of predatory arthropods, insect
185 pests, flower-visiting insects and spontaneous vegetation. Predatory arthropods (carabids;
186 *Coleoptera: Carabidae*), spiders (*Araneae*), staphylinids (*Coleoptera: Staphylinidae*),
187 ladybirds (*Coleoptera: Coccinellidae*) and insect pests (aphids; *Hemiptera: Aphidoidea*) were
188 collected twice, in May and June 2020, using a vacuum method (D-vac), with a series of five
189 aspirations performed at 10-m intervals along a 50 m-long transect located in each habitat
190 (hedgerow and centre of the field; see details in Appendix S1). The D-vac aspirations were
191 carried out through the vegetation and on the ground in order to capture the arthropods present
192 on these two strata. Data from the series of aspirations (N = 5) and the sampling periods (N =
193 2) were pooled to obtain estimates of the total abundance of predatory arthropods and aphids
194 per habitat type (hedgerow or crop field). Carabid beetles were identified at the species level
195 following Roger et al. (2010). Visual counts of flower-visiting insects were performed three
196 times in May, June and July 2020, by walking along 50 m-long transects (one per habitat) at a
197 slow pace for 5 min. Flower-visiting insects were assigned to one of the following morpho-
198 groups: honeybees, *Bombus terrestris* agg., *Bombus lapidarius*, *Bombus pascuorum*, solitary
199 bees < 1 cm, solitary bees > 1 cm, aphidophagous hoverflies, non-aphidophagous hoverflies,
200 butterflies, other Diptera, other Coleoptera and other Hymenoptera. Data were pooled over the
201 three sampling periods to determine the abundance and richness of morphogroups of flower-
202 visiting insects per habitat. Single surveys of spontaneous vegetation were conducted in 10
203 quadrats (1 × 1 m) placed at 5 m intervals along each 50 m-long transect. Plant species were
204 identified according to *Flora Europaea* (Tutin et al., 1993) and corresponding percentage cover
205 was estimated visually. We distinguished troublesome weeds (i.e. species that potentially cause

206 high yield losses or hinder harvesting operations) based on expert knowledge from personnel
207 at the Chamber of Agriculture of Brittany, France).

208 From this dataset, we estimated the biodiversity conservation function by
209 simultaneously considering the total species richness of carabid beetles, vascular plants, and
210 the number of morpho-groups of flower-visiting insects. The abundance of flower-visiting
211 insects was used as a proxy of the pollination function whereas the abundance of all predatory
212 arthropods was used as a proxy of the pest control function. Aphid abundance and the mean
213 cover of troublesome weeds were selected as proxies of the pest infestation function.

214 ***2.2.2 Proxies of agronomic and socio-economic functions***

215 We conducted interviews with farmers (OF fields = 16 farmers; CF fields = 17 farmers) to
216 obtain data on soil preparation practices (from harvest of the preceding crop [$n - 1$] to sowing
217 of the next crop [$n + 1$]), pest management (mechanical or chemical weeding, fungicide,
218 insecticide and molluscicide use), fertilisation (mineral or organic), and harvested products
219 (yield). In a few cases, two to three fields were managed by the same farmer. Regardless, data
220 collected were specific to each field (i.e. farmers who managed more than one field provided
221 information for each field). We used Agrosyst software (Jolys et al., 2016) to calculate socio-
222 economic performance (i.e. labour and semi-net margin). The labour proxy ($\text{h}\cdot\text{ha}^{-1}$)
223 corresponded to the cumulative duration of interventions in sampled fields, while the semi-net
224 margin ($\text{€}\cdot\text{ha}^{-1}$) was calculated by subtracting operational expenses (seeds and inputs) and
225 equipment (depreciation, maintenance and gasoline) from the market price of crops. The semi-
226 net margin closely approximates the actual income of farmers.

227 **2.3. Multifunctionality indices**

228 Various methods exist for synthesising the multifunctionality of ecosystems that attribute
229 different weight to the importance of individual functions and services. A straightforward and

230 common technique consists of summing or averaging all functions and services in a considered
231 ecosystem. Alternatively, the ‘threshold approach’ accounts for functions and services that are
232 above a certain threshold, based on the assumption that only high supply levels contribute a
233 value to the multifunctional environment (Byrnes et al. 2014; Hölting et al. 2019). Here, we
234 used the ‘averaging approach’, by averaging the normalised values of proxies to yield a single
235 index. The two main methods for normalization are standardisation by the maximum value
236 (Mouillot et al. 2011) or using z-score (Maestre et al. 2012). Here, we standardised each
237 function using the maximum observed value across all sites to remove the effects of differences
238 in the scales of measurement among functions. In the case of functions for which negative
239 values indicate higher levels of function (i.e. infestation and labour), the values of the proxies
240 were inverted such as 1-infestation and 1-labour. Although there are certain reservations
241 regarding the use of maximum values for standardisation (e.g. sensitivity to outliers),
242 standardising the scale of a multifunctional index by a maximum value creates a metric that is
243 intuitively understandable in comparison with the z-score method (Manning et al., 2018). We
244 also applied normalisation using the z-score method (by subtracting the mean of the values and
245 dividing by the standard deviation) to compare the sensitivity of our results in relation to the
246 standardisation method. In that latter case, we transformed labour and infestation to a negative
247 scale by multiplying by -1. Differences in results between the two methods were highlighted.

