1 **Plugging the hunger gap: Organic farming supports more abundant nutritional** 2 **resources for bees at critical periods**

3

4 Alexander J. Austin^{1†}, Lori Lawson-Handley¹, James D. J. Gilbert¹

5

6 ¹Department of Biological and Marine Sciences, University of Hull, UK

7 [†]To whom correspondence should be addressed. Email: alexander.j.austin17@gmail.com

8

9

10 **Abstract**

- 11 1. Understanding the decline in bee populations and their plant mutualists is of
12 paramount concern for ecosystem health, as well as our future food security.
13 Intensive farming practices are one of the major drivers behind such declines.
14 Organic farming is one of the principal alternatives to conventional practices yet the
15 evidence for its effects are mixed, with some studies showing limited benefits.
- 16 2. We conducted bee and floral surveys on 10 paired organic and conventional farms
17 across Yorkshire, UK, to investigate how farming practice influenced the
18 abundance, richness and community composition of bees and flowering plants.
- 19 3. Firstly, we found that species richness for flowering plants and bees was similar
20 across organic and conventional farms. Floral composition differed between organic
21 and conventional farms with the greatest differences seen in May and June, whereas
22 bee community composition was similar among farming practices.
- 23 4. Secondly, both bee and floral abundance were higher in organic farms. Peaks in
24 floral abundance, and corresponding bee abundance, occurred in particular months,
25 most notably in July, with abundance during the rest of the season being similar
26 across both farming practices.
- 27 5. *Synthesis and applications:* Our results suggest that higher floral availability on
28 organic farms corresponds with increased bee abundance. Of particular importance
29 was the higher floral abundance during spring, in the pollinator ‘*hungry gap*’, where
30 floral resources are traditionally scarce. However, conventional farms performed
31 comparably to organic farms across the rest of the season, as well as showing
32 similar levels of species richness, diversity and species composition for both
33 flowering plants and bees. We suggest that targeted management on conventional

34 farms, aimed at boosting floral abundance in the spring, when floral abundance is
 35 low, could allow conventional farms to make up the shortfall. Additionally,
 36 focusing on increasing the diversity of flowering plants, in terms of both phenology
 37 and nutritional composition, for both adult bees and their larvae, could improve bee
 38 community diversity across both farming systems.

39
 40 Keywords: wildlife-friendly farming, pollinators, wildflowers, bee conservation,
 41 community composition, phenology, nutritional quality, targeted management

42

43

44

45

46

47

48

49

50

51

52

53

54

55

56

57

58

59 **Introduction**

60 Insects are in the midst of a global crisis, with unprecedented population reductions
61 being seen across numerous taxa (Sánchez-Bayo & Wyckhuys 2019). Some of the strongest
62 evidence for declines occurs within pollinating insect guilds (Rhodes 2018), and more
63 specifically, from bees, a key pollinator group (Goulson *et al.* 2015; Goulson & Nicholls
64 2016). Similar patterns are also seen in plants (Niedrist *et al.* 2008), with losses in
65 agricultural habitat particularly prominent (Sotherton & Self 2000). In bees, as with plants,
66 there are multiple drivers involved in their declines (Goulson *et al.* 2015); however,
67 intensive agriculture is widely regarded as one of the largest contributors (Goulson &
68 Nicholls 2016). This loss of bee species, along with other pollinators, is of particular
69 concern as they are essential for the pollination of not only many wild plants (Ollerton *et al.*
70 2011) but also the majority of commercially important crop species (Aizen *et al.* 2009).

71 Ecologically-friendly farming methods have the potential to mitigate the effects of
72 intensive agriculture upon pollinator declines and, as such, have received much attention
73 (Kovács-Hostyánszki *et al.* 2017). Agri-environment schemes (AES) are often used to
74 encourage such practices (Batáry *et al.* 2015). Certain AES aim to encourage wildflowers
75 and pollinating insects specifically, including wildflower strips, seed mixes and hedgerow
76 enrichment, many of which have been shown to benefit plant-pollinator communities
77 (Wood *et al.* 2015). Yet AES remain controversial, often benefiting a limited suite of
78 species (Wood *et al.* 2016; MacDonald *et al.* 2019), with doubts on whether they are truly
79 effective for conservation management on farmland (Ansell *et al.* 2016; Riley *et al.* 2017).

80 Another such route is the adoption of organic farming practices. Organic farming
81 tends to be less intensive, utilising less pesticide and fertiliser (Rigby & Cáceres 2001;
82 Pimentel *et al.* 2005) whilst supporting increased habitat heterogeneity (Fuller *et al.* 2005);
83 attributes which have been shown to benefit bee and plant communities (Rader *et al.* 2014;

84 Basu *et al.* 2016). Many studies have demonstrated benefits in terms of species richness and
85 abundance, for both plants and bees (Gabriel & Tschardt 2007; Kennedy *et al.* 2013).

86 Despite this, studies investigating both organic farming or AES do not show how
87 these patterns shift across a season. Both plant and bee phenology are mutually dependent
88 (Morente-López *et al.* 2018), an important factor to consider when planning interventions
89 as understanding where troughs in abundance and diversity occur can aid targeted
90 management, allowing farmers to concentrate their efforts during times of shortage. For
91 example, spring is often referred to as the pollinator ‘*hungry gap*’ on farmland
92 (Nowakowski & Pywell 2016), where floral resources can be scarce. Yet, this is a critical
93 time, with adequate floral resources in this period being essential for emerging bees
94 (Moquet *et al.* 2015) and initial colony growth (Williams *et al.* 2012). However, any
95 differences between these early months and later summer months may be lost when
96 analysed together, or inadequately compensated for with general pollinator management
97 schemes.

98 Despite the evidence for the positive effects of organic farming, findings are not
99 universal, with results often mixed (Weibull *et al.* 2003; Holzschuh *et al.* 2008; Rundlöf *et al.*
100 2009; Brittain *et al.* 2010). These conflicting findings suggest that other factors may
101 confound effects of farming practice (Roschewitz *et al.* 2005). Benefits can be seen at the
102 farm scale (Weibull *et al.* 2003), demonstrating the importance of individual farmers in any
103 effects seen within their particular farming system. Farms can also vary greatly within their
104 designation in terms of management practices, intensity, and adoption of AES, which
105 themselves vary in intensity (Wood *et al.* 2016). These discrepancies between studies
106 highlight the need for more fine-grained studies, conducted across a broader array of
107 farming landscapes than currently exist.

