

Wild insect diversity increases inter-annual stability in global crop pollinator communities

Deepa Senapathi^{1*}, Jochen Fründ², Matthias Albrecht³, Michael P. D. Garratt¹, David Kleijn⁴, Brian J. Pickles⁵, Simon G. Potts¹, Jiandong An⁶, Georg K. S. Andersson⁷, Svenja Bänisch^{8,9}, Parthiba Basu¹⁰, Faye Benjamin¹¹, Antonio Diego M. Bezerra¹², Ritam Bhattacharya¹⁰, Jacobus C. Biesmeijer¹³, Brett Blaauw¹⁴, Eleanor J. Blitzer¹⁵, Claire A. Brittain¹⁶, Luísa G. Carvalheiro^{17,18}, Daniel P. Cariveau¹⁹, Pushan Chakraborty¹⁰, Arnob Chatterjee¹⁰, Soumik Chatterjee¹⁰, Sarah Cusser²⁰, Bryan N. Danforth²¹, Erika Degani¹, Breno M. Freitas¹², Lucas A. Garibaldi^{7,22}, Benoit Geslin²³, G. Arjen de Groot²⁴, Tina Harrison²⁶, Brad Howlett²⁶, Rufus Isaacs^{27,28}, Shalene Jha²⁹, Björn Kristian Klatt^{9,30}, Kristin Krewenka³¹, Samuel Leigh¹, Sandra A. M. Lindström^{30,32,33}, Yael Mandelik³⁴, Megan McKerchar³⁵, Mia Park^{21,36}, Gideon Pisanty³⁷, Romina Rader³⁸, Menno Reemer¹³, Maj Rundlöf³⁰, Barbara Smith^{10,39}, Henrik G. Smith⁴⁰, Patricia Nunes Silva⁴¹, Ingolf Steffan-Dewenter⁴², Teja Tscharntke⁹, Sean Webber¹, Duncan B. Westbury³⁵, Catrin Westphal^{8,9}, Jennifer B. Wickens¹, Victoria J. Wickens¹, Rachael Winfree¹¹, Hong Zhang⁶, Alexandra-Maria Klein⁴³.

*Corresponding author

Author affiliations:

1. Centre for Agri-Environmental Research, School of Agriculture, Policy & Development, University of Reading, Reading, United Kingdom
2. Biometry and Environmental System Analysis, Faculty of Environment and Natural Resources, University of Freiburg, Freiburg, Germany
3. Institute for Sustainability Sciences, Agroscope, Zurich, Switzerland
4. Plant Ecology and Nature Conservation Group, Wageningen University, Wageningen, The Netherlands
5. School of Biological Sciences, University of Reading, Reading, United Kingdom
6. Institute of Apicultural Research, Chinese Academy of Agricultural Sciences, Beijing, China
7. Universidad Nacional de Río Negro, Instituto de Investigaciones en Recursos Naturales, Agroecología y Desarrollo Rural, Río Negro, Argentina
8. Functional Agrobiodiversity, Department of Crop Sciences, University of Göttingen, Göttingen, Germany