248 **2.4. Landscape variables**

249 Land-cover maps of the landscape sites were digitised using aerial ortho-photographs (BD
250 ORTHO IGN, 2017) and field surveys using Arcgis 10.8.1 (Environmental Systems Resource
251 Institute; ESRI, 2020). Nine land-cover types (woodland, hedgerows, grassland, herbaceous
252 strips, winter cereal, maize, other crop, water, and urban area) were mapped in 1000 m radius
253 circles centred on each sampled field. In addition, maps of farming systems (OF vs. CF) were

254 created based on existing data obtained for the same study area (Puech et al., 2015) and updated
255 based on information obtained from our interviews with farmers in the present study.

256 From these maps, we calculated two metrics for landscape composition (the percentage
257 cover of SNH [% SNH including woodlands, permanent grasslands, hedgerows and fallows]
258 and the percentage cover of OF (without the focal OF fields [% OF]); and one metric for
259 landscape configuration: (hedgerow density [total hedgerow length]; Fig. S2). All metrics were
260 calculated in 250 m, 500 m and 1000 m radius circles using Chloe software (Boussard et al.,
261 2020). According to Dormann et al. (2013), we considered data not overly correlated when
262 Spearman $\rho < |0.7|$. We detected no strong correlation between landscape metrics (Table S2).

263 **2.5. Statistical analysis**

264 First, we compared the multifunctionality of hedgerows and crop fields. We generated a
265 ‘biodiversity-related’ multifunctionality index based upon the four proxies describing
266 ecological performance. We used generalized linear mixed models (GLMMs) with habitat type
267 (hedgerow vs. crop field) as a fixed effect and the identity of the field (Field ID) as a random
268 effect to account for the spatial non-independence between fields and hedgerows. The model
269 formula was:

$$270 [1] \quad X \sim \text{Habitat type (hedgerow vs. crop field)} + (1 | \text{Field ID})$$

271 where X is the biodiversity-related multifunctionality index or associated proxies of ecological
272 functions.

273 Second, we tested the effect of agricultural management (CF, OF Cereal crops and OF
274 Mixed crops) on the multifunctionality index and proxies of ecological, agronomic and socio-
275 economic functions using generalized linear models (GLMs). We generated a second
276 (agroecosystem) multifunctionality index, dedicated to crop fields, integrating the seven

277 proxies describing ecological, agronomic and socio-economic performances. The model
278 formula was:

$$279 \quad [2] \quad Y \sim \text{Agricultural management (CF vs. OF}_{\text{cereal crops}} \text{ vs. OF}_{\text{mixed crops}})$$

280 where Y is the agroecosystem multifunctionality index or associated proxies of functions.

281 Lastly, GLMs were used to assess the effects of local farming system (OF vs. CF) and
282 landscape heterogeneity (% SNH, % OF and hedgerow density) on the agroecosystem
283 multifunctionality index and associated proxies of functions at 250 m, 500 m and 1000 m,
284 according to the formula:

$$285 \quad [3] \quad Y \sim \text{Farming system (CF vs. OF) + \% SNH + \% OF + hedgerow density}$$

286 According to standardisation by the maximum value, multifunctionality index and proxy
287 values ranged from 0 to 1. We thus used the Beta family in GLMMs (model [1]) with the
288 ‘glmmTMB’ R package (Brooks et al., 2020) and a Beta distribution in GLMs (models [2] and
289 [3]) using the ‘betareg’ R package (Zeileis et al., 2021). According to standardisation by z-
290 score, multifunctionality index and proxy values followed a normal distribution. Explanatory
291 variables were centred and scaled to enhance the interpretability and comparison of regression
292 coefficients (Schielezeth, 2010). For model [3], a full averaging procedure of models was
293 performed with a ΔAICc value <4 (Burnham et al., 2011) using the MuMIn R package (Bartoń,
294 2020). We checked for multi-collinearity (Cade, 2015) using variance inflation factors (VIFs),
295 and they were below the collinearity threshold (<2.5) for all models (Dormann et al., 2013).
296 Post-hoc tests were performed to distinguish among the effects of the three agricultural
297 management regimes using the ‘emmeans’ package (Lenth, 2021). No deviations in model
298 residuals for normality and homoscedasticity were observed. No spatial autocorrelation was
299 found in models except for pest control (Fig. S3). We thus re-run model at 250 m for this proxy
300 adding geographical coordinates (X, Y) as covariates. Finally, we estimated variance explained

301 using the pseudo-R² statistic (or R² when using the z-score transformation) of the full models
302 (Nakagawa & Schielzeth, 2013).