108 In this study we investigated how organic and conventional farming practices
109 influenced the floral and bee communities, across the season from spring through to late
110 summer. Few studies have specifically looked at how the benefits (or lack thereof) of
111 different farming practices change within the bee flight season (Power *et al.* 2012), despite
112 the importance of phenology in structuring pollinator communities (Encinas-Viso *et al.*
113 2012) and the obvious effects this may have on the design of certain pollinator management
114 schemes, such as wildflower seed mixes and strips (Nowakowski & Pywell 2016). This
115 temporal aspect is of particular importance for bees, given the importance of the ‘*hungry*
116 *gap*’ mentioned above (Nowakowski & Pywell 2016). Therefore, investigating the effects
117 of farming practice with a phenological mindset is important for understanding effects of
118 farming at finer temporal scales, and for allowing targeted management interventions that
119 maximise plant-pollinator community benefit. As the effects of organic farming can also be
120 influenced by other factors such as the size of the farm (Fuller *et al.* 2005), the surrounding
121 habitat (Roschewitz *et al.* 2005), and crop type (Tuck *et al.* 2014), we paired conventional
122 and organic farms together to reduce confounding effects as far as possible.

123 We first predicted that richness and community composition (both floral and bee)
124 would not differ between farming types. In many cases, species richness does not differ
125 between farm types (Power & Stout 2011) and organic farms situated in otherwise
126 intensively farmed landscapes have been shown to have little benefit for bee and plant
127 communities (Brittain *et al.* 2010). Second, as organic farms use more of the crop area for
128 additional floral resources (Pimentel *et al.* 2005), and ‘weed’ species are more common
129 (Romero *et al.* 2008), we predicted that the abundance of flowers and consequently bees
130 would be higher on organic sites when compared to conventional sites. Third, given the
131 ‘*hungry gap*’, we predicted that organic farms would show higher seasonal floral
132 abundance peaks (Morente-López *et al.* 2018), and correspondingly higher seasonal peaks

133 in bee abundance. This study provides (a) valuable information to practitioners about the
134 status of bee-plant communities on differing farm types, (b) insights into where
135 improvements can be made to bolster or improve such communities, and (c) information for
136 a more precise assessment of where key shortages in floral resource occur throughout the
137 bee flight season, allowing for more efficient and targeted interventions for farmland floral
138 enhancement.

139

140

141 **Methods**

142 *Study Sites*

143 Ten matched pairs of conventional and organic farms were recruited in the East
144 Riding of Yorkshire and North Yorkshire, UK. Initial contact was made with farmers via
145 letter, email or telephone and, upon response, face-to-face meetings were arranged to allow
146 both site visits and the exchange of information. Organic farming is relatively uncommon
147 in the East Riding of Yorkshire in comparison to other parts of the UK therefore organic
148 farms were recruited first and then conventional farms local to the organic farms were
149 contacted afterwards. Farms were paired together based on soil type and local
150 environmental conditions (see Fig. S1 and Table S1 for farm pair locations and details) and
151 were paired as closely as possible, in terms of distance. All survey locations within a pair
152 were at least 4 km apart, minimising the chance of any bees caught being able to have
153 foraged at both locations (Knight *et al.* 2005; Zurbuchen *et al.* 2010). Eight of the ten farm
154 pairs were arable or arable/pastoral mixed farms and two pairs were dairy/beef farms.
155 Sample sites on arable/pastoral mixed farms were all located in the arable region of the
156 farm.

157

158

159

160 *Organism Surveys & Sample Identification*

161 A single field was chosen at each farm within a pair to be the sampling site. Where
162 possible, fields within a pair were matched by crop or, when this was not possible, by crop
163 type. Cereals were the primary crop at all farm sites (barring dairy/beef). Each field within
164 a pair was sampled five times from May to September, 2016, between 09:00 and 16:00 on
165 dry, sunny days with only moderate wind speeds (Forup & Memmott 2005). The order in
166 which each farm within a pair was visited was alternated every sampling session to ensure
167 that, a) farms within pairs were sampled at the same time of day, and b) each farm was
168 sampled during both the morning and afternoon (Power & Stout 2011). An 80 x 1 m
169 transect was walked at a steady pace during each sampling session at each site. The transect
170 consisted of crop, margin and hedgerow habitat types and was ‘E’ shaped with the spine
171 running along the hedgerow/margin and the arms stretching out into the crop. Both spine
172 and arms were 20 x 1 m each. This shape was chosen to reflect the relative land-use of the
173 farm as margins and hedgerows make up comparatively less of the area of a farm than does
174 the crop (Evans *et al.* 2013). By adopting this shape and walking the transect at a steady
175 pace, more time was spent sampling within the crop compared to the hedgerows and
176 margins. The initial location of the transect was chosen using a random number generator
177 where the northern edge of the field was assigned 1, the eastern 2 etc. Subsequent visits
178 then followed a clockwise fashion, to ensure that each start point was random whilst also
179 ensuring each margin was sampled at least once.

180 Floral surveys were conducted at the beginning of each site visit. Any flowering
181 plants (excluding grasses) along the transect were identified (using Rose & O’Reilly 2006)
182 and the number of floral units taken to provide a measure of floral abundance. A single

183 floral unit was defined as any inflorescence or group of inflorescences that could be
184 navigated without a medium sized bee needing to fly between them (Dicks *et al.* 2002).
185 Flowering plants that were not in flower at the time of sampling were not recorded during
186 that visit.

