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1 **Effects of conventional vs. organic farming practices on raptor nestling health:**

2 **Neither black nor white**

3
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14

15 **Abstract**

16

17 Agricultural intensification is one of the main threats to biodiversity. Farmland bird specialists
18 such as Montagu's harrier, *Circus pygargus*, are particularly at risk and declining. Conventional
19 farming (CF) production systems usually involve landscape homogenisation, mechanisation,
20 and the use of synthetic pesticides that may have direct and indirect effects on individuals. By
21 contrast, organic farming (OF) systems typically promote agro-ecosystem health, which
22 benefits biodiversity and the reproductive success of birds. However, the potential effects of
23 agricultural systems on life history traits of Montagu's harrier chicks have not been
24 investigated. Still, altered life history traits could impair chick survival and future reproductive
25 success, which may in turn impact population dynamics. Here, we investigated the effects of
26 OF (measured as a percentage around nests at different buffer sizes from 100 m to 2000 m)
27 on a set of life history traits covering the behaviour, physiology (haematological, immune and
28 nervous systems) and body condition of 380 chicks from 137 nests monitored between 2016
29 and 2021. At a local scale (<2000 m), only the H/L ratio (indicative of physiological stress) and
30 carotenoid-based ornaments were clearly related to OF percentage. At 600 m around the nest,
31 a higher OF percentage increased the H/L ratio, suggesting that chicks experienced greater
32 stress due to either increased human disturbance or higher intra-/interspecific negative
33 interactions around OF crop plots. Carotenoid-based ornaments were more strongly coloured
34 with increasing OF around the nest at 1500 m. Considering the role of carotenoids in both
35 detoxification processes and expression of secondary sexual traits, this result may indicate
36 that CF would lead either to a difference in nestlings' diet and/or to a trade-off between
37 organism's maintenance and sexual character. These findings suggest that farming practices
38 at a local scale surrounding nest locations may have subtle effects on chick development, but

39 also on trade-offs between important physiological functions. This study highlights the
40 importance of a multi-trait approach when assessing adverse and beneficial effects of both OF
41 and CF on individuals.

42

43

44 **Keywords:** Behaviour, carotenoid, *Circus pygargus*, physiology, stress, trade-off

45 **Introduction**

46

47 The biodiversity crisis, faced nowadays, spares no species. Among the most affected taxa, bird
48 numbers decreased by 25% in Europe between 1980 and 2016 with farmland birds showing
49 the steepest decline (Heldbjerg *et al.* 2018; Reif & Hanzelka, 2020; Rigal *et al.* 2023). At the
50 same time, agricultural practices changed to increase yields, leading ecologists to hypothesise
51 a causal link between agricultural intensification and farmland bird decline (Fuller *et al.* 1995;
52 Krebs *et al.* 1999; Chamberlain *et al.* 2000). Among the features of this intensification,
53 mechanisation appeared to have a direct negative impact on ground-nesting birds (Crick *et al.*
54 1994; Tews *et al.* 2013; Santangeli *et al.* 2015). Landscape homogenisation and the use of
55 pesticides also raised concerns because they can have insidious effects on farmland species
56 (Matson *et al.* 1997; Benton *et al.* 2003; Mason *et al.* 2013; Sumasgutner *et al.* 2019; Moreau
57 *et al.* 2022a). To counter the negative impacts of conventional farming (CF) involving intensive
58 agricultural practices, organic farming (OF) emerged as an alternative in the late 1970s
59 (Lockeretz, 2007). OF is defined as a production system excluding synthetic pesticides and
60 fertilisers that uses nature-based solutions (Keesstra *et al.* 2018) to promote and enhance
61 agro-ecosystem health (Lockeretz, 2007).

62 Three main interrelated characteristics distinguish OF from CF: agricultural practices,
63 natural and semi-natural habitat proportion and farm inputs. Agricultural practices can be
64 harmful to farmland birds either directly or indirectly. A direct impact of agricultural machines
65 used under intensive practices is the death of ground-nesting birds (Crick *et al.* 1994; Vickery
66 *et al.* 2001; Tews *et al.* 2013). Incubating adults, broods and chicks are frequently destroyed
67 during mechanical mowing, tilling and harvesting activities (Schekkerman *et al.* 2009;
68 Santangeli *et al.* 2015; Bretagnolle *et al.* 2018a). Agricultural practices can also have indirect

69 effects on birds, by increasing disturbance and decreasing available resources. For instance,
70 manure spreading, manual and mechanical weed and pest control, tillage and multiple
71 cultivations all together generally increase labour in OF systems (Karlen *et al.* 1995; Jansen,
72 2000; Orsini *et al.* 2018), and can be identified as a potential source of disturbance for
73 farmland birds. Human presence and activity are known to affect bird feeding rates (Exposito-
74 Granados *et al.* 2020), induce physiological stress (Mougeot & Arroyo, 2017; Rabdeau *et al.*
75 2023), and alter behaviour including parental care (Fernández & Azkona, 1993), sometimes
76 leading to nest failures (Strasser & Heath, 2013). Farming activity has even been shown to
77 increase nest abandonment in passerine birds and to cause up to 32% nest failure in river
78 lapwing, *Vanellus duvaucelii* (Assandri *et al.* 2017; Mishra *et al.* 2020). Moreover, intensive
79 agricultural practices that involve clearing of ditches, removal of hedgerows, and
80 intensification of grassland management are associated with lower territory and breeding
81 densities in yellowhammer, *Emberiza citrinella* (Bradburry *et al.* 2000) and barn owl, *Tyto alba*
82 (de Bruijn, 1994). These intensive land-uses commonly found in CF lead to simplified
83 landscapes where important habitats for birds are no longer available (Bradburry *et al.* 2000;
84 Sumasgutner *et al.* 2019; Tarjuelo *et al.* 2020) and where their food supplies are reduced
85 through fewer weed seeds and natural insect reservoirs (Matson *et al.* 1997; Chamberlain &
86 Wilson, 2000; Benton *et al.* 2002). Insects rely on the availability of non-uniform patches of
87 grass, weeds and hedgerows for food and shelter (Benton *et al.* 2002). These features are thus
88 associated with higher insect diversity (Holland & Fahrig, 2000) and higher bird diversity and
89 abundance (Chamberlain *et al.* 1999; Chamberlain & Wilson, 2000; Freemark & Kirk, 2001).
90 Hedgerows and landscape complexity also maintain small mammal populations (Butet *et al.*
91 2006; Gelling *et al.* 2007) and consequently have a positive effect on populations of birds of
92 prey (Koks *et al.* 2007; Butet *et al.* 2010), even if some find such a link only under favourable