303 **3. Results**

304 We collected 17,820 spiders, 10,963 carabid beetles (67 species), 8390 staphylinids, 3414
305 aphids, and 159 ladybird larvae (Table S3). We observed 4076 pollinating insects and 170 plant
306 species.

307 **3.1. Comparison between hedgerows and crop fields**

308 The value of the biodiversity-related multifunctionality index was higher for hedgerows than
309 adjacent crop fields (Fig. 2; details of the GLMM results are presented in Table S4). Three of
310 the four assessed proxies of ecological function were higher for hedgerows than crop fields
311 (Fig. 2). No difference in pollination function proxy was observed between hedgerows and crop
312 fields. These results hold true regardless of standardisation method for multifunctionality index,
313 while values of the pollination and pest infestation functions were similar for hedgerows and
314 fields when using the z-score transformation; Table S5).

315 **3.2. Comparison between agricultural management**

316 Values for the agroecosystem multifunctionality index were lower for CF fields than OF Mixed
317 crops, but no significant differences were found between CF fields and OF Cereal crops (Fig.
318 3; Table S6). Difference between CF and OF Mixed crops was no longer significant when using
319 the z-score transformation (Table S7).

320 Focusing on ecological performance, values for the proxies of conservation and
321 pollination functions were found to be significantly higher for OF (Cereal crops and Mixed
322 crops) than CF fields. Higher values for the pest control proxy were obtained for OF Mixed
323 crops, whereas no significant difference was observed between OF Cereal crops and CF fields.

324 Higher values of the pest infestation proxy were obtained for OF Mixed crops fields than for
325 CF fields (Fig. 3). Pollination was identified as the proxy showing the greatest difference among
326 agricultural management types, ranging from 0.002 ± 0.008 for CF fields to 0.53 ± 0.37 for the
327 OF Cereal crops (Fig. 3). Focusing on agronomic performance, crop yields were higher for CF
328 than OF (Cereal crops and Mixed crops) fields (Fig. 3; Table S6). Higher values for labour were
329 obtained for OF Cereal crops than for CF fields, whereas no significant difference was observed
330 between OF Mixed crops and CF fields. No significant difference among CF and OF was
331 observed with respect to semi-net margin (Fig. 3; Table S6). Similar results were obtained with
332 the z-score transformation except for labour (Table S7). Significant difference in labour among
333 agricultural management types was no longer observed with the z-score transformation.

334 **3.3. Relative effects of local farming system and landscape heterogeneity**

335 Local farming system had a significant and overriding impact on ecological and agronomic
336 performances of agroecosystems, but did not influence their socio-economic performance nor
337 their multifunctionality. Proxies for ecological functions had higher values for OF than CF,
338 while crop yields were lower for OF than CF (Table 1). Overall, no landscape effects were
339 observed (Table 1). No significant effect of landscape metrics on the agroecosystem
340 multifunctionality index were observed, regardless of the spatial scale considered or the
341 standardisation methods used (Tables S8-9). The amount of semi-natural habitat (% SNH) was
342 significantly and positively correlated with biodiversity conservation at 500 m and 1000 m with
343 the z-score transformation while no significant effect was detected with standardisation using
344 the maximum value (Tables S8-9). The amount of semi-natural habitat (% SNH) also had a
345 significant and positive effect on the pest control function at 500 m (Table S9), but this effect
346 was no longer observed following standardisation using the maximum value (Table S8). No
347 significant landscape effects were observed on socio-economic nor agronomic performance,

348 and this result hold true regardless of the standardisation method used for indices (Tables S8-
349 9).

350 **4. Discussion**

351 In this study, by combining a global assessment of the multifunctionality (aggregated index)
352 and proxies of the ecological, socio-economic, and agronomic performance of ecosystems, we
353 were able to identify broad trends in the effects of hedgerows and OF at local and landscape
354 scales on the multiple performances of ecosystems in agricultural landscapes.