187 To sample the bee community, the transect was walked for an hour (total sampling
188 effort) using a stopwatch, catching all bees possible in a sweep net. Upon capture, the
189 stopwatch was paused for sample processing so as to ensure the full hour was spent
190 walking the transect. All captured bees were stored singly in 50 ml falcon tubes, the time of
191 capture recorded (along with any flower they were interacting with at capture), and then
192 placed in a cool bag containing ice packs. Once the transect was complete, all captured
193 samples were placed into a freezer (-20°C) on-site to euthanise and store them. Thawed
194 bees were identified to species level using Falk (2015) and sexed under a light microscope.

195

196

197 *Statistical Analysis*

198 All analyses were performed with R statistical software v3.5 (R Core Team, 2018)
199 and bee and floral data were analysed in the same way. Community indices (species
200 richness, Simpson's index, and Shannon's index) were calculated from abundance data per
201 site per sampling visit using the package iNEXT (Hsieh *et al.* 2019). The extrapolated
202 values for all indices were used as species accumulation curves fell short of an asymptote.

203 Generalised Linear Mixed effect Models (GLMMs) were used to investigate
204 whether farm type influenced bee and floral abundance as well as community indices.
205 Farming type and visit month, along with their interaction, were used as predictors, and
206 farm pair as a random factor in the maximal model. Minimal models were determined by
207 reverse stepwise model selection. GLMMs were also used to investigate whether bee

208 abundance was influenced by the floral abundance on a farm, with bee abundance as the
209 response variable and floral abundance, farm type and visit month, as well as all
210 interactions, as predictor variables.

211 Community structure was analysed within the package vegan (Oksanen *et al.* 2018)
212 in R. Community similarity of both bees and flowers was investigated using
213 PERMANOVA (ADONIS) of relative species abundances with farm type and visit month,
214 plus their interaction, as predictors. Permutations were restricted to within-farm-pair
215 comparisons only. Nonmetric multidimensional scaling (NMDS) ordination on Bray-Curtis
216 distance matrices was used to visualise differences.

217

218

219

220

221

222 **Results**

223 A total of 1332 bees (780 from organic and 552 from conventional) from 39 species
224 were caught across all farm sites (Table 1), with 4 species unique to conventional sites and
225 6 to organic sites (Table S2). 67,401 floral units were recorded from 105 flowering plant
226 taxa across farm types (Table 2), with 31 taxa unique to conventional sites and 21 unique to
227 organic sites (Table S3).

228

229

230

231

232 **Table 1. The proportion of each bee species caught on organic and conventional as a**
 233 **percentage of the total number of bees caught per farming type. Ordered by organic farms,**
 234 **highest proportion to lowest.**

Bee Species	percentage	
	Conventional	Organic
<i>Bombus lapidarius</i>	28	30
<i>Bombus pascuorum</i>	23	26
<i>Bombus terrestris</i>	13	9.9
<i>Bombus hortorum</i>	5.6	6.8
<i>Andrena haemorrhoa</i>	3.6	6.3
<i>Bombus vestalis</i>	2.4	2.6
<i>Bombus rupestris</i>	1.4	2.3
<i>Lasioglossum calceatum</i>	2.2	2.3
<i>Apis mellifera</i>	3.4	1.9
<i>Bombus pratorum</i>	1.6	1.8
<i>Lasioglossum albipes</i>	1.6	1.5
<i>Andrena scotica</i>	0.54	1.3
<i>Andrena subopaca</i>	1.4	1
<i>Bombus barbutellus</i>	2.4	0.77
<i>Andrena fucata</i>	0.18	0.64
<i>Bombus hypnorum</i>	1.3	0.64
<i>Bombus campestris</i>	1.3	0.51
<i>Bombus lucorum</i>	1.1	0.51
<i>Andrena helvola</i>	0.9	0.38
<i>Nomada leucophthalma</i>	0	0.38
<i>Andrena chrysosceles</i>	1.3	0.26
<i>Andrena fulva</i>	0.18	0.26
<i>Nomada flava</i>	0.72	0.26
<i>Nomada panzeri</i>	0.18	0.26
<i>Andrena minutula</i>	0	0.13
<i>Andrena nigroaenea</i>	0.36	0.13
<i>Bombus jonellus</i>	0.18	0.13
<i>Coelioxys rufescens</i>	0	0.13
<i>Halictus rubicundus</i>	0.36	0.13
<i>Hylaeus communis</i>	0	0.13
<i>Lasioglossum villosulum</i>	0.18	0.13
<i>Megachile willughbiella</i>	0	0.13
<i>Melecta albifrons</i>	0	0.13
<i>Nomada flavoguttata</i>	0.36	0.13
<i>Andrena barbilabris</i>	0.18	0
<i>Lasioglossum morio</i>	0.36	0
<i>Lasioglossum sp.</i>	0.18	0
<i>Nomada ruficornis</i>	0.18	0
<i>Sphecodes gibbus</i>	0.18	0

236 **Table 2. The proportion of each flowering plant taxa recorded on organic and conventional as**
 237 **a percentage of the total number of flowering plants recorded per farming type. Ordered by**
 238 **organic farms, highest proportion to lowest.**

Community diversity indices

The number of bee species caught overall did not differ between farm types (GLMM, dropping effect of farm type. $\chi^2_{1,7} = 0.85$, $p = 0.36$). Shifts were seen, however, between months (GLMM, $\chi^2_{4,6} = 12.24$, $p = 0.016$), with notable peaks in richness being seen in the months of July and August (Fig. 1a). The same trends were seen in the number of flowering plant species, with farm type having no effect on floral species richness (GLMM, $\chi^2_{1,7} = 2.01$, $p = 0.16$) and only the visit month showing a significant effect ($\chi^2_{4,6} = 24.50$, $p < 0.001$), with higher richness being seen in the summer months (Fig. 1b).