9. Agroecology, Department of Crop Sciences, University of Göttingen, Göttingen, Germany
10. Centre for Pollination Studies, University of Calcutta, Kolkata, India
11. Department of Ecology, Evolution and Natural Resources, Rutgers, The State University of New Jersey, New Brunswick, USA
12. Setor de Abelhas, Departamento de Zootecnia, Universidade Federal do Ceará, Fortaleza - CE, Brazil
13. Naturalis Biodiversity Centre, Leiden, The Netherlands
14. Department of Entomology, University of Georgia, Athens, Georgia, USA
15. Department of Biology, Carroll College, Harrison Helena, USA
16. Syngenta, Jealott's Hill International Research Centre, Bracknell, Berkshire RG42 6EY, UK
17. Departamento de Ecologia, Universidade Federal de Goiás, Campus Samambaia, Goiânia, Brazil
18. Centre for Ecology, Evolution and Environmental Changes (cE3c), University of Lisboa, Lisbon, Portugal
19. Department of Entomology, University of Minnesota, St. Paul, USA
20. W. K. Kellogg Biological Station, Michigan State University, Michigan, USA
21. Department of Entomology, Cornell University, Ithaca, New York, USA
22. Consejo Nacional de Investigaciones Científicas y Técnicas. Instituto de Investigaciones en Recursos Naturales, Agroecología y Desarrollo Rural. San Carlos de Bariloche, Río Negro, Argentina.
23. IMBE, Aix Marseille Univ, Avignon Université, CNRS, IRD, Marseille, France.
24. Wageningen Environmental Research, Wageningen University and Research, Wageningen, The Netherlands
25. Department of Entomology and Nematology, University of California Davis, Davis, USA
26. The New Zealand Institute for Plant & Food Research Limited, New Zealand
27. Department of Entomology, Michigan State University, East Lansing, USA
28. Ecology, Evolutionary Biology, and Behavior Program, East Lansing, USA
29. Department of Integrative Biology, The University of Texas at Austin, USA
30. Department of Biology, Biodiversity, Lund University, Lund, Sweden
31. Heidelberg Research Service, University of Heidelberg, Heidelberg, Germany
32. Department of Ecology, Swedish University of Agricultural Sciences, Uppsala, Sweden
33. Swedish Rural Economy and Agricultural Society, Kristianstad, Sweden
34. Department of Entomology, The Robert H. Smith Faculty of Agriculture, Food and Environment, The Hebrew University of Jerusalem, Rehovot, Israel
35. School of Science and Environment, University of Worcester, Worcester, United Kingdom
36. Field Engine Wildlife Research and Management, Moodus, CT 06469, USA
37. Agriculture and Agri-Food Canada, Canadian National Collection of Insects, Arachnids and Nematodes, Ontario, Canada

38. School of Environment and Rural Science, University of New England, Armidale, Australia
39. Centre for Agroecology, Water and Resilience, Coventry University, United Kingdom
40. Centre of Environmental and Climate Research & Dept. Biology, Lund University, Sweden
41. Programa de Pós-Graduação em Biologia, Universidade do Vale do Rio dos Sinos (UNISINOS), Av. Unisinos, 950, São Leopoldo, RS, Caixa Postal 93022-750, Brazil
42. Department of Animal Ecology and Tropical Biology, University of Würzburg, Würzburg, Germany
43. Nature Conservation and Landscape Ecology, Faculty of Environment and Natural Resources, University of Freiburg, Freiburg, Germany

Author emails (provided in the same order as authorship indicated above)

g.d.senapathi@reading.ac.uk*; jochen.fruend@biom.uni-freiburg.de;
matthias.albrecht@agroscope.admin.ch; m.p.garratt@reading.ac.uk; david.kleijn@wur.nl;
b.j.pickles@reading.ac.uk; s.g.potts@reading.ac.uk; anjiandong@caas.cn; gandersson@unrn.edu.ar;
svenja.baensch@agr.uni-goettingen.de; bparthib@gmail.com; faye.benjamin@gmail.com;
antoniodiego@hotmail.com; itisrb@gmail.com; koos.biesmeijer@naturalis.nl; bblaauw@uga.edu;
blitzbug@gmail.com; claireabrittain@gmail.com; lgcarvalho@gmail.com; dcarivea@umn.edu;
pushan.zoology@gmail.com; chatterjeearnob@gmail.com; soumikc83@gmail.com;
sarah.cusser@gmail.com; bnd1@cornell.edu; e.degani@pgr.reading.ac.uk; Freitas@ufc.br;
lgaribaldi@unrn.edu.ar; benoit.geslin@imbe.fr; g.a.degroot@wur.nl; tinaharrison09@gmail.com;
brad.howlett@plantandfood.co.nz; isaacs@msu.edu; sjha@austin.utexas.edu;
klattbk@googlemail.com; kristin.krewenka@zuv.uni-heidelberg.de; samuel.leigh@defra.gov.uk;
sandra@v-data.se; yael.mandelik@mail.huji.ac.il; megan.mckerchar@gmail.com;
miagpark@gmail.com; gidpisa79@yahoo.com; rrader@une.edu.au; menno.reemer@naturalis.nl;
maj.rundlof@biol.lu.se; ac0738@coventry.ac.uk; henrik.smith@biol.lu.se; patriciabiene@gmail.com;
ingolf.steffan@uni-wuerzburg.de; ttschar@gwdg.de; seanwebber@hotmail.co.uk;
d.westbury@worc.ac.uk; cwestph@gwdg.de; jenniferbwickens@gmail.com;
victoriajwickens@gmail.com; rwinfree.rutgers@gmail.com; zhanghong@caas.cn;
alexandra.klein@nature.uni-freiburg.de