355 At the local scale, we detected higher biodiversity-related multifunctionality for hedgerows
356 than for crop fields. This is consistent with the findings of previous studies that focused on
357 individual taxa or functions, and that highlighted higher species diversity of spiders (Mestre et
358 al., 2018) and higher levels of pest control in hedgerows compared to crop fields (Morandin et
359 al., 2016; Van Vooren et al., 2017). The higher ecological value of hedgerows can be explained
360 by the lower levels of disturbance they suffer compared with crops. Hedgerows are not
361 ploughed and rarely chemically treated, which are practices that have detrimental effects on
362 arthropods and plants (Holland & Reynolds, 2003; Zaller & Brühl, 2021). However, hedgerows
363 may be influenced to some extent by chemical drift. Unlike fields, hedgerows are typically
364 characterised by a complex structure, comprising diverse vegetal strata, high-quality floral
365 resources over time, dead wood, and a stony ground cover, together providing suitable habitat
366 conditions and/or diverse food resources for ground-dwelling arthropods, pollinators and plants
367 (Lecq et al., 2017; Dover, 2019). By promoting the diversity of natural enemies, hedgerows are
368 also assumed to favour the natural control of pests that may infest adjacent fields (Van Vooren
369 et al., 2017; Mestre et al., 2018), although in this regard, our observations of high pest
370 abundance (aphids and troublesome weeds) in hedgerows may counteract any beneficial effects.
371 While previous work reported higher diversity of pollinators (Hannon & Sisk, 2009) and higher
372 levels of pollination in hedgerows (Morandin & Kremen, 2013) compared to crop fields, no

373 significant difference in pollination function proxy was observed here. This result could be
374 explained by the fact that crop fields encompassed mixed crops, sown with legume species
375 (Fabaceae) known to be particularly attractive for long-tongued pollinator species, i.e. most
376 bumblebees and some solitary bees such as Apidae and Megachilidae (Cole et al., 2022).

377 Contrary to our expectations and previous studies (e.g. Wittwer et al., 2021), we did not
378 find higher agroecosystem multifunctionality in OF fields than in CF fields. This result can be
379 attributed to the antagonistic effects of organic farming on ecological and agronomic
380 performances (Herzog et al. 2019). Our results indicated enhanced ecological performance of
381 organically cultivated fields. Similar findings have been reported previously showing higher
382 levels of pest control and pollination in OF fields, as a consequence of increases in the
383 abundance of predatory arthropods and pollinators (Lichtenberg et al., 2017; Tamburini et al.,
384 2020). The greater diversity and abundance of these beneficial taxa can be ascribed to the
385 absence of chemical pesticide and mineral fertiliser inputs in organic systems, the use of which
386 is known to have direct or indirect deleterious effects on above-ground biodiversity (Desneux
387 et al., 2007; Sánchez-Bayo, 2021). By contrast, crop yields were notably lower in OF fields,
388 thereby suggesting an antagonism between ecological and agronomic performance (Wittwer et
389 al., 2021; Duflot et al., 2022). Such reductions in crop yields under OF can be explained, at
390 least in part, by the accumulation of pathogens and troublesome weeds in the absence of
391 pesticide application (Shennan et al., 2017), as observed in the present study. Interestingly, the
392 lower yields in OF we observed were not mirrored by reductions in the semi-net margins
393 obtained by farmers, indicating that in the context of our study, any economic losses due to
394 reduced yields in OF can be offset by the price premiums commanded by organic products and
395 lower input costs (Crowder & Reganold, 2015).

396 Contrary to expectations, we found that social performance related to labour (cumulative
397 duration of interventions) was comparable under organic and conventional cultivation (Orsini

398 et al., 2018). The comparable levels of labour observed between organic and conventional fields
399 could be associated with the calculation of this proxy *per se*, with interventions by organic
400 farmers being less frequent but more prolonged. The duration of interventions might also have
401 been underestimated for OF since manual weeding operations were not considered.
402 Nevertheless, OF would appear to be advantageous in terms of farmer workload, in addition to
403 being more diversified and less repetitive than CF (Jansen, 2000). Moreover, in general, higher
404 levels of farmer satisfaction (e.g. health, work satisfaction, and social recognition) are reported
405 among those engaged in OF (Shennan et al., 2017).

406 Further in-depth analysis of agricultural management in OF revealed higher values for
407 biodiversity conservation and pest regulation in systems cultivating mixed legume-cereal crops
408 than on farms monocropping cereals. This could be attributed to the provision of abundant floral
409 resources (during the blooming of faba beans and peas) for nectar-consuming natural enemies
410 (Beyer et al., 2020), as well as a more favourable microclimate and complex vegetation
411 structure that provides shelter for certain natural enemies (De Heij et al., 2022). Our results also
412 highlighted differences in social and economic performances according to agricultural
413 management, but only when using the standardisation by the maximum value. OF cereal crops
414 were characterised by higher labour than the two other management types, indicating that they
415 were less advantageous in terms of farmer workload in comparison with CF crops and OF
416 mixed crops. This result can be explained by the fact that organic crops rely on frequent
417 mechanical weeding for weed control (Bondy & Grundy, 2001). However, in mixed crops with
418 legumes, mechanical interventions are difficult, even not possible, due to differences in growth
419 stage of the two sown species (Bedoussac et al., 2015). Organic mixed crops had also lower
420 economic performance than organic cereal crops, probably because they are specifically grown
421 by farmers for animal feeding. These findings accordingly underline the importance of taking
422 into account the diversity of agricultural practices in OF to better understand the drivers of the