93 food conditions (Sumasgutner *et al.* 2019). OF has been shown to have a positive effect on
94 biodiversity, an effect which is even greater in simplified landscapes (Roschewitz *et al.* 2005;
95 Fischer *et al.* 2011; Henckel *et al.* 2015). In fact, OF practices that might imply non-cropped
96 habitat management such as the establishment of hedgerows and field margins benefit
97 insects and therefore insectivorous birds (Hole *et al.* 2005; Lockeretz, 2007). Under OF
98 agricultural systems, natural and semi-natural areas are typically higher than under CF systems
99 (Gibson *et al.* 2007; Norton *et al.* 2009), hence OF promotes resources for birds, especially
100 food abundance (Fischer *et al.* 2011). Different meta-analyses support that view, showing that
101 OF promotes higher overall biodiversity, from flora to insects and bird species richness and
102 abundance (Tuck *et al.* 2014; Stein-Bachinger *et al.* 2021). Lastly, farm inputs are the main
103 characteristic contrasting OF from CF. Although organic plant protection products can be used,
104 no synthetic pesticides or fertilisers are employed for crop production in OF systems. Indeed,
105 in Europe for farms to be considered organic the prohibition of use of synthetic pesticides and
106 fertilisers is the only mandatory practice, other practices such as natural or semi-natural areas
107 management being generally recommended but not systematic in OF systems (European
108 regulation (EU) 2018/848). Recent reviews highlighted that synthetic pesticides are the main
109 factor negatively affecting farmland birds (Stanton *et al.* 2018; Rigal *et al.* 2023). Pesticides
110 can have indirect effects on birds through the elimination of crop pests and weeds, reducing
111 food and habitat resources (Hole *et al.* 2005; Gibbons *et al.* 2014). Furthermore, pesticides
112 lack specificity and can affect non-target species (Sánchez-Bayo & Goka, 2014; Vyas, 2017).
113 The use of pesticides can thus have direct effects on birds, either inducing lethal effects
114 (immediate death after exposure) or delayed sublethal effects altering life history traits. In
115 fact, different functions of a bird's organism can be affected by pesticides, from the cellular
116 level to higher physiological functions and behaviours (Mitra *et al.* 2011; Moreau *et al.* 2021,

117 2022a; Gaffard *et al.* 2022). Many experimental studies have revealed altered life history traits
118 due to pesticide toxicity, which may compromise bird survival, and consequently populations
119 dynamics (Lopez-Antia *et al.* 2015a, 2015b; Ortiz-Santaliestra *et al.* 2020; see Moreau *et al.*
120 2022a for a recent review). *In natura*, birds are exposed to numerous molecules as multiple
121 pesticides are usually applied to fields either at the same time or sequentially, inducing
122 cocktail effects (Gaffard *et al.* 2022). Moreover, the persistence of some molecules in soil and
123 water can lead to contamination without direct contact with the applied chemicals (Jagannath
124 *et al.* 2008; Goulson, 2013; Fuentes *et al.* 2023). A recent study on wild passerines showed
125 that birds nesting in hedges surrounded by CF were less vigorous than those nesting in hedges
126 surrounded by OF, and that this might be due to pesticide contamination under CF (Moreau
127 *et al.* 2022b).

128 Montagu's harriers, *Circus pygargus*, a migratory raptor species inhabiting agricultural
129 lands in Europe, nest on the ground in cereal crops. In France, populations have declined by
130 10–30% over the past 30 years (Millon & Bretagnolle, 2004; Comolet-Tirman *et al.* 2015) and
131 the principal cause is believed to be agricultural intensification (Butet & Leroux, 2001; Arroyo
132 *et al.* 2002; Arroyo *et al.* 2004; Santangeli *et al.* 2015). Montagu's harriers mostly feed on
133 common voles, *Microtus arvalis*, which display cyclic population dynamics in Western Europe,
134 hence food availability and diet vary from year to year (Millon & Bretagnolle, 2008). In years
135 of low vole abundance, Montagu's harriers compensate by feeding on Orthopterans
136 (grasshoppers and crickets) (Salamolard *et al.* 2000). For this farmland specialist bird, the type
137 of agricultural system at a local scale might be of great importance during the breeding season.
138 Indeed, eggs and chicks are located on the ground in crop fields, and the altricial chicks stay
139 in the nest during the whole rearing period (~35 days). Consequently, at all developmental
140 stages, Montagu's harrier offspring might be affected by the composition and management

141 of the habitats in the close surroundings. If the agricultural system in the vicinity leads to
142 altered life history traits, survival may be compromised, reducing future recruitment of
143 fledglings into the population of this declining species.