Statement of authorship: DS collated datasets, analysed the data and wrote the manuscript based on initial ideas conceived by AMK. JF wrote the R code for the initial data analyses, and along with MA, MPDG, DK, BJP, SGP & AMK was involved in helping structure subsequent data analyses and in commenting on several early drafts of the manuscripts. BB produced the insect illustrations used in

Figure 1 in addition to contributing data. All other authors provided the data utilised in the analyses and contributed to revisions of the manuscript.

1 **Abstract:** While an increasing number of studies indicate that range, diversity and abundance of
2 many wild pollinators has declined, the global area of pollinator-dependent crops has significantly
3 increased over the last few decades. Crop pollination studies to date, have mainly focused on either
4 identifying different guilds pollinating various crops, or on factors driving spatial changes and
5 turnover observed in these communities. The mechanisms driving temporal stability for ecosystem
6 functioning and services, however, remain poorly understood. Our study quantifies temporal
7 variability observed in crop pollinators in 21 different crops across multiple years at a global scale.
8 Using data from 43 studies from six continents, we show that (i) higher pollinator diversity confers
9 greater inter-annual stability in pollinator communities, (ii) temporal variation observed in pollinator
10 abundance is primarily driven by the three most dominant species, and (iii) crops in tropical regions
11 demonstrate higher inter-annual variability in pollinator species richness than crops in temperate
12 regions. We highlight the importance of recognising wild pollinator diversity in agricultural
13 landscapes to stabilize pollinator persistence across years to protect both biodiversity and crop
14 pollination services. Short-term agricultural management practices aimed at dominant species for
15 stabilising pollination services need to be considered alongside longer-term conservation goals
16 focussed on maintaining and facilitating biodiversity to confer ecological stability.

17 **Introduction:**

18 The crucial role played by pollinators in the reproduction of flowering plants is well-established [1].
19 Biotic pollination is important for the reproduction of at least 78% of wild plants [2], and insects
20 contribute to the pollination of 75% of leading global crops [3]. Crop systems have also recently
21 become more pollinator dependent because of a disproportionate increase in the area cultivated with
22 entomophilous flowering crops [4]. Given the documented declines of wild insect pollinators in some
23 NW European and North American landscapes where these crops are grown [1, 5, 6] understanding
24 temporal variation in assemblages is important to maintain ongoing food security.

25

26 Higher pollinator diversity can lead to increases in fruit and seed set in plants and is an important
27 predictor of crop yields worldwide [7, 8]. Conversely, pollinator communities with lower diversity
28 and fewer species, have been linked to lower fruit set or seed production, and decreased temporal and
29 spatial stability within seasons [9-11], and may be one reason for lower inter-annual stability of yields
30 in pollinator-dependent crops [1]. While biologically diverse communities can enhance ecological
31 resilience [12, 13], and diversity is a key factor affecting system stability [14], most ecological
32 communities are generally made up of a few species that are numerically abundant and may have
33 many rarer species with very few individuals [15].

34

35 Evidence suggests that numerically dominant species may provide most of the ecosystem services
36 [16], with Kleijn *et al.* [17] finding that ~80% of biotic crop pollination in Europe and North America
37 are fulfilled by ~2% of the pollinator species in a community. In addition, the scale of spatial
38 assessment, is also important, with Winfree *et al.* [18] showing that the number of wild bee species
39 required for reaching a minimum pollination service threshold rapidly increased with spatial scale,
40 indicating that maintaining pollination services across large areas requires many species, including
41 rare ones. Providing stable pollination services for crop systems across several years is needed for
42 sustainable crop production, but the mechanisms driving temporal stability for ecosystem functioning
43 and services still remains an important but poorly understood phenomenon [19].