423 multiple performances of agroecosystems (Puech et al., 2014). The similar value of
424 agroecosystem multifunctionality index between the three management types can again
425 probably be explained by the fact that we averaged functions during index calculation (i.e.
426 mixing high ecological performance with reduced yields in OF Cereal crops).

427 Most studies that have sought to integrate the landscape level in analyses of ecosystem
428 multifunctionality have involved a global assessment of land-use scenarios (e.g. Gong et al.,
429 2019), but without due consideration of ecological, socioeconomic and agronomic performance
430 simultaneously, although recent research points in this direction (Martin et al., 2019; Sirami et
431 al., 2019). To the best of our knowledge, the present study is the first to investigate the effects
432 of landscape heterogeneity related to semi-natural habitat (% SNH and hedgerow density) and
433 farming practices (% OF) on multifunctionality. We predicted higher agroecosystem
434 multifunctionality in landscapes with a high density of hedgerows and extent of OF, as a
435 consequence of enhanced ecological (Holzschuh et al., 2008; Muneret et al., 2019; Zirbel et al.,
436 2019) and agronomic (Redhead et al., 2020) performance. However, in contrast to expectations,
437 our findings indicate that landscape heterogeneity had no appreciable influence on
438 multifunctionality. The amount of semi-natural habitat had a positive effect on biodiversity
439 conservation when using the z-score transformation. Although our biodiversity conservation
440 index was composed of three taxa only and was restricted to above-ground biodiversity, this
441 result provides additional evidence that increasing the amount of semi-natural cover in the
442 landscape enhances local diversity in agroecosystems (Tschardt et al., 2005). We also showed
443 that the extent of organic farming did not have any effect on multifunctionality nor
444 performances. Care must be taken when considering this result because confounding factors
445 might occur despite our effort. We cannot fully disentangle the amount of organic farming in
446 the immediate vicinity of fields from farming systems (i.e. aggregation of fields under organic
447 farming at small scales; Fig. S2). Finally, we did not observe any effect of landscape

448 configuration related to hedgerow density. This result might reflect the contrasting responses
449 of the studied taxa, given that hedgerows can serve as either a barrier or corridor to species
450 dispersal, as demonstrated for carabid beetles, plants and pollinator guilds (Mauremooto, 1995;
451 Krewenka et al., 2011; Klaus et al., 2015; Vanneste et al., 2020). Another explanation may
452 come from the truncated gradient of hedgerow density towards high values. Indeed, our study
453 area was characterised by a dense hedgerow network (bocage). It is therefore possible that our
454 hedgerow density gradient was not broad enough to observe significant responses.

455 Lastly, the ‘averaging’ approach employed here produces a single metric to estimate the
456 multifunctionality index by averaging the values of all standardised ecosystem functions. Using
457 two standardisation methods (maximum value *vs.* z-score), we showed that our main results
458 hold true, underlining their robustness. Nevertheless, the antagonistic responses of individual
459 functions underline the limitation in calculating a single aggregated index to assess the effects
460 of environmental drivers on ecosystem multifunctionality, as highlighted by Byrnes et al.
461 (2014). We advocate that such an approach, in which functions are assumed to be substitutable,
462 is indissociable from a ‘function by function’ analysis to elucidate trade-offs and synergies
463 among ecosystem functions, and provide more reliable information for management and
464 decision-making processes.

465 **5. Conclusion**

466 To meet multiple societal expectations regarding environmental preservation, agricultural
467 efficiency, and the maintenance of human well-being, it is necessary to develop management
468 approaches that enhance the multifunctionality of ecosystems and, at broader spatial scales, of
469 agricultural landscapes (Stürck & Verburg, 2017). This represents a considerable challenge,
470 given that it requires not only identifying management options that simultaneously target the
471 ecological, agronomic and socio-economic performance of ecosystems, but also the appropriate
472 scales at which to implement them (Marja et al., 2022).