144 In the present study, we explored the patterns of life history traits variation in nestlings
145 along a gradient of OF near their nests. Accordingly, we investigated the relative impacts of
146 OF vs. CF on multiple life history traits of Montagu's harrier chicks at a local scale (up to 2000
147 m) around nests. Compared with OF, CF may decrease food availability (due to both lower
148 quality habitats and intensive management practices) and increase exposure to pesticides
149 (through contact or prey consumption). Therefore, we hypothesised that a higher percentage
150 of CF around the nest may adversely affect fledglings. Since all life history traits involve
151 complex interconnected functions, expectations for a single trait are complicated to raise. A
152 multi-trait approach is therefore crucial to elucidate the effects of agricultural systems (OF vs.
153 CF) on birds, and eventually to highlight potential trade-offs between life history traits. We
154 expect chicks reared in nests surrounded by a lower percentage of OF (i.e., a higher
155 percentage of CF) would have a poorer overall health status that might be reflected by inferior
156 body condition, more markers (physical and biochemical) of chronic stress, a depressed
157 immune system, and lower vigour than chicks surrounded by a higher percentage of OF.

158

159 **2. Material and methods**

160

161 **2.1. Ethics statement**

162

163 All experiments conformed to the French guidelines for the ethical use of animals in research
164 (APAFIS#18557-2019010822312199v2). Bird handling was allowed and licensed by the Centre

165 de Recherches sur la Biologie des Populations d'Oiseaux (CRBPO; Museum National d'Histoire
166 Naturelle; licence #1308).

167

168 **2.2. Study area and model species**

169

170 The study site is located in southwestern France (46°11'N, 0°28'W), in the Long-Term Social-
171 Ecological Research 'Zone Atelier Plaine & Val de Sèvre' (LTSER ZAPVS), a 450 km² area where
172 annual crop identification is carried out, allowing mapping of organic crop plots in detail. In
173 France, OF is regulated by the European legislation (European regulation (EU) 2018/848) on
174 organic production, which details all practices to respect for farms to be considered organic,
175 the main one being the complete ban on the use of synthetic pesticides and fertilizers. Other
176 farming practices, including weeding or non-cropped habitat management, being at the
177 discretion of each farmer. Nonetheless, Catarino et al. (2019) report general information on
178 CF and OF systems of the study area; the main differences being smaller farm areas, more
179 diversified crops and a lower nitrogen supply in OF systems. In this intensive agricultural area,
180 cereal crops are the predominant cultures (average coverage of 41.5% between 2009 and
181 2016), followed by corn, sunflowers and oilseed rape (Bretagnolle *et al.* 2018b). Natural (or
182 semi-natural) habitats and urbanized areas represent only a small proportion of the study area
183 (average coverage of 13.5% and 9.8% respectively between 2009-2016; Bretagnolle *et al.*
184 2018b) thus only organic crop plots were used for analyses (see section 2.7 for further
185 information). Montagu's harrier monitoring has taken place in this site since 1994 (Bretagnolle
186 *et al.* 2018b). This species nests on the ground, mainly in cereal crops, and lays up to eight
187 eggs (Arroyo *et al.* 1998; Millon *et al.* 2008). The incubation period lasts 29 days and the
188 rearing period between 30 and 35 days (Arroyo *et al.* 2007). The mean productivity in this site

189 is 2.05 fledglings per breeding attempt (Arroyo *et al.* 2004), breeding success depending
190 mainly on the availability of common voles, their main prey in this area (Salamolard *et al.*
191 2000). Foraging range varies with location; in the study area males use home ranges of ~14
192 km² (Salamolard, 1997), but home ranges during the breeding season can stretch to 100 km²
193 (Guixé & Arroyo, 2011).

194

195 **2.3. Overall experimental design**

196

197 From 2016 to 2021, the reproduction of Montagu's harrier was monitored from late April until
198 late July. All nests were searched by professional ornithologists, and once located, visited and
199 mapped using a global positioning system (GPS) receiver, they were stored on a geographical
200 information system (GIS; QUANTUMGIS 3.16.5; QGIS Development Team, 2021, see Fig. 1).
201 Nests were visited twice during the incubation period and every week after hatching (lag time
202 between visits 7 ± 2 days). At 15 days old, chicks were sexed and banded with a unique coded
203 aluminium ring from the Museum National d'Histoire Naturelle. Sex was determined by the
204 colour of the iris (brown for females and grey for males) (Leroux & Bretagnolle, 1996).

205 For the present study, we focused on data collected during the last visit before
206 fledgling, when nestlings were 26 ± 2 days old. Briefly (see details below), chicks were caught
207 in the nest and carefully handled to take morphometric measurements and breath rate and
208 collect blood samples (Fig. 2). A phytohemagglutinin (PHA) skin injection was performed, and
209 behaviour during handling was also recorded (Fig. 2). Chicks were handled and released at the
210 nest, and the handling time was minimised to reduce potential stress. The following day of
211 the visit, nests were again visited to record chicks' inflammatory response to the PHA skin
212 injection (see details below). A total of 380 chicks were monitored ($N_{2016} = 40$, $N_{2017} = 32$, N_{2018}

213 = 81, N₂₀₁₉ = 84, N₂₀₂₀ = 85, N₂₀₂₁ = 58) from 137 nests (N₂₀₁₆ = 15, N₂₀₁₇ = 16, N₂₀₁₈ = 24, N₂₀₁₉
214 = 31, N₂₀₂₀ = 29, N₂₀₂₁ = 22). No sex ratio bias was observed for the entire period (187 females
215 and 193 males; binomial test $p = 0.80$).