44

45 Previous studies aimed at disentangling the mechanisms of temporal stability highlight the role of
46 both diversity and dominance. Lehman & Tilman [20] showed that greater diversity increases
47 temporal stability of the entire community but decreases temporal stability of individual populations.
48 The counterview is that dominant species, rather than diversity itself, might regulate temporal stability
49 – for e.g. Sasaki and Lauenroth [21] found that temporal stability in a shortgrass steppe plant
50 community was controlled by dominant species rather than by community diversity. In addition,
51 species asynchrony has also been considered an important mechanism of diversity-stability
52 relationships and may lead to higher stability on the community level even when stability of
53 individual populations decreases with diversity. However, the majority of such studies have utilised
54 long-term observations of the same plant communities over time [for e.g. 22], while such equivalent
55 information on pollinators in general or even crop pollinator communities in particular are lacking.

56

57 A few multi-year, single crop studies exist showing that pollinator communities can vary over
58 longer time periods [9, 23, 24]. What implications this may have for stability remains unknown
59 due to lack of synthesized knowledge on temporal dynamics of crop pollinator communities and
60 underlying driving factors. For example, evidence for the contribution of managed pollinators to the
61 temporal stability of the overall crop pollinator community is largely lacking. Such knowledge gaps,
62 if addressed, could lead to better understanding of the stability and long-term resilience of global crop
63 systems that rely on insect pollination. Temporal stability of ecosystem functioning increases
64 predictability and reliability of ecosystem services and understanding the drivers of stability across
65 spatial scales is important for land management and policy decisions [25].

66

67 Here we synthesise data from multiple studies to examine factors that affect temporal stability of crop
68 pollinator communities, which in turn has implications for stability of pollination services provided.
69 Using data from 43 studies across six continents, we characterise the annual variation observed in
70 crop pollinators and explore the following questions 1. Is temporal stability of crop pollinator
71 communities primarily driven by diversity of pollinator communities or by inter-annual stability of
72 dominant species? 2. What crop characteristics if any (e.g., annual/perennial, flower morphology,

73 mass flowering / non mass flowering crops) influence inter-annual stability of crop pollinator
74 communities? 3. Does inter-annual variation observed in pollinator communities differ between
75 climatic regions (i.e. tropics and temperate study areas)?

76

77 **Material and methods:**

78 Data collection: We collated datasets from 12 countries across six continents on 21 crop species to
79 examine the variations in richness and abundance of insect pollinators in crop systems. The criteria
80 for inclusion in the analyses were as follows: Data on crop pollinator species / morpho-species were
81 required (a) from the same crop for two or more years, (b) with consistent sampling methods used
82 across years, (c) focused on flower visitation data, and (d) in the case of annual crops, field sites were
83 required to be within 500m of the crop field used for recording in previous years to make sure they
84 could be visited by the same pollinator communities. Our final dataset included information on 375
85 crop fields (hereafter referred to as sites) from 43 studies (see Supplementary Table S1 for additional
86 information). Data were standardised to ensure that species names and taxonomic groups were
87 consistent across all studies prior to analyses.

88

89 Each dataset was classified on the basis of climatic region (tropical/temperate), crop type
90 (annual/perennial), plant family and flower type (open / not open) – based on nectar accessibility
91 criteria in Garibaldi *et al.* [26]. In addition, we distinguished crop species that exhibit mass-flowering
92 (MFC) - i.e. short duration intense bloom with high floral density, from those with extended flowering
93 periods with lower density and more sparse blooms. Some crops are clearly defined as mass flowering
94 in the literature [27-31], while others remain ambiguous. To overcome this uncertainty, we requested
95 the original authors to indicate if their crop was considered as MFC in their study and that is reflected
96 in the dataset and subsequent analyses (see Supplementary Table S2). Almonds (*Prunus dulcis*),
97 apples (*Malus domestica*), highbush blueberry (*Vaccinium corymbosum*), cranberry (*Vaccinium*
98 *angustifolium*), red clover (*Trifolium pratense*), field beans (*Vicia faba*), oilseed rape or canola
99 (*Brassica napus*), pears (*Pyrus communis*), pak choi (*Brassica rapa* subsp. *chinensis*) and turnips
100 (*Brassica rapa* subsp. *rapa*) were classified as MFC. Non mass-flowering crops in our analyses