Fig. 1. Species richness of bees (A) and flowering plants (B) recorded on organic and conventional farms plotted by sampling month

As the same patterns were seen for both bees and flowering plants for Shannon's Index and Simpson's Index, the results for Shannon's Index only are visualised here. In

258 accordance with the results for richness, Shannon's Index was not influenced by farm type
 259 for either bees (GLMM, $\chi^2_{1,8} = 0.88$, $p = 0.35$) or flowering plants ($\chi^2_{1,8} = 0.075$, $p = 0.78$),
 260 but was significantly influenced by visit month (Bees, $\chi^2_{1,8} = 17.55$, $p = 0.0015$, Fig. 2a;
 261 Flowering plants, $\chi^2_{4,7} = 17.36$, $p = 0.002$, Fig. 2b). For bees, lower index values were seen
 262 in September ($t_{88} = 3.94$, $p < 0.001$) but with flowering plants, May was the lowest diversity
 263 month ($t_{89} = 9.87$, $p < 0.001$), with higher values seen across all other months.
 264

265
 266
 267 **Fig. 2. Shannon's Diversity Index for bees (A) and flowering plants (B) on organic and**
 268 **conventional farms plotted by sample month**

269
 270
 271 The same results were seen for Simpson's Index for both bees and flowering plants,
 272 whereby farm type had no effect (Bees, $\chi^2_{4,8} = 2.68$, $p = 0.1$; Flowering plants, $\chi^2_{1,8} = 0.06$,
 273 $p = 0.81$), with the majority of variation being driven by visit month (Bees, $\chi^2_{4,8} = 14.21$, p

274 = 0.0067; Flowering plants, $\chi^2_{4,8} = 12.77$, $p = 0.012$). Again, as with Shannon's Index,
 275 Simpson's Index was significantly lower in September for bees ($t_{91} = 2.86$, $p = 0.0042$) and
 276 significantly lower for flowering plants in May ($t_{89} = 9.87$, $p < 0.001$).

277

278 *Community composition*

279 The bee community composition at farm sites was not influenced by farm type
 280 (ADONIS: $R^2 = 0.002$, $p = 0.986$) but was significantly affected by visit month (ADONIS:
 281 $R^2 = 0.176$, $p < 0.001$), clustering together by the visit month when visualised with NMDS
 282 ordination (Fig. 3a,b).

283 The floral community, however, was influenced by both farming type (ADONIS: R^2
 284 = 0.018, $p = 0.0042$) and visit month (ADONIS: $R^2 = 0.13$, $p < 0.001$). This influence of
 285 farming type remained even when one outlying conventional community sample in May
 286 was removed (ADONIS: $R^2 = 0.019$, $p = 0.0044$, Fig. S2a). Under NMDS, floral
 287 community samples clustered together by visit month, as with the bee communities (Fig.
 288 3c,d). Note that one visit to a conventional site, was removed from ordination analysis (due
 289 to only a single specimen being recorded) along with its organic partner. NMDS
 290 visualisation with this point included can be seen in Fig. S2. The same conventional site
 291 was removed from both bee and floral data and the removal did not influence the outcome
 292 of ADONIS analyses.

293

294 **Fig. 3. (A, B) NMDS plots both showing the same data: counts of bee species at each site**
 295 **during each sampling month (raw data converted to percentages), but shaded by (A) farm**
 296 **type and sampling month (B). (C, D) NMDS plots both showing the counts of flowering plant**
 297 **species at each site during each sampling month but shaded by farm type (C) and sampling**
 298 **month(D). Note: visit one from one conventional farm was removed as an outlier, its paired**
 299 **organic site was also removed.**

300

301 *Bee & floral abundance*

302 The abundance of bees was influenced by both farming type and visit month with a
303 significant interaction between the two predictors (Generalised Linear Mixed effects Model
304 - GLMM - containing farm type and visit month as predictors with farm pair as a random
305 factor, dropping interaction. $\chi^2_{4,11} = 87.727$, $p < 0.001$). Overall, more bees were caught on
306 organic farms than on conventional farms (Fig. 4a) with this difference primarily being
307 driven by the months of July and August (Fig. 4b).

308 There was a significant interaction between farm type and visit month when
309 analysing the floral abundance (GLMM, dropping the interaction. $\chi^2_{7,11} = 2312.8$, $p < 0.001$).
310 Overall, there was a higher number of floral units (greater floral abundance) recorded on
311 organic farms (Fig. 4c) and, as with bee abundance, floral abundance was higher on organic
312 farms in the summer months of July and August, as well as in May (Fig. 4d).

313 There was a significant 3-way interaction (all predictors) when modelling bee
314 abundance against floral abundance (GLMM, $\chi^2_{4,21} = 10.71$, $p = 0.03$), with bee abundance
315 being positively associated with floral abundance to different degrees based on month and
316 farm type (Fig. 5a-e,f). However, it seems clear that the month of May is driving this
317 interaction (Fig. 5a), with bee abundance being negatively associated with floral abundance
318 on organic sites but not on conventional sites.

319

320

321 **Fig. 4. Abundance of bees and flowers recorded on farm sites. Number of bees recorded on**
322 **organic and conventional farms in totality (A), and within each visit month separately (B).**

323 **Number of floral units (square root transformed) recorded on organic and conventional farms**
324 **in totality (C), and within each visit month separately (D).**

Fig. 5. (A-E) the number of bees and the corresponding number of floral units recorded on conventional and organic farms plotted by sampling month. Each point represents a single farm. (F) The total number of bees and corresponding floral units recorded on organic and conventional sites pooled across sampling months. Each point represents a single month at a single farm.

332 Discussion

333 As predicted, organic farms supported higher seasonal and overall floral and bee
334 abundances than conventional farms, though these increases were driven by particular
335 months (e.g. May, July; Fig. 4). Equally, we found no difference in diversity or richness of
336 flowering plants or bees between farming practices (Fig. 1, 2), despite floral community
337 composition differing between farm types (Fig. 3). Overall, we found that phenology and
338 not farming practice had the strongest influence on bee and flowering plant communities in
339 terms of variation in abundances, diversity and community structure. Whilst the benefits of
340 organic farming have received much attention (Hole *et al.* 2005) the relative similarities
341 between farming practices found here suggests that with focussed management
342 interventions, differences in abundance between farm types could be reduced.