216

217 **2.4. Morphometric measurements**

218

219 2.4.1. Morphometrics for body condition assessment

220

221 Body condition is a morphometric estimate reflecting the overall health status of individuals,
222 notably involved in post-fledgling survival of birds (Blums *et al.* 2005; Vitz & Rodewald 2011;
223 Duijns *et al.* 2017). Body condition for each nestling was estimated from the scale mass index
224 following Peig and Green (2009):

$$225 \quad SMI_i = Mass_i \times \left(\frac{\text{Mean tarsus length of the group}}{\text{Mean tarsus length}_i} \right)^{b_{sma}}$$

226 where b_{sma} is the slope of the major axis regression of log (body mass) on log (mean of the
227 two measures of the left and right tarsus length) with the standard major axis method
228 (package 'smatr') (Warton *et al.* 2012) for each chick i . The mass was obtained by weighing
229 chicks with a Pesola 500 g spring scale (accuracy ± 5 g) (Schindellegi, Switzerland) and the left
230 and right tarsus were measured twice with a digital calliper (accuracy ± 0.1 mm).

231

232 2.4.2. Fault bars

233

234 Fault bars are malformations in feathers induced by punctual stressors during chick growth,
235 which may result in feather and even rachis breaks (Jovani & Rohwer, 2016; see Rabdeau *et*

236 *al.* 2023 for an example of recent usage). Chick tails were photographed and the number of
237 fault bars (all breaks in barbs and barbules) was counted on the most affected rectrix feather
238 by the same experimenter to avoid observer bias. The number of fault bars on each chick
239 ranged between 0 and 10.

240

241 2.4.3. Colouration

242

243 Colouration of nestling bare parts, a carotenoid-related trait, can be limited through the diet
244 and mediated by different physiological effects (Garcia-Heras *et al.* 2017). The colour of the
245 cere and tarsus (bare parts) were scored by direct comparison with a colorimetric chart from
246 Yolk Colour Fan (Roche, Neuilly-sur-Seine, France). Scores ranged from 0 (almost white / pale
247 yellow) to 15 (orange) and were highly correlated with colour parameters obtained using a
248 spectroradiometer (Faivre *et al.* 2001). Cere scores ranged from 0 to 5 and tarsi ranged from
249 0 to 6. Both scores were highly correlated (Spearman's correlation test, $\rho > 0.77$, $p < 0.0001$,
250 95% confidence interval CI = [0.72, 0.81], $n = 380$), and only cere scores were used for
251 statistical analyses.

252

253 **2.5. Physiological measures**

254

255 2.5.1. Breath rate score

256

257 Breath rate usually refers to a proxy of physiological stress (Carere & van Oers, 2004; Torné-
258 Noguera *et al.* 2014; Rabdeau *et al.* 2019). Breath rate was measured using chicks handled in
259 back position, and corresponded to the number of thoracic movements counted during 15s

260 for three consecutive replicates. The breath rate score was then obtained by averaging the
261 three replicates.

262

263 2.5.2. Physiological parameters assessed from blood

264

265 2.5.2.1. Blood collection

266

267 Blood sampling was made on the brachial vein through a puncture using a sterile needle and
268 heparinised capillaries. A single microcapillary of 10 µL was used for both sedimentation rate
269 and haematocrit, a droplet of blood was used for blood smear (see below), and two capillaries
270 of 100 µL each were placed in Eppendorf tubes and kept refrigerated (0–5°C) for 2–3 h while
271 transporting to the lab, where they were stored at -20°C until further analyses (carotenoid
272 titration and acetylcholinesterase activity; see below).

273

274 2.5.2.2. Sedimentation rate and haematocrit

275

276 Erythrocyte sedimentation rate (ESR) corresponds to the proportion of red blood cells
277 sedimented per hour, and it increases in response to various inflammatory or infectious
278 processes (Saino & Møller, 1996). Microcapillaries were kept vertical for 5 h in a refrigerated
279 container (0–5°C), lengths were measured with an electronic calliper to the nearest 0.1 mm,
280 and ESR in millimetres per h (mm/h) was estimated as follows:

$$281 \quad ESR = \frac{\text{volume not filled by erythrocytes}}{\text{total blood volume in the tube} \times \text{time of sedimentation}}$$

282

283 Once ESR was measured, microcapillary tubes were centrifuged at 5000 rpm for 5 min
284 to measure haematocrit. Haematocrit is used as an index of anaemia and corresponds to the
285 proportion of the tube filled with erythrocytes divided by the total volume of blood sample in
286 the tube, given as a percentage (Saino & Møller, 1996; see also Biard *et al.* 2015; Moreau *et*
287 *al.* 2021).

288

289 *2.5.2.3. Carotenoid titration*

290

291 Carotenoids are involved in different functions of birds, including as antioxidants, and a high
292 concentration in blood can reflect physiological stress (McGraw & Ardia, 2003). Eppendorf
293 tubes containing ~150 µL of blood were centrifuged (10 min at 9000 rpm) and plasma was
294 collected and kept at -20°C until laboratory analyses. Plasma carotenoid concentration was
295 subsequently obtained in micrograms per millilitre (µg/mL) using a standardised colorimetric
296 technique (see Biard *et al.* 2010 for additional information).

297

298 *2.5.2.4. Acetylcholinesterase activity*

299

300 Acetylcholinesterase (AChE) activity is negatively affected by different pesticide molecules
301 altering neural functions, which in turn has disruptive consequences on diverse behaviours
302 and complex functions (Grue *et al.* 1997; Eng *et al.* 2017; Moreau *et al.* 2022a). AChE activity
303 in milliunits per minute (mU/min) was obtained by a method derived from Ellman *et al.* (1961)
304 using 5 µL of blood diluted in 100 µL of a 1% Triton X-100 solution and measured using a
305 SpectraMax iD3 microplate reader (Molecular Devices Inc., Sunnyvale, CA, USA) over 40 min
306 at 324 nm and 37°C. AChE activity was calculated using SoftMax Pro7 software (Molecular