101 include avocado (*Persea americana*), bitter melon (*Momordica charantia*), brinjal (*Solanum*
102 *melongena*) – also known as eggplant or aubergine, cashew (*Anacardium occidentale*), cotton
103 (*Gossypium hirsutum*), kiwifruit (*Actinidia deliciosa*), mango (*Mangifera indica*), mustard (*Brassica*
104 *napus*), onion (*Allium cepa*), pumpkin (*Cucurbita pepo*), ridge gourd (*Luffa acutangula*), spine gourd
105 (*Momordica dioica*), strawberry (*Fragaria x ananassa*) and watermelon (*Citrullus lanatus*). Note:
106 *Brassica napus* includes oilseed rape (OSR) – a MFC in Europe and North America but a different
107 subspecies considered as a type of mustard in India which is not grown as MFC.

108

109 Characterising year to year variation in crop pollinators: Initially, crop pollinators recorded were
110 classified into taxonomic groups which included the following: (i) honeybees (including *Apis*
111 *mellifera*, *Apis cerana*, *Apis dorsata* and other recorded as *Apis* sp.); (ii) bumblebees (all *Bombus* sp.);
112 (iii) other bees (wild solitary and social bees including stingless bees but excluding bumblebees and
113 honeybees); (iv) butterflies and moths; (v) hoverflies; (vi) other Diptera (flies excluding hoverflies);
114 (vii) wasps, and (viii) beetles. The single most dominant taxonomic group and species were identified
115 at all study sites (see Figure 1) based on recorded abundance and a binary (change / no change)
116 analysis was used to determine whether the most dominant group and species remained constant
117 across all years of sampling.

118

119 To characterise between year variation in crop pollinators, (i) a coefficient of variation (CV) of total
120 pollinator abundance and (ii) a CV of pollinator species richness were calculated for each site across
121 all years of the study. The CV (which incorporates a bias correction) is defined as the ratio of the
122 sample standard deviation ‘s’ to the sample mean \bar{x} - i.e. $CV = s / \bar{x}$, and shows the extent of
123 variability in relation to the mean of the population. These measures were calculated using species
124 level data for each study site and the mean and standard deviation of these two measures were also
125 calculated for each individual study (Supplementary Figure S1). In addition, the CV of abundance and
126 CV of richness were calculated for each site for every pairwise year comparisons (i.e. Y1& Y2;
127 Y2&Y3; Y3&Y4 etc) to account for studies having different number of years of data.

128

129 Other calculated indices included (a) CV of honeybee abundance, (b) CV of proportion of honeybees,
130 (c) CV of the most dominant pollinator species across all years and (d) the mean Shannon index of
131 pollinator diversity (H') were calculated across years. The Shannon diversity index was chosen as it
132 accounts for evenness of the species present, thus reflecting effective diversity, and is less sensitive to
133 sampling effects than species richness [32, 33]. Since a subset of studies (28 out of 43) also recorded
134 temperature at the study sites, a standard deviation (SD) of temperature was also calculated as a
135 measure of variation in local climatic condition across years.

136

137 *Factors influencing the observed variation:* In order to examine the potential drivers of inter-annual
138 variation in crop pollinator communities, linear mixed-effects models were constructed using (i) CV
139 of total pollinator abundance and (ii) CV of pollinator species richness. These two indices were
140 calculated across all years of each study and for every pairwise year in each study to account for
141 studies with different numbers of years of observations and ensure checks for sensitivity and
142 robustness. The models included descriptors of pollinator communities such as Shannon diversity (H')
143 of pollinators, CV of dominant species, and change in dominant pollinator species between years
144 (Y/N) as fixed effects. External predictors including climatic region (tropical/temperate), crop type
145 (annual/perennial), crop family, flower type, MFC (Y/N) and SD of site temperature were also
146 included as other explanatory variables. Study ID was included in all models as a random effect and
147 for models where the response variables were calculated for every two years of the study, site ID
148 nested within the study ID were used as random effects (and identified as relevant indicated by
149 positive variance estimates).