343 Perhaps unsurprisingly, organic farms supported greater abundances of bees and
344 flowering plants, as has been shown previously (Bengtsson *et al.* 2005; Rundlöf *et al.* 2008,
345 2009). Interestingly however, the higher abundances in organic farms only occurred in
346 certain months. Organic farms showed the highest abundance relative to conventional farms
347 in July, in both bees and flowering plants, with modest differences in May and August;
348 however, during June and September conventional farms were comparable. May is of
349 particular interest, as spring is often a pollinator ‘*hungry gap*’ on farmland (Nowakowski &
350 Pywell 2016) traditionally linked with poor floral availability. This period is critically
351 important for bees and our results suggest that organic sites may be providing better support
352 during this crucial time. This also suggests that spring should be a focus period for
353 improvement on conventional farms, whereby farmers focus on ensuring spring flowering
354 species in management interventions such as seed mixes, wildflowers strips and hedgerow
355 enrichment.

356 Increases in bee numbers were related to higher floral unit abundance overall (Fig.
357 3). As organic farms tend to support high floral abundances (Batáry *et al.* 2013) and,
358 broadly speaking, more flowers tends to mean more bees (Biesmeijer *et al.* 2006; Potts *et*
359 *al.* 2010) it could be said that organic farms support more bees. However, this positive
360 association does not simply apply to organic farms; the same is true for conventional sites
361 (Fig. 3; Power & Stout 2011), suggesting conventional farms will also be able to support
362 more bees, if floral availability is improved. Moreover, the increase in bee abundance on
363 organic farms could also be driven by additional factors such as more nesting habitat or
364 reduced exposure to harmful pesticides (Goulson *et al.* 2015). Interestingly, bee abundance
365 on organic farms in May was negatively related to flower abundance (Fig. 3a), unlike
366 previously identified trends (Gabriel *et al.* 2013; Kennedy *et al.* 2013). This pattern may
367 reflect non-floral resources: without appropriate nesting sites or overwintering sites bee
368 populations can also struggle (Kells & Goulson 2003). Alternatively, with floral resources
369 scarce during the hungry gap, individual bees may spend more time foraging and are
370 therefore encountered more frequently when sampling. In summer months, when
371 availability is high, more bees can be supported and therefore more bees are caught during
372 sampling.

373 The bee communities found on organic and conventional farms were similar,
374 running counter to some studies (Holzschuh *et al.* 2007, 2010) but agreeing with others
375 (Brittain *et al.* 2010). It is possible that the positive benefits of organic farming may only be
376 apparent when such land makes up a threshold proportion of the agricultural landscape
377 (Brittain *et al.* 2010). As organic farms in Yorkshire are relatively isolated, and far fewer in
378 number than in other parts of the UK, this could explain the uniformity in bee community
379 structure in this case. Equally, as the majority of conventional farms in this study were

involved in AES (either ELS or HLS) differences could be expected to be smaller in comparison to their more intensive counterparts (Albrecht et al. 2007)

Unlike with bees, we found that farming practice did influence floral communities, whereby (a) a significant difference in the flowering plant community was seen between organic and conventional sites, and (b) organic sites were more similar to each other than their conventional counterparts (Figs. 3, S2). Although they do share floral species, organic and conventional farms have been shown to support different plant taxa also (Hawes *et al.* 2010). Organic farms support more non-crop species (Gabriel & Tschardt 2007), which may go some way to explaining the community differences. The bias towards unique flowering plants on organic farms was not found in this study (Table S3), yet the fact that different farming practices supported differing flowering plant species yet similar bee species is interesting. The vast majority of the bees caught in this study were polylectic, i.e. plant generalists, which tend to dominate agricultural landscapes (Ahrenfeldt *et al.* 2019). This generality may help to explain the similarity in bee communities despite the floral differences. Despite the difference seen in the floral communities between farm types it is important to note that the differences seen between months were far greater, suggesting that differences in farmland floral communities during the bee season are affected more by phenological drivers than by farming practice *per se*, as stated above. Therefore, understanding the effects of phenology should not be overlooked in farmland bee-plant communities as it likely has a stronger influence on the health of such systems than the farming practice itself. As such, a focus on ensuring floral availability across the flight season may be just as important to bee communities as a focus on maintaining floral diversity by altering farming practices *per se*.

Despite the differences seen in flowering plant community structure across sampling months, there was no difference in *overall* species richness or diversity between

405 farming practices. Previous studies show mixed results for both plants and bees, with some
 406 showing higher levels of richness and diversity on organic farms (Gabriel & Tschardtke
 407 2007; Kennedy *et al.* 2013) but others not (Gibson *et al.* 2007; Brittain *et al.* 2010). The
 408 effects of farming practice can be heavily influenced by the composition of the surrounding
 409 landscape (Roschewitz *et al.* 2005; Brittain *et al.* 2010). Although statistically there was no
 410 difference between farming practices, it is worth noting that floral richness and diversity do
 411 seem to fluctuate across months, with May in particular showing lower diversity and
 412 species richness, coinciding with that of bees (Fig. 1, 2), highlighting the ‘*hungry gap*’ on
 413 farmland.

414 We found little difference in the richness and diversity of flowering plants, or bees,
 415 between farming practices (Fig. 4b, 5b), however, what is clear is that spikes in floral
 416 abundance correspond with spikes in bee abundance (Fig. 4b, d). These gluts in floral
 417 abundance may be useful sources of nutrition but bee communities require floral constancy
 418 across the season in order to support them throughout their life cycles (Goulson & Nicholls
 419 2016); something both farming systems could improve upon.