307 Devices, San Jose, CA, USA) as the maximum change in absorbance per minute during kinetics
308 analysis.

309

310 2.5.2.5. *Blood smear*

311

312 For each bird, a blood smear was performed with a droplet of blood sample. Slides were air-
313 dried and fixed in absolute methanol before being stained with Giemsa solution (Sigma
314 Chemical, St. Louis, MO, USA). Blood smears were examined with an oil immersion microscope
315 under 1000x magnification. Total white blood cells (WBC) count was estimated from the
316 number of leucocytes found among 8000 erythrocytes. A high number of leucocytes reflects
317 stress and inflammatory processes (Ots *et al.* 1998). Different types of leucocytes were
318 counted and used to estimate the relative proportion of heterophils to lymphocytes (H/L
319 ratio). The H/L ratio is used as an index of physiological stress, as it is supposed to increase in
320 response to various stressors (Maxwell, 1993; Ots *et al.* 1998; Moreau *et al.* 2021; see Biard
321 *et al.* 2015 for details).

322

323 2.5.3. Immune challenge

324

325 Before release into the nest, the immune system of nestlings was challenged using
326 phytohemagglutinin (PHA) skin tests (Smits *et al.* 1999). Briefly, 0.5 ± 0.1 mg of PHA (Sigma
327 Chemical, St. Louis, MO, USA) diluted into 0.1 mL of phosphate-buffered saline (PBS) was
328 injected subcutaneously in the wing patagium as described by Sternalski *et al.* (2012a). The
329 thickness of the patagium was measured three times before injection using a pressure-
330 sensitive dial thickness gauge (spessimeter accuracy ± 0.01 mm) and again 24 h after injection.

331 The response to the PHA skin test corresponds to the change in average thickness (in mm) of
332 the injection site, and thus the magnitude of this change reflects the immune potential of
333 nestlings (Sternalski *et al.* 2012a; see also Biard *et al.* 2015).

334

335 **2.6. Behavioural measures**

336

337 Behaviour is considered an indicator of individual health that can be altered by multiple
338 chemicals and is often regarded as a more sensitive response to stress or toxicity levels than
339 other physiological measures (Grue *et al.* 1997; Clotflelter *et al.* 2004; Hellou, 2011; Moreau
340 *et al.* 2022a). When handling chicks (i.e., from capture in the nest to release), the behaviour
341 of bird was scored using four behavioural traits as described by Rabdeau *et al.* (2019): (i)
342 activity during nest approach (act-nest); (ii) total activity during handling (act-tot); (iii) rate of
343 beak attacks (beak); (iv) rate of claw attacks (claws). Act-nest was assessed when the
344 experimenter approached the nest to catch the chicks and scored as follows: stayed
345 motionless = 0, chicks retreated = 1, chicks ran away = 2. Act-tot was measured throughout
346 handling and scored as follows: chicks stayed motionless = 0, chicks rarely moved = 1, chicks
347 moved regularly = 2, chicks moved continuously = 3. The number of beak and claw attacks
348 were counted during handling and divided by the duration of handling, resulting in a rate
349 (number of attacks per minute).

350

351 **2.7. Statistical analyses**

352

353 A principal component analyses (PCA) was performed on the four behavioural scores using
354 singular value decomposition of a standardised (centred and scaled) data matrix (Crawley,

355 2012). The first axis of the PCA reflecting global activity and vigour during handling (PC1-
356 activity) was retained as its eigenvalue was >1 , and it accounted for 48.69% of the variance.
357 PC1-activity was positively correlated with both rates of beak ($r = 0.56$) and claw ($r = 0.57$)
358 attacks, act-tot ($r = 0.55$) and act-nest ($r = 0.24$) scores.

359 Normality and homoscedasticity of all response variables were tested using the
360 'fitdistrplus' package prior to model implementation, and when these assumptions were not
361 met, distribution with the best fit was selected using the same package (Delignette-Muller &
362 Dutang, 2015). Model residuals and spatial autocorrelation (using Moran's I) were also
363 checked using 'DHARMA' package (Hartig, 2022). PC1-activity, body condition, ESR, breath rate
364 score, AChE activity and PHA response were used as response variables in Linear Mixed-effects
365 Models (LMMs). Carotenoid concentration was square root transformed, haematocrit and H/L
366 ratio were log-transformed prior to LMM execution, since the distributions of these variables
367 did not meet normality. Generalised LMMs fitted with a Poisson distribution (PGLMMs) were
368 implemented for fault bars and colouration scores and a Generalised LMM fitted with a
369 Negative Binomial distribution (NB-GLMM) was used for the total WBC count. For all models
370 (LMMs, PGLMMs and NB-GLMM), the percentage of OF around the nest (log-transformed,
371 hereafter OF effect) and the year as factor were included as fixed effects, and the nest identity
372 as a random effect (to avoid pseudo-replication as chicks can belong to the same nest) (Bolker
373 *et al.* 2009). The year was considered a fixed effect because we wanted to control for inter-
374 annual variability of environmental conditions (phenology, food availability and weather for
375 instance). Because year could have been considered a random factor, we ran all models
376 changing only the year fixed effect into a random effect. This approach did not change the
377 results obtained with year as a fixed effect, hence we used the results of the first analyses. All
378 models were run with the 'lme4' package (Bates *et al.* 2015).