150

151 The calculated indices were tested for collinearity and correlated variables were not used within the
152 same models (see correlation matrix in Table S3 of supplementary material). Similarly, categorical
153 predictors which exhibited significant collinearity were not used as variables within the same models.
154 A series of candidate models were constructed for each response variable. Each candidate model was
155 'dredged' to obtain a series of plausible intermediate models. Intermediate models with $\Delta AICc$ value
156 < 7 of the model with lowest $AICc$ were averaged (using the default zero average method) to obtain

157 the final outputs. Residual plots for final models were used to check for heteroscedasticity. Models
158 were fitted using maximum likelihood (ML) and analysed using the ‘lme4’ [34] and ‘MuMIn’ [35]
159 packages. All statistical analyses were carried out in R v. 4.0.3 statistical software [36].

160

161 *Influence of dominant pollinator species:* To test whether variation in total crop pollinator abundance
162 was driven primarily by variation of the most dominant pollinator species, a paired t-test was used to
163 determine whether CV of total pollinator abundance was significantly different from CV of
164 abundance of the single most dominant pollinator species. The same test was repeated using the
165 combined CV of abundance of the two-most, three-most and four-most dominant species to determine
166 how many dominant pollinator species were required to influence the overall variation in total
167 abundance observed. While abundance of dominant species will always be a subset of the total
168 pollinator abundance, these tests were conducted to determine how many dominant species it took to
169 match the change in overall pollinator abundance across years and determine the minimum number of
170 species that drive the temporal variation in overall pollinator abundance. A Welch Two Sample t-test
171 was used to determine if inter-annual variation in pollinator abundance differed between sites
172 dominated by honeybees versus other pollinator species. Sites where there was mixed dominance
173 between honeybees and other pollinators were excluded from this analysis.

174

175 *Dominance species and stability effect:* To further understand mechanisms of stability and particularly
176 the relationship of the dominant species to the whole community, we calculated the correlation
177 between the changes in abundance of the dominant species and the changes in abundance of the rest
178 of the community. Negative correlation (negative covariance) suggests asynchrony, which is
179 considered a key driver of stability and a main mechanism of diversity-stability relationships [37].
180 Negative correlations could indicate density compensation or different responses to environmental
181 variation [12]. In general, higher the asynchrony (i.e. more negative the correlation), the stronger the
182 contribution to stability. With our short time series, many correlations are -1 or +1, without an even
183 continuous gradient in the degree of asynchrony. Therefore, we separated sites by asynchronous ($r \leq$
184 0) or synchronous ($r > 0$) fluctuations of the dominant pollinator species in comparison to the rest of

185 the pollinator community, and for each group separately, repeated the paired t-test of the CV of the
186 dominant species vs. the whole community.

187

188 **Results:**

189 *Characterising year to year variation in crop pollinators*

190 Honeybees were dominant across 41.9% of studies with other wild bees (32.6%) representing the next
191 most dominant group (Figure 1A). At the site level, other wild bees were the most dominant group at
192 41.6%, with honeybees (38.0%) the second most dominant (Figure 1B). The dominant taxonomic
193 group did not change between years in most of the studies or the sites, whereas the dominant species
194 varied between years in approximately half the studies and half the sites (Table 1). The mean (\pm SD)
195 of the CV of total pollinator abundance, and the CV of total pollinator richness for all sites within
196 each study is provided in Supplementary Figure S1.

197

198 *Factors influencing the observed variation*

199 The relative variability of total pollinator abundance across all years was significantly related to the
200 Shannon diversity (Table 2, Estimate = -0.16, $z = 3.96$, $p < 0.0001$, Figure 2A). It was also significant
201 whether the most dominant species varied between years: systems where dominant species stayed the
202 same showed less inter-annual variation in overall pollinator abundance (Table 2, Estimate = -0.08, z
203 = 2.23, $p = 0.03$, Figure 2B). However, in models using CV of abundance for every two years, the
204 variability in dominant species showed no significant relationship (Table 2, Estimate = -0.05, $z =$
205 1.42, $p = 0.16$)