420 Organic farming appears to support greater abundances of floral resources and bee
 421 pollinators, yet, in line with some previous studies, does not seem to support higher levels
 422 of diversity in either group (Gibson *et al.* 2007; Brittain *et al.* 2010). The higher floral
 423 abundances coincide with higher abundance in bees, and these levels are substantially
 424 higher during the months of May and July on organic farms. However, floral and bee
 425 communities on both farm types are similar and conventional sites may be able to plug the
 426 gaps by creating flower-rich habitats (Carvell *et al.* 2007). Additionally, as organic farms
 427 only showed increases in floral resources during specific months, targeted management
 428 towards these periods of scarcity (Nowakowski & Pywell 2016) on conventional farms may
 429 allow then to catch up. However, as we have seen from our study, along with others (Power

430 & Stout 2011), increased floral and bee abundance does not correspond to an increase in
 431 diversity, therefore “more flowers equals more bees” could be seen as a rather simplistic
 432 view of a complex issue. As such, ensuring that management practices for both farming
 433 methods take into account diversity and quality (in terms of nutrition) of floral resources
 434 will likely support a greater number and diversity of not only flowers (Gibson *et al.* 2007)
 435 but bees also (Filipiak *et al.* 2017). Additionally, individual farmers can make a difference,
 436 as many of these effects can be seen at the farm scale (Weibull *et al.* 2003), especially for
 437 solitary bee species, which respond to relatively small management improvements at
 438 smaller scales (Steffan-Dewenter *et al.* 2002). Our findings reinforce the idea that
 439 biodiversity support in agriculture is more complex than simply organic or conventional,
 440 with other parameters also playing a role (Kennedy *et al.* 2013). Perhaps then, such pigeon-
 441 holing may be of little benefit, and encouraging farmers to adopt wildlife-friendly farming
 442 practices (Pywell *et al.* 2015) irrespective of their designation should be the focus, as well
 443 as communicating the benefits of such methods (Gabriel *et al.* 2013; Pywell *et al.* 2015)
 444 directly to the end user i.e. the farmers themselves. Both making farmers aware of such
 445 benefits, as well as continuing to research new ways to improve management schemes,
 446 should be a priority. For example, pollinator seed mixes have been shown to benefit certain
 447 species (Blackmore & Goulson 2014), yet provide little support during certain periods
 448 (Pywell *et al.* 2011) or for some groups, such as solitary bees (Wood *et al.* 2016).
 449 Additionally, an increased focus on the nutritional *quality* of such resources should be used
 450 to inform the inclusion of particular flowers into such seed mixes. The importance of
 451 quality nutrition to bee health is becoming more and more apparent (Fowler *et al.* 2016;
 452 Nicholls & Hempel de Ibarra 2016), with pollen in particular being a highly variable
 453 (Roulston & Cane 2000) yet critical resource for bee development (Donkersley *et al.* 2017;
 454 Filipiak 2019). Improvements to these schemes, coupled with targeted management, could

not only allow for conventional farms to plug the gap in floral and bee abundances seen in comparison to organic farms, but also lead to improvements in the diversity of bee (and wider pollinator) communities across all farm practices.

References

Ahrenfeldt, E.J., Kollmann, J., Madsen, H.B., Skov-Petersen, H. & Sigsgaard, L. (2019). Generalist solitary ground-nesting bees dominate diversity survey in intensively managed agricultural land. *Journal of Melittology*, 1–12.

Aizen, M.A., Garibaldi, L.A., Cunningham, S.A. & Klein, A.M. (2009). How much does agriculture depend on pollinators? Lessons from long-term trends in crop production. *Ann. Bot.*, 103, 1579–1588.

Ansell, D., Freudenberger, D., Munro, N. & Gibbons, P. (2016). The cost-effectiveness of agri-environment schemes for biodiversity conservation: A quantitative review. *Agric. Ecosyst. Environ.*, 225, 184–191.

Basu, P., Parui, A.K., Chatterjee, S., Dutta, A., Chakraborty, P., Roberts, S., *et al.* (2016). Scale dependent drivers of wild bee diversity in tropical heterogeneous agricultural landscapes. *Ecol. Evol.*

Batáry, P., Dicks, L.V., Kleijn, D. & Sutherland, W.J. (2015). The role of agri-environment schemes in conservation and environmental management. *Conserv. Biol.*, 29, 1006–1016.

481 Batáry, P., Sutcliffe, L., Dormann, C.F. & Tschardt, T. (2013). Organic farming favours insect-pollinated
482 over non-insect pollinated forbs in meadows and wheat fields. *PLoS One*, 8, e54818.

483 Bengtsson, J., Ahnström, J. & Weibull, A.-C. (2005). The effects of organic agriculture on biodiversity and
484 abundance: a meta-analysis. *J. Appl. Ecol.*, 42, 261–269.

485 Biesmeijer, J.C., Roberts, S.P.M., Reemer, M., Ohlemüller, R., Edwards, M., Peeters, T., *et al.* (2006).
486 Parallel declines in pollinators and insect-pollinated plants in Britain and the Netherlands. *Science*, 313,
487 351–354.

488 Blackmore, L.M. & Goulson, D. (2014). Evaluating the effectiveness of wildflower seed mixes for boosting
489 floral diversity and bumblebee and hoverfly abundance in urban areas. *Insect Conserv. Divers.*, 7, 480–
490 484.

491 Brittain, C., Bommarco, R., Vighi, M., Settele, J. & Potts, S.G. (2010). Organic farming in isolated landscapes
492 does not benefit flower-visiting insects and pollination. *Biol. Conserv.*, 143, 1860–1867.

493 Carvell, C., Meek, W.R., Pywell, R.F., Goulson, D. & Nowakowski, M. (2007). Comparing the efficacy of
494 agri-environment schemes to enhance bumble bee abundance and diversity on arable field margins. *J.*
495 *Appl. Ecol.*, 44, 29–40.

496 Dicks, L.V., Corbet, S.A. & Pywell, R.F. (2002). Compartmentalization in plant–insect flower visitor webs. *J.*
497 *Anim. Ecol.*, 71, 32–43.

498 Donkersley, P., Rhodes, G., Pickup, R.W., Jones, K.C., Power, E.F., Wright, G.A., *et al.* (2017). Nutritional
499 composition of honey bee food stores vary with floral composition. *Oecologia*.

500 Encinas-Viso, F., Revilla, T.A. & Etienne, R.S. (2012). Phenology drives mutualistic network structure and
501 diversity. *Ecol. Lett.*, 15, 198–208.

502 Evans, D.M., Pocock, M.J.O. & Memmott, J. (2013). The robustness of a network of ecological networks to
503 habitat loss. *Ecol. Lett.*, 16, 844–852.