379 As we had no *a priori* information on the scale of the OF effect on life history traits for
380 each chick, we estimated the percentage OF around the nest for 20 buffer sizes (i.e., radii
381 every 100 m, from 100 m to 2000 m). To this end, the GPS coordinates of nests and a database
382 of the LTSER ZAPVS, which georeferenced the agricultural plots using OF practices, were used
383 with the ‘sf’ package (Pebesma, 2018). Since OF agricultural plots varied over time, the
384 percentage of OF around nests for a given year was calculated using the georeferenced plots
385 of the corresponding year. We ran 20 models per life history trait (one per buffer size) and
386 extracted an Akaike Information Criterion corrected for small sample size (AICc) using the
387 ‘AICcmodavg’ package (Mazerolle, 2020). From a set of candidate models, AICc allows
388 selection of the model with the most support, which has the lowest AICc, assuming that
389 models with $\Delta\text{AICc} < 2$ (i.e., a difference in AICc between candidate models < 2) are similarly
390 supported and cannot be distinguished from each other (Burnham & Anderson, 2004). For
391 every life history trait, a plot was generated representing the AICc of the 20 models (one for
392 each buffer size), with a red dotted line illustrating the model selection criterion (lowest AICc
393 of the candidate models + 2), with the shape and colour reflecting the significance and
394 direction of the OF effect. To avoid type II errors, we chose to present our results based on
395 effect sizes (estimates of the model) assorted with their 95% confidence intervals (CI)
396 (following Garamszegi, 2006; Nakagawa, 2004; Nakagawa & Cuthill, 2007; Cumming, 2014).
397 The OF effect direction corresponded to the sign of the estimate and was considered
398 significant when 95% CI did not include 0. Calculation of the bootstrapped CI was obtained for
399 2000 iterations and using the package ‘boot’ (Canty & Ripley, 2022). We discuss effect sizes
400 assorted with their 95% CI which allow to quantify the biological effect we tested and provide
401 comparable estimates for future research and meta-analyses, still, we provide the results from

402 model comparison using likelihood ratio-based χ^2 -statistics in supplementary materials (Fox &
403 Weisberg, 2011).

404 To assess potential links between variables, Spearman's rank correlation tests were
405 performed. All statistics were conducted with R v4.0.5 software (R Core Team, 2021),
406 implemented using the aforementioned packages.

407

408 **3. Results**

409

410 Summary statistics and Spearman's rank correlation coefficients of the 12 life history traits are
411 presented in the Supplementary Material (see Table S1 and Fig. S2). Only ESR and haematocrit
412 (Spearman's correlation test, $\rho > -0.42$, $p < 0.0001$, 95% CI = [-0.51; -0.32], $n = 343$) were
413 correlated (Supplementary Material Fig. S2). The set of candidate models for body condition,
414 fault bars, breath rate score, ESR, haematocrit, carotenoid concentration, AChE activity, WBC
415 count, and PHA skin test did not yield any specific buffer size with substantial support (i.e.,
416 AICc < 2 with a significant OF effect) for an influence of OF percentage around nests (Fig. S2 in
417 supplementary materials). For cere colouration score and H/L ratio, the best models (i.e.,
418 those with $\Delta\text{AICc} < 2$) identified a positive effect for OF percentage at a range of radii (Fig. 3).
419 The cere colouration score increased with OF percentage around the nest for buffer sizes > 500
420 m (Fig. 3a). For H/L ratio, a positive relationship was detected between 300 and 900 m (Fig.
421 3b). Concerning the PC1-activity, a positive relationship with the percentage of OF was
422 detected at 200 m around the nests.

423 We then selected the model with the lowest AICc to probe the relationships between
424 the trait and the OF percentage around the nest (Fig. 4). Chicks displayed a significantly higher
425 cere colouration score when surrounded by a higher percentage of OF at 1500 m (effect size

426 = 0.14; 95% CI = [0.04; 0.22]), the lowest AICc for this life history trait (Fig. 4a). The lowest AICc
427 for the H/L ratio was at a radius of 600 m around nests; at this distance the H/L ratio
428 significantly increased with increasing OF percentage (effect size = 0.11; 95% CI = [0.04; 0.18];
429 Fig. 4b). For PC1-activity, the lowest AICc was at 200 m, an increase in OF at this distance from
430 nests significantly increased the global activity of chicks (effect size = 0.20; 95% CI = [0.06;
431 0.40]; Fig. 4c).

432

433 **4. Discussion**

434

435 The aim of the present study was to explore life history traits variation of Montagu's harrier
436 chicks linked to agricultural systems around nests. The results revealed an effect on two of the
437 12 traits investigated, although moderate. Cere colouration and H/L ratio were positively
438 linked to OF at different radii, suggesting that the effects of the agricultural system operate at
439 different distances, but not necessarily at the same range. The cere colouration score
440 increased with increasing OF percentage at distances >500 m with the best model selected at
441 1500 m. The H/L ratio increased significantly with OF at distances from 300 to 900 m, the best
442 model being at 600 m. Global activity of chicks increased with increasing OF percentage at 200
443 m only. For all other life history traits, namely body condition, fault bars, breath rate score,
444 ESR, haematocrit, carotenoid concentration, AChE activity, WBC count, and PHA skin test, no
445 effect of OF was detected at any of the buffer sizes.

446 In the present study, we found evidence for the impacts of farming practices (CF and
447 OF) on Montagu's harrier chicks at a low spatial scale (<2 000 m) around nests. First, OF was
448 found to be associated with a higher H/L ratio. This trait is indicative of stress undergone by
449 chicks during their rearing period. Indeed, H/L ratio, is considered a reliable indicator of mild