206

207 Having a diverse pollinator community also reduced the inter-annual variation in pollinator species
208 richness (Table 2, Estimate = -0.16, $z = 5.61$, $p < 0.0001$, Figure 3A) and this was true for indices
209 calculated across all years of the studies as well as every two years of the studies (see Table 2). The
210 relative change in species richness between years was related to the change in the abundance of the
211 most dominant species, with study systems showing larger changes in species richness if there was
212 increased inter-annual variation in dominant species abundance across all years (Table 2, Estimate =

213 0.09, $z = 3.31$, $p < 0.001$, Figure 3B). This was also significant in models accounting for change in
214 species richness for every two years (Table 2, Estimate = 0.12, $z = 3.77$, $p < 0.001$). However, any
215 change in dominant species across years showed no significant relationship with relative change in
216 species richness. The change in pollinator species richness also varied between climatic regions with
217 crops grown in temperate systems showing less inter-annual variability in pollinator species richness
218 than crops in tropical areas (Table 2, Estimate = 0.15, $z = 2.22$, $p = 0.03$, Figure 3C).

219

220 Other factors tested including crop family, flower type, annual versus perennial crop type, mass
221 flowering, or site temperature did not show any significant relationship with variability observed in
222 the abundance or richness of species across years.

223

224 *Influence of dominant pollinator species*

225 It took the pooled abundance of the three most dominant pollinator species to match the relative
226 variability of total pollinator abundance (respective mean CVs: 0.58 vs 0.55, $t = 1.09$, $df = 362$, $p =$
227 0.2 , difference in means = 0.03). The relative variability of total pollinator abundance at the site level
228 was found to be significantly lower than that of the single ($t = 9.56$, $df = 362$, p -value < 0.001 ,
229 difference in means = 0.17) and top two most dominant species ($t = 6.34$, $df = 362$, p -value < 0.001 ,
230 difference in means = 0.07). Sites where honeybees were dominant species (mean CV = 0.46) were
231 found to have significantly lower variability ($t = 3.25$, $df = 295.26$, $p = 0.001$) than sites where other
232 bees were dominant species (mean CV = 0.60).

233

234 Where the dominant species changed asynchronously to the rest of the community, the difference
235 between the CV of the dominant species and CV of total abundance was strong, with less than half the
236 variability in the whole community than in the dominant species ($t = -11.02$, $df = 125$, p -value $<$
237 0.0001 , mean of total 0.31, mean of single most dominant species 0.67; difference in means = 0.36).

238 In contrast, CV of total abundance was only slightly lower than CV of the dominant species where the
239 dominant species changed synchronously with the rest of the community ($t = -3.48$, $df = 219$, p -value
240 = < 0.001 , mean of total 0.65, mean of single most dominant species 0.71, difference in means = 0.06,

241 Figure 4). In simple terms, the stability of the whole pollinator community only increased to a
242 considerable degree when other species buffered changes by asynchronous fluctuations.

243

244 **Discussion:**

245 This study is the first to use a global dataset to explore inter-annual variation in crop pollinator
246 communities and has revealed several important features of community stability. Our findings
247 indicate that: (i) crop pollinator communities with higher pollinator diversity are more stable between
248 years, and (ii) the variation observed in pollinator communities is driven by dominant species changes
249 across years. The importance of other species in addition to the stability of the dominant species was
250 in line with mechanisms of diversity-stability relationships: while stability of the dominant species
251 was similar to the total community where the dominant species fluctuated synchronously with the rest
252 of the community, community abundance was much more stable than abundance of the dominant
253 species where these fluctuations were asynchronous. Neither the variation in abundance nor the
254 variation in species richness was significantly affected by any crop characteristics.

255

256 Our results show that sites with higher pollinator species diversity experience less variation in total
257 crop pollinator abundance and less change in pollinator species richness between years. These results
258 concur with studies from individual cropping systems which have shown that diversity provides
259 greater spatial and temporal stability and resilience [12, 23], and supports the theory that ecological
260 systems with higher species diversity are better buffered against inter-annual variation in species
261 abundance, and possibly more resilient to changes in the longer term [14]. This has implications
262 beyond ecological resilience, as stable pollination services could help mitigate risks and uncertainties
263 for farmers growing pollinator dependent crops, providing economic resilience..