473 By investigating the effects of semi-natural habitat and farming systems at local and
474 landscape scales, our study provides insights on their potential contributions to sustaining
475 multifunctionality within agricultural landscapes. We found that hedgerows represent valuable
476 semi-natural habitats at the local scale and contribute to enhancing ecosystem
477 multifunctionality, owing to their higher importance for biodiversity conservation and
478 associated ecological functions compared with cultivated fields. We also demonstrated that
479 cultivation of organic crops has higher ecological performance but lower agronomic
480 performance than cultivation of conventional crops resulting in similar levels of agroecosystem
481 multifunctionality. Planting hedgerows and expanding organic farming are two key elements
482 among a diverse collection of agri-environment schemes (AESs) developed in Europe to
483 counteract the detrimental environmental effects of intensive agriculture. Our current findings
484 highlight that these two AESs are potentially effective tools that can make a valuable
485 contribution to promoting ecological performance underlying multifunctionality in agricultural
486 landscapes, particularly in the bocage-type landscapes characteristic of north-western Europe.
487 However, our observations also underline the fact that the adoption of organic practices on
488 farms might necessitate trade-offs between crop productivity and ecological benefits.
489 Moreover, the apparent lack of any significant multifunctionality-associated effects of
490 hedgerows and organic farming at the landscape scale would tend to indicate that local
491 agricultural fields and adjacent margins represent pertinent levels of management for the
492 implementation of these AESs on farms.

493 **Authors' contributions**

494 Audrey Alignier, Stéphanie Aviron, Julien Pétilon, and Eloïse Couthouis conceived the study;
495 Audrey Alignier and Stéphanie Aviron obtained funding; Eloïse Couthouis, Audrey Alignier,
496 and Stéphanie Aviron performed data collection and curation, and identified species; Eloïse
497 Couthouis, Audrey Alignier and Stéphanie Aviron analysed the data; Eloïse Couthouis, Audrey

498 Alignier, Stéphanie Aviron, and Julien Pétilion wrote the manuscript. All authors contributed
499 critically to the manuscript and gave final approval for publication.

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508

509 **Conflicts of interest**

510 The authors declare that they have no conflicts of interest.

511

512 **Data availability statement**

513 Data available via the Dryad Digital Repository <https://doi.org/10.5061/dryad.k98sf7m8z>
514 (Couthouis et al., 2022).

515

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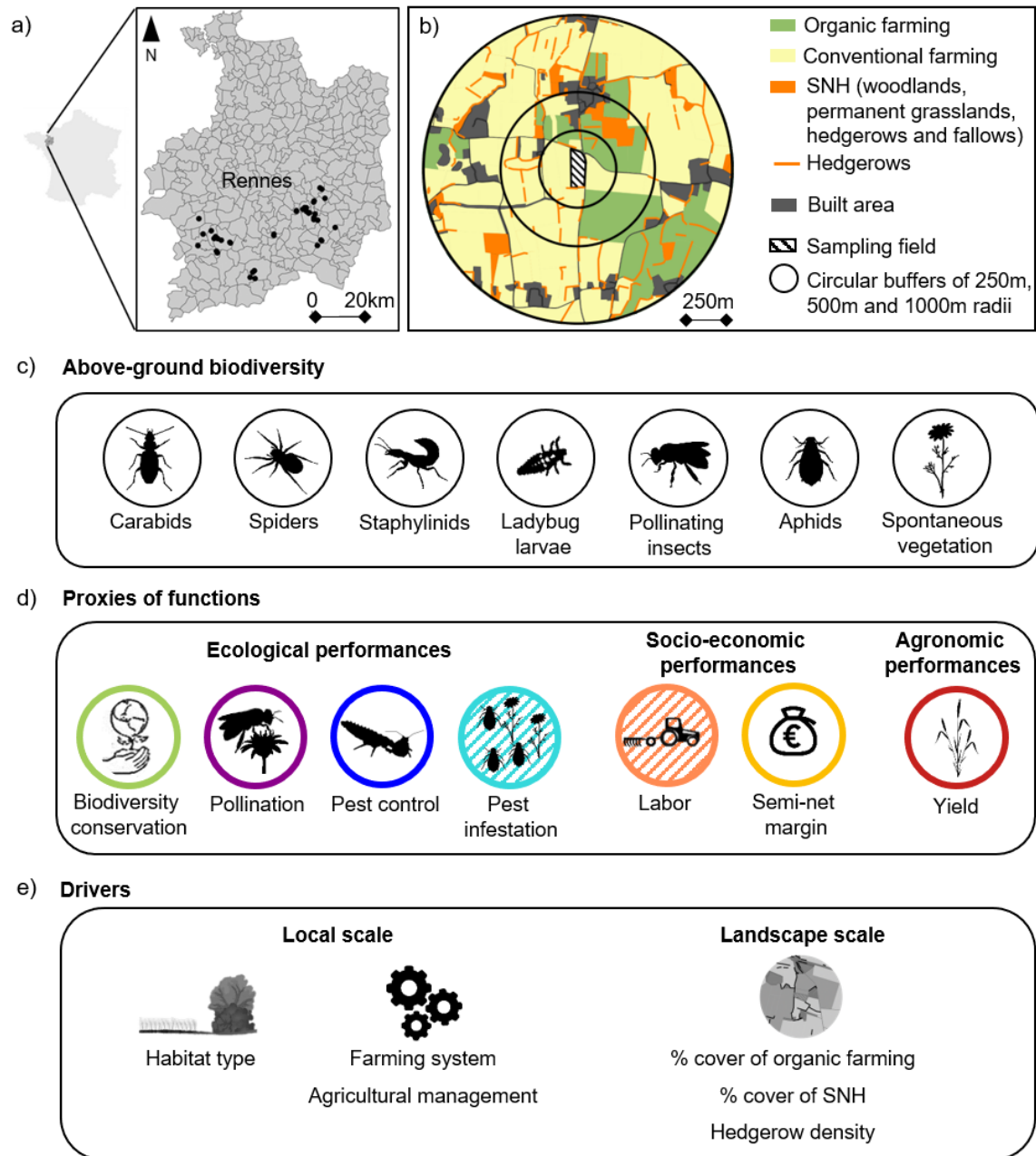
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792 **Table 1.** Summary of the results from model averaging using generalised linear models (GLMs) for the effects of local farming system
793 (conventional vs. organic) and landscape heterogeneity on the agroecosystem multifunctionality index (standardised by the maximum value) and
794 individual functions. +, positive effect, -, negative effect, n.s., not significant. Brackets indicate the spatial scale for which the significant effect
795 was observed. Where not mentioned, the significant effect was observed over all spatial scales. OF, organic farming; SNH, semi-natural habitats.
796 For details, see Table S8.