504 Falk, S.J. (2015). *Field guide to the bees of Great Britain and Ireland*. British Wildlife Publishing.

505 Filipiak, M. (2019). Key pollen host plants provide balanced diets for wild bee larvae: A lesson for planting
506 flower strips and hedgerows. *J. Appl. Ecol.*

507 Filipiak, M., Kuszewska, K., Asselman, M., Denisow, B., Stawiarz, E., Woyciechowski, M., *et al.* (2017).
508 Ecological stoichiometry of the honeybee: Pollen diversity and adequate species composition are needed
509 to mitigate limitations imposed on the growth and development of bees by pollen quality. *PLoS One*, 12,
510 e0183236.

511 Forup, M.L. & Memmott, J. (2005). The Restoration of Plant–Pollinator Interactions in Hay Meadows.
512 *Restor. Ecol.*, 13, 265–274.

513 Fowler, R.E., Rotheray, E.L. & Goulson, D. (2016). Floral abundance and resource quality influence
514 pollinator choice. *Insect Conserv. Divers.*

515 Fuller, R.J., Norton, L.R., Feber, R.E., Johnson, P.J., Chamberlain, D.E., Joys, A.C., *et al.* (2005). Benefits of
516 organic farming to biodiversity vary among taxa. *Biol. Lett.*, 1, 431–434.

517 Gabriel, D., Sait, S.M., Kunin, W.E. & Benton, T.G. (2013). Food production vs. biodiversity: comparing
518 organic and conventional agriculture. *J. Appl. Ecol.*, 50, 355–364.

519 Gabriel, D. & Tscharntke, T. (2007). Insect pollinated plants benefit from organic farming. *Agric. Ecosyst.*
520 *Environ.*, 118, 43–48.

521 Gibson, R.H., Pearce, S., Morris, R.J., Symondson, W. & Memmott, J. (2007). Plant diversity and land use
522 under organic and conventional agriculture: a whole-farm approach. *J. Appl. Ecol.*, 44, 792–803.

523 Goulson, D. & Nicholls, E. (2016). The canary in the coalmine; bee declines as an indicator of environmental
524 health. *Sci. Prog.*, 99, 312–326.

525 Goulson, D., Nicholls, E., Botías, C. & Rotheray, E.L. (2015). Bee declines driven by combined stress from
526 parasites, pesticides, and lack of flowers. *Science*, 347, 1255957.

527 Hawes, C., Squire, G.R., Hallett, P.D., Watson, C.A. & Young, M. (2010). Arable plant communities as
528 indicators of farming practice. *Agric. Ecosyst. Environ.*, 138, 17–26.

529 Hole, D.G., Perkins, A.J., Wilson, J.D., Alexander, I.H., Grice, P.V. & Evans, A.D. (2005). Does organic
530 farming benefit biodiversity? *Biol. Conserv.*, 122, 113–130.

531 Holzschuh, A., Steffan-Dewenter, I., Kleijn, D. & Tscharntke, T. (2007). Diversity of flower-visiting bees in
532 cereal fields: effects of farming system, landscape composition and regional context. *J. Appl. Ecol.*, 44,
533 41–49.

534 Holzschuh, A., Steffan-Dewenter, I. & Tscharntke, T. (2008). Agricultural landscapes with organic crops
535 support higher pollinator diversity. *Oikos*, 117, 354–361.

536 Holzschuh, A., Steffan-Dewenter, I. & Tscharntke, T. (2010). How do landscape composition and
537 configuration, organic farming and fallow strips affect the diversity of bees, wasps and their parasitoids?
538 *J. Anim. Ecol.*, 79, 491–500.

539 Hsieh, T.C., Ma, K.H. & Chao, A. (2019). iNEXT: iNterpolation and EXTrapolation for species diversity. R
540 package version 2.0. 19.

541 Kells, A.R. & Goulson, D. (2003). Preferred nesting sites of bumblebee queens (Hymenoptera: Apidae) in
542 agroecosystems in the UK. *Biol. Conserv.*, 109, 165–174.

543 Kennedy, C.M., Lonsdorf, E., Neel, M.C., Williams, N.M., Ricketts, T.H., Winfree, R., *et al.* (2013). A global
544 quantitative synthesis of local and landscape effects on wild bee pollinators in agroecosystems. *Ecol.*
545 *Lett.*, 16, 584–599.

546 Knight, M.E., Martin, A.P., Bishop, S., Osborne, J.L., Hale, R.J., Sanderson, R.A., *et al.* (2005). An
547 interspecific comparison of foraging range and nest density of four bumblebee (*Bombus*) species. *Mol.*
548 *Ecol.*, 14, 1811–1820.

549 Kovács-Hostyánszki, A., Espíndola, A., Vanbergen, A.J., Settele, J., Kremen, C. & Dicks, L.V. (2017).
550 Ecological intensification to mitigate impacts of conventional intensive land use on pollinators and
551 pollination. *Ecol. Lett.*

552 MacDonald, M.A., Angell, R., Dines, T.D., Dodd, S., Haysom, K.A., Hobson, R., *et al.* (2019). Have Welsh
553 agri-environment schemes delivered for focal species? Results from a comprehensive monitoring
554 programme. *J. Appl. Ecol.*, 49, 871.

555 Moquet, L., Mayer, C., Michez, D., Wathelet, B. & Jacquemart, A.-L. (2015). Early spring floral foraging
556 resources for pollinators in wet heathlands in Belgium. *J. Insect Conserv.*, 19, 837–848.

557 Morente-López, J., Lara-Romero, C., Ornos, C. & Iriondo, J.M. (2018). Phenology drives species
558 interactions and modularity in a plant - flower visitor network. *Sci. Rep.*, 8, 9386.

559 Nicholls, E. & Hempel de Ibarra, N. (2016). Assessment of pollen rewards by foraging bees. *Funct. Ecol.*

560 Niedrist, G., Tasser, E., Lüth, C., Dalla Via, J. & Tappeiner, U. (2008). Plant diversity declines with recent
561 land use changes in European Alps. *Plant Ecol.*, 202, 195.

562 Nowakowski, M. & Pywell, R. (2016). *Habitat Creation and Management for Pollinators*. Centre for
563 Ecology & Hydrology, Wallingford, UK.

564 Oksanen, J., Blanchet, F.G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., *et al.* (2018). vegan:
565 Community Ecology Package. R package version 2.5-2. 2018.