450 to moderate stress, and to reflect chronic stress levels rather than short-term stress responses
451 (Maxwell, 1993; O'Dell *et al.* 2014). This result suggests that chicks in areas with a higher OF
452 percentage may suffer more disturbance. Indeed, compared with CF, OF practices involve
453 more repetitive passages (Karlen *et al.* 1995; Reissig *et al.* 2016; Orsini *et al.* 2018), which may
454 equate to more stress experienced by chicks. Furthermore, areas with more OF fields are
455 generally better appreciated than areas with CF fields by urban inhabitants attracted to
456 naturalistic features and elements (Zasada, 2011). Diversified habitats offer more
457 opportunities for recreation and leisure than uniform ones (Hansen *et al.* 2006). Anthropoc
458 disturbances can induce stress in Montagu's harrier chicks, leading to physiological responses
459 to this stress and even to the formation of fault bars (see Rabdeau *et al.* 2023). Repeated
460 human activities, whether related to OF practices or recreation, could also induce prolonged
461 absence of adults, resulting in reduced parental care, and thus more stress. Additionally, a
462 higher presence of conspecifics or other raptor species around OF crops is also possible.
463 Competition between Montagu's harriers nesting in semi-colonies is presumably low but
464 could increase in years of low vole abundance. The presence of other raptor species foraging
465 in the same area would also increase competition for food (Garcia & Arroyo, 2002).
466 Competition for food resources might increase the time parents spend foraging, leaving chicks
467 alone for longer periods. The presence of more raptors may increase the risk of predation of
468 Montagu's harrier nests, which are particularly vulnerable and attractive in low vole years
469 (Arroyo *et al.* 2001). Pairs are often seen mobbing common buzzards, *Buteo buteo*, or black
470 kites, *Milvus migrans*, to protect their nests (authors' personal observations), and this might
471 result in more frequent parental absences. Consequently, an increase in intra- and
472 interspecific negative interactions surrounding OF crop plots would increase the time chicks
473 are unattended.

474 An alternative explanation for the higher H/L ratio observed for chicks in nests
475 surrounded by a high OF percentage is the presence of a higher number and/or diversity of
476 pathogens. Indeed, H/L ratio is known to increase in response to infectious diseases as well as
477 psychological disturbances (Ots *et al.* 1998), hence we cannot exclude the potential effect of
478 increased pathogen exposure in OF systems. Pesticides may reduce pathogen diversity in CF
479 systems compared with areas in which OF is more prevalent (Goutte & Molbert, 2022).
480 Therefore, chicks from nests located in these zones might be more prone to parasite exposure,
481 which could, in turn, explain why they exhibit a higher number of heterophil leucocytes, and
482 thus a higher H/L ratio. Moreover, several studies reported that H/L ratio is species-specific,
483 and that it may vary between captive and wild individuals, depending on sex, age, nutritional
484 and infectious status, and even brood size (Ruiz *et al.* 2002; Limiñana *et al.* 2009; Ortego *et al.*
485 2009; Parejo & Silva, 2009; Banbura *et al.* 2013; Catitti *et al.* 2022). Previous studies on
486 Montagu's harriers attempted to set reference interval values for haematological parameters
487 of captive adults and free-living nestlings, but reliable comparisons were difficult to make with
488 the present work, and further investigation is required (Lavin *et al.* 1993; Limiñana *et al.* 2009).
489 Additionally, even if chicks in OF and CF areas face similar parasite diversity, their investment
490 in different life history traits might vary. For instance, chicks from nests mainly surrounded by
491 CF may face a trade-off between investment for immune parameters and other life history
492 traits such as growth (Sheldon & Verhulst, 1996; Norris & Evans, 2000). A recent study on grey
493 partridge showed that hatchlings exposed to pesticides were of lower body size compared
494 with those not exposed, but they underwent compensatory growth to compensate for the
495 initial differences (Gaffard *et al.* 2022). In the present work, we did not observe any difference
496 in body condition, but growth trajectories should be properly investigated to exclude this
497 hypothesis.

498 Although we did not detect any effect of the agricultural system on the immune
499 responses of nestlings assessed by PHA skin tests at a local scale, colouration of the cere, a
500 sexual trait indicative of chick quality (Sternalski *et al.* 2012b), was lower in chicks mainly
501 surrounded by CF. Various studies highlighted the covariation between colouration and
502 immunocompetence in bird nestlings, due to the role of carotenoids in both immune functions
503 and colouration (Saino *et al.* 2000, 2003; Baeta *et al.* 2008). Thus, competing demand for
504 carotenoids for colouration and the immune system might occur. At a local scale, a large
505 percentage of CF is presumed to reduce available resources; carotenoids are provided by the
506 diet, which may explain why chick colouration is adversely affected compared with chicks
507 surrounded by OF. Another potential trade-off leading to lower colouration scores in chicks
508 surrounded by CF is the allocation of carotenoids to detoxification processes (Edge *et al.* 1997;
509 Krinsky, 1998; see Bustnes *et al.* 2007). Indeed, exposure of birds to pollutants is known to
510 induce oxidative stress, leading to a higher demand for antioxidants (including carotenoids)
511 for redox processes (Ortiz-Santaliestra *et al.* 2015; Moreau *et al.* 2021, reviewed in Moreau *et*
512 *al.* 2022a). Some studies on wild raptors found compensatory responses between different
513 functions, linked to low concentrations of pesticides altering bird health (Bustnes *et al.* 2004;
514 Rivera-Rodríguez & Rodríguez-Estrella, 2011; Ortiz-Santaliestra *et al.* 2015; Garcia-Heras *et al.*
515 2018). Despite the absence of a significant effect of the agricultural system on plasma
516 carotenoid concentrations in the present work, we can suppose that pesticides used in CF
517 might affect carotenoid allocation in Montagu's harrier nestlings, leading to trade-offs
518 involving other physiological functions such as detoxification and oxidative stress, not
519 measured here. Nevertheless, even if CF and OF provide an equivalent amount of food
520 resources, it is possible that OF provides a greater diversity of food supply. Indeed, as
521 mentioned above, OF promotes insect and passerine bird diversity, both of which are

522 alternative prey for Montagu's harriers. Nestling colouration mainly depends on the
523 proportion of insects and birds in their diet since these are richer in carotenoids (Sternalski *et*
524 *al.* 2010). Thus, it is likely that chicks surrounded by OF benefit from higher carotenoid levels
525 in their diet, resulting in more intense colouration of secondary sexual traits.