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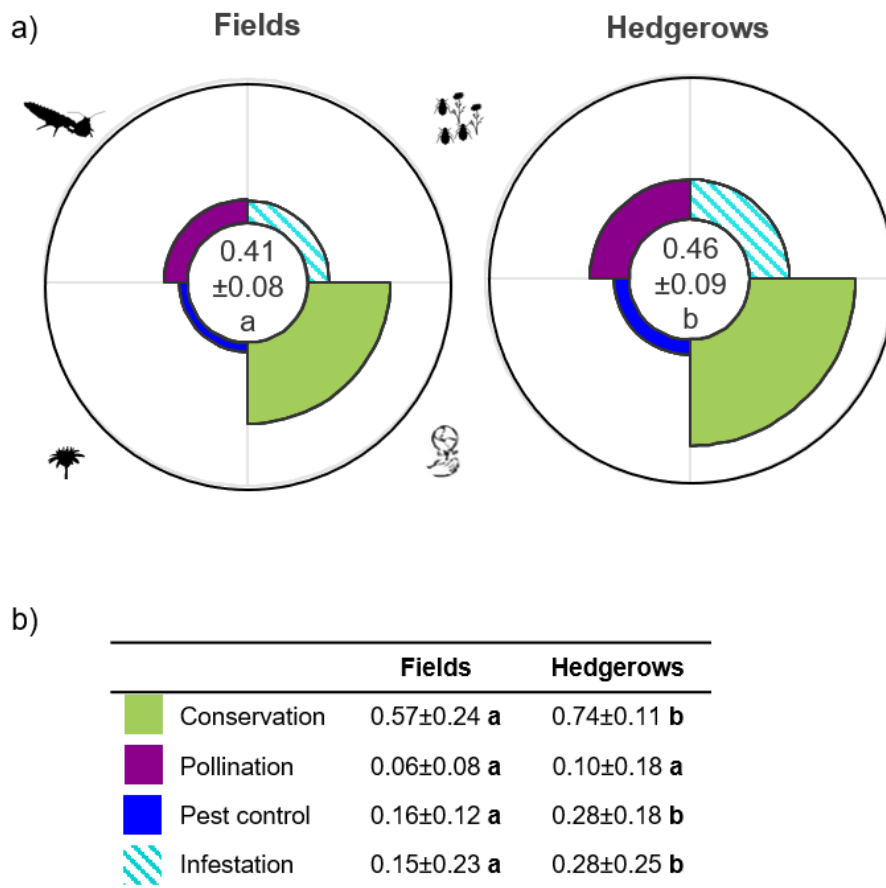
	Multifunctionality index	Ecological performance				Socio-economic performance		Agronomic performance
		Conservation	Pollination	Pest control	Pest infestation	Labour	Semi-net margin	Yield
Local OF	n.s.	+	+	+	+	n.s.	n.s.	-
% SNH	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
% OF	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Hedgerow density	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