566 Ollerton, J., Winfree, R. & Tarrant, S. (2011). How many flowering plants are pollinated by animals? *Oikos*.

567 Pimentel, D., Hepperly, P., Hanson, J., Douds, D. & Seidel, R. (2005). Environmental, Energetic, and
568 Economic Comparisons of Organic and Conventional Farming Systems. *Bioscience*, 55, 573–582.

569 Potts, S.G., Biesmeijer, J.C., Kremen, C., Neumann, P., Schweiger, O. & Kunin, W.E. (2010). Global
570 pollinator declines: trends, impacts and drivers. *Trends Ecol. Evol.*, 25, 345–353.

571 Power, E.F., Kelly, D.L. & Stout, J.C. (2012). Organic farming and landscape structure: effects on insect-
572 pollinated plant diversity in intensively managed grasslands. *PLoS One*, 7, e38073.

573 Power, E.F. & Stout, J.C. (2011). Organic dairy farming: impacts on insect–flower interaction networks and
574 pollination. *J. Appl. Ecol.*, 48, 561–569.

575 Pywell, R.F., Heard, M.S., Woodcock, B.A., Hinsley, S., Ridding, L., Nowakowski, M., *et al.* (2015).
576 Wildlife-friendly farming increases crop yield: evidence for ecological intensification. *Proceedings of*
577 *the Royal Society B: Biological Sciences*, 282, 20151740.

578 Pywell, R.F., Meek, W.R., Hulmes, L., Hulmes, S., James, K.L., Nowakowski, M., *et al.* (2011). Management
579 to enhance pollen and nectar resources for bumblebees and butterflies within intensively farmed
580 landscapes. *J. Insect Conserv.*, 15, 853–864.

581 Rader, R., Birkhofer, K., Schmucki, R., Smith, H.G., Stjerner, M. & Lindborg, R. (2014). Organic farming
582 and heterogeneous landscapes positively affect different measures of plant diversity. *J. Appl. Ecol.*, 51,
583 1544–1553.

584 Rhodes, C.J. (2018). Pollinator decline - an ecological calamity in the making? *Sci. Prog.*, 101, 121–160.

585 Rigby, D. & Cáceres, D. (2001). Organic farming and the sustainability of agricultural systems. *Agric. Syst.*,
586 68, 21–40.

587 Riley, M., Sangster, H., Smith, H., Chiverrell, R. & Boyle, J. (2017). Will farmers work together for
588 conservation? The potential limits of farmers’ cooperation in agri-environment measures. *Land use*
589 *policy*.

590 Romero, A., Chamorro, L. & Sans, F.X. (2008). Weed diversity in crop edges and inner fields of organic and
591 conventional dryland winter cereal crops in NE Spain. *Agric. Ecosyst. Environ.*, 124, 97–104.

592 Roschewitz, I., Gabriel, D., Tschardt, T. & Thies, C. (2005). The effects of landscape complexity on arable
593 weed species diversity in organic and conventional farming. *J. Appl. Ecol.*, 42, 873–882.

594 Rose, F. & O’Reilly, C. (2006). *The Wild Flower Key: How to Identify Wild Flowers, Trees and Shrubs in*
595 *Britain and Ireland*. Frederick Warne.

596 Roulston, T.H. & Cane, J.H. (2000). Pollen nutritional content and digestibility for animals. *Plant Syst. Evol.*,
597 222, 187–209.

598 Rundlöf, M., Edlund, M. & Smith, H.G. (2009). Organic farming at local and landscape scales benefits plant
599 diversity. *Ecography*, 18, 303.

600 Rundlöf, M., Nilsson, H. & Smith, H.G. (2008). Interacting effects of farming practice and landscape context

601 on bumble bees. *Biol. Conserv.*, 141, 417–426.

602 Sánchez-Bayo, F. & Wyckhuys, K.A.G. (2019). Worldwide decline of the entomofauna: A review of its
603 drivers. *Biol. Conserv.*, 232, 8–27.

604 Sotherton, N. & Self, M.J. (2000). Changes in plant and arthropod diversity on lowland farmland : an
605 overview. In: *Ecology and conservation of lowland farmland birds* (eds. Aebischer, N.J., Evans, A.D.,
606 Grice, P.V. & Vickery, J.A.). British Ornithologists Union, pp. 26–35.

607 Steffan-Dewenter, I., Münzenberg, U., Bürger, C., Thies, C. & Tschamtkke, T. (2002). Scale-Dependent
608 Effects of Landscape Context on Three Pollinator Guilds. *Ecology*, 83, 1421–1432.

609 Tuck, S.L., Winqvist, C., Mota, F., Ahnström, J., Turnbull, L.A. & Bengtsson, J. (2014). Land-use intensity
610 and the effects of organic farming on biodiversity: a hierarchical meta-analysis. *J. Appl. Ecol.*, 51, 746–
611 755.

612 Weibull, A.-C., Östman, Ö. & Granqvist, Å. (2003). Species richness in agroecosystems: the effect of
613 landscape, habitat and farm management. *Biodiversity & Conservation*, 12, 1335–1355.

614 Williams, N.M., Regetz, J. & Kremen, C. (2012). Landscape-scale resources promote colony growth but not
615 reproductive performance of bumble bees. *Ecology*, 93, 1049–1058.

616 Wood, T.J., Holland, J.M. & Goulson, D. (2016). Providing foraging resources for solitary bees on farmland:
617 current schemes for pollinators benefit a limited suite of species. *J. Appl. Ecol.*

618 Wood, T.J., Holland, J.M., Hughes, W.O.H. & Goulson, D. (2015). Targeted agri-environment schemes
619 significantly improve the population size of common farmland bumblebee species. *Mol. Ecol.*, 24, 1668–
620 1680.

621 Zurbuchen, A., Landert, L., Klaiber, J., Müller, A., Hein, S. & Dorn, S. (2010). Maximum foraging ranges in
622 solitary bees: only few individuals have the capability to cover long foraging distances. *Biol. Conserv.*,
623 143, 669–676.

624

625

626

627

628