526 The global activity level of chicks has been found to be higher when the surrounding
527 OF at 200 m increases. This result matches with previous findings on 6 passerine birds (Moreau
528 *et al.* 2022b), which reported a higher vigour of individuals when they originated from organic
529 hedgerows compared to those captured in conventional ones. The main hypothesis raised by
530 the authors is a lower exposition of birds to pesticides in OF systems and not an increased
531 food abundance as birds did not show variation in body condition (Moreau *et al.* 2022b). In
532 our case, the same pattern arises as we did not detect an effect of OF on body condition of
533 Montagu's harrier chicks. Still, as we detected a beneficial effect of OF on chicks' activity only
534 at 200 m around nests, we can question the potential role of pesticides in their behavioural
535 differences. The increased chick activity when there is more OF at 200 m could be alternatively
536 explained by human disturbances. In fact, after crops harvests, nests are exposed to curious
537 walkers who can visit nests untimely, generating aggressive reactions of chicks and eventually
538 sensitization to humans (Rabdeau *et al.* 2019, 2023). However, even if the effect size seems
539 to indicate a medium effect of OF on the vitality of chicks, the assorted CI is relatively large
540 suggestive of a large variability among chicks (Nakagawa & Cuthill, 2007; Cumming, 2014),
541 interpretation on this result should thus be considered with caution.

542

543 **5. Conclusion**

544

545 In the current context of overall biodiversity loss, it is crucial to understand the relative
546 impacts of CF and OF practices which are often opposed one to the other. However, as
547 evidenced by our results, the picture is quite more complex than just black and white. The
548 multi-trait approach used here revealed that CF practices can have detrimental effects on
549 chick quality, and that OF can also exert adverse effects on their physiological stress. In fact,
550 studying only the colouration of secondary sexual traits would have led to partial conclusions
551 about the relative effects of CF on chick quality, whereas studying additionally morphometric
552 and physiological traits that are indicative of stressors, such as H/L ratio, facilitated complete
553 conclusions. In fact, both agricultural systems may impact Montagu's harrier chicks, with
554 potential consequences for immediate survival during migration and later during adulthood.
555 Multi-trait approaches are important because population dynamics reflect complex
556 physiological processes of individuals that shape life history traits (development,
557 reproduction, and survival), which in turn impact populations.

558 However, the present study is preliminary, as based on a rough cost/benefit analysis
559 of these agricultural systems. One may also consider that we did not expect large effect size
560 for the impact of agricultural systems on chicks since the relationships among the different
561 life history traits and how they are shaped are quite complex. For example, this study did not
562 consider that chicks are fed by their father, who may hunt up to several kilometres away,
563 potentially masking/compensating for low habitat quality at the local scale (Guixé & Arroyo
564 2011; Krupiński *et al.* 2020). Our study only considered the habitats in the vicinity of the nest
565 from a binary point of view (OF vs. CF), and therefore did not capture all parameters such as
566 the proportion of natural, semi-natural or urban habitats in the landscape potentially
567 influencing chick health. Human activities related to OF and CF should be investigated in more
568 detail to further determine the effects of different types and frequencies of disturbances on

569 ground-nesting farmland birds. Finally, OF and CF contrast in their use of pesticides, which
570 may partly explain some of our results (see Moreau *et al.* 2022a for an overview), especially
571 knowing that pesticide use is the main driver of birds' decline in Europe (Rigal *et al.*, 2023).
572 Therefore, in future work, titration of pesticides in blood should be performed to explore their
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574

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590

591 **Declaration of competing interest**

592 The authors declare that they have no competing financial interests or personal relationships
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594

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974

975 **Figure legends**

976

977 **Fig. 1:** Spatial distribution of Montagu's harrier nests across the Long-Term Socio-Ecological
978 Research Zone Atelier Plaine & Val de Sèvres (LTSER ZAPVS). Only nests corresponding to data
979 for fledglings included in the present study are shown (the number of nests monitored each
980 year is given in brackets). Organic farming (OF) agricultural plots correspond to data available
981 for 2021 from our GIS database. Infrastructure corresponds to buildings, sport fields,
982 cemeteries, locks and bridges present in the study area.

983

984 **Fig. 2:** Summary of the experimental design measuring different morphological, physiological
985 and behavioural traits of Montagu's harrier, *Circus pygargus*, chicks before fledging. For each
986 chick, act-nest = activity at nest approach, act-tot = total activity during handling, and beaks
987 and claws = the rates of beak and claw attacks during handling.

988

989 **Fig. 3:** Model selection using AICc to assess the responses of life history traits (life history
990 traits) of Montagu's harrier, *Circus pygargus*, chicks to the effect of the percentage of organic
991 farming (OF) around the nest at different buffer sizes (from 100 m to 2000 m radius).
992 Measured life history traits are (a) cere colouration score, (b) H/L ratio, and (c) PC1-activity.
993 AICc = Akaike Information Criterion corrected for small sample sizes. Red dotted lines
994 correspond to the lowest AICc of candidate models + 2. Red triangles indicate a positive
995 significant OF effect (i.e., a positive model estimate and assorted 95% confidence interval (CI)
996 not crossing 0). Black dots represent a non-significant OF effect (i.e., the 95% CI of model
997 estimate crosses 0).

998

999 **Fig. 4:** Organic farming effect on (a) cere colouration score, (b) H/L ratio, and (c) PC1-activity
1000 of chicks at 1500 m, 600 m and 200 m around the nest respectively. A dot represents a value
1001 measured for a chick (darker = more chicks had this value). Lines predict values of each life
1002 history trait depending on the percentage of organic farming. Shading represents the 95%
1003 confidence interval.
1004