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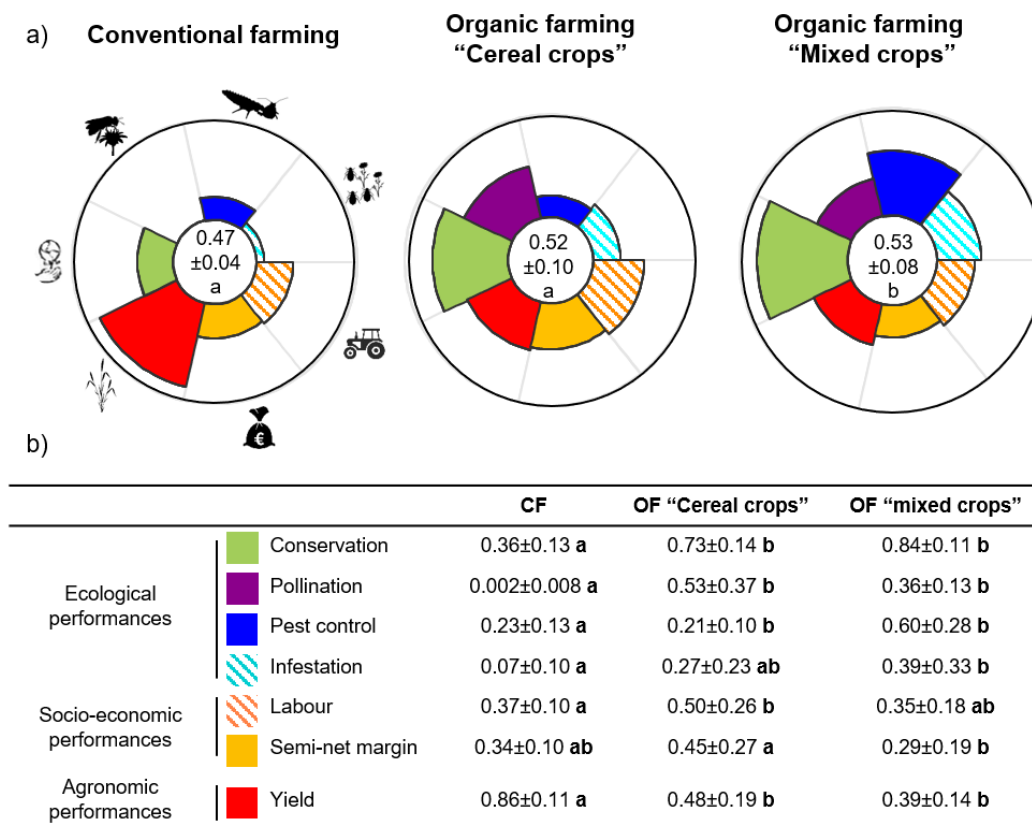
799

800 **Figure 1.** (a) Map showing the location of the 40 sampled fields and adjacent hedgerows in the
 801 study area. (b) Landscape mapping of farming systems and SNH. Three buffer radii (250 m,
 802 500 m, 1000 m) were considered around sampled fields. (c) Details of the above-ground
 803 biodiversity studied. (d) Overview of proxies of the seven ecological, socio-economic and
 804 agronomic functions. The two hatched proxies of functions (infestation and labour) are those
 805 providing negative externalities. (e) Local and landscape drivers considered in the study. SNH,
 806 semi-natural habitats. Adapted from Valdés et al. (2019).



807

808 **Figure 2.** (a) Standardised proxies of ecological functions averaged for the two habitats studied
 809 (crop fields vs. hedgerows). Average values of the biodiversity-related multifunctionality index
 810 (\pm standard error, SE) are shown in the centre of the diagrams. Negative externalities are
 811 indicated by the hatched sectors and have been inverted for easier interpretation (i.e. the higher
 812 the proxy of the function, the lower the overall index of multifunctionality). (b) Means (\pm SE)
 813 of the standardised proxies of ecological functions. Different letters indicate significant
 814 differences between the two habitats (pairwise comparison with least squares means).



815

816 **Figure 3.** (a) Standardised proxies of ecological, socio-economic and agronomic functions
817 according to agricultural management. Average values of the multifunctionality index (\pm SE)
818 are shown in the centre of diagrams. Negative externalities are indicated by the hatched sectors
819 and have been inverted for easier interpretation (i.e. the higher the function proxy, the lower
820 the overall index of multifunctionality). (b) Mean values (\pm SE) of the standardised proxies of
821 functions. Different letters indicate significant differences between agricultural management
822 (pairwise comparison with least squares means calculated using the R package emmeans). NS,
823 not significant; CF, conventional farming; OF, organic farming.