264

265 In addition to diversity, our results demonstrate that dominant species play a significant role in inter-
266 annual stability of crop pollinator communities. Honeybees were found to be the single most
267 dominant species in 18 out of 43 datasets and in 140 out of 375 sites which concurs with the findings
268 of Kleijn *et al.* [17]. Sites where honeybees were the dominant species across all years also showed

269 greater inter-annual stability in abundance when compared to sites dominated by other species. Unlike
270 wild pollinators, managed pollinators are often placed near crops, and due to hive management
271 practices may show less variability in abundance between years. Managed pollinators are considered
272 to supplement rather than substitute pollination by wild insects in most crop pollination systems [38],
273 but there is experimental evidence to suggest that managed bees in high numbers could displace wild
274 pollinators from crop fields [39]. Our study systems from Argentina, for instance, were entirely reliant
275 on managed *Apis mellifera* and no other species were recorded. The management of bees could
276 therefore be an important contributor to the inter-annual variability observed in the crop pollinator
277 community depending on placement of hives, stocking densities and how much these vary from one
278 year to the next. Careful targeting of managed pollinators could be used to increase the stability of
279 pollination [40-42], particularly in those crops for which inter-annual variation is high due to
280 fluctuations in populations of the dominant wild pollinators.

281

282 While we can say with a high level of certainty that most honeybees recorded in the USA and
283 European studies were from managed hives, it is difficult to distinguish between managed and wild
284 honeybees in other studies. For example, in China and India, while almost all *Apis mellifera* were
285 managed and all *Apis dorsata* wild, it is difficult to distinguish between wild and managed *Apis*
286 *cerana* with any degree of certainty. In addition, certain areas – particularly in Western Europe, utilise
287 *Bombus terrestris* as a managed pollinator, and managed and wild individuals of this species are
288 indistinguishable from each other. Therefore, we cannot draw specific conclusions on the effect of
289 managed pollinators on the changes in richness and turnover of wild pollinator communities but raise
290 this as a possible question to be explored in future studies.

291

292 From our results, we also infer that a significant part of the year to year variation in crop pollinator
293 abundance is driven by as few as three of the most dominant species within each system (see list of
294 dominant species by study in supplementary Table S4). This is consistent with the findings of Kleijn
295 *et al.* [17] who showed that the three most dominant pollinator species account for two-thirds of
296 flower visits recorded. Even if only few species are quantitatively important in crop pollination

297 systems, enhancing stability by managing for diversity effects delivered through asynchrony among
298 species could be really effective as our results above have indicated. It is worth noting that while
299 delivery of crop pollination services may be predominantly driven a few key functional pollinator
300 species [17], depending on the context, the diversity and abundance of other pollinators may
301 complement or largely replace the functional role of dominant species [43].

302

303 The Winfree *et al.* [18] study – which explored functional consequences of spatial turnover in crop
304 pollinator communities – indicated that more species would be required to fulfil the minimum
305 pollination service threshold if dominance effects were to be removed or lost, but that is based on the
306 assumption that another species would be unable to take over the dominant role through increased
307 abundance. This raises questions of which systems would remain resilient in the event these specific
308 dominant species are lost due to future environmental conditions. For example, field beans flower
309 morphology excludes small solitary bees and depends predominantly on effective flower visits from
310 long-tongued bumblebees [44, 45], may be less resilient to loss of dominant pollinators when
311 compared to crops like oilseed rape dependent on a diverse suite of pollinators [44].

312

313 While no effect of climatic region was observed on the inter-annual change in pollinator abundance,
314 there was less variation in pollinator species richness in temperate crops than in crops grown in the
315 tropics. Studies from temperate regions (n=29) showed a higher average Shannon diversity ($H' = 1.21$)
316 than studies from the tropics (n=13, $H' = 1.19$) but the difference was not statistically significant
317 (Figure S2, $t = 0.26$, $df = 356$, $p = 0.74$), and it is difficult to disentangle whether this result may be due
318 to differences in sampling effort. The difference between the temperate and tropical studies could not
319 be attributed to contrasting temperature regimes in the different climatic regions as we did not detect a
320 significant effect of temperature on inter-annual stability of crop pollinators in any of the models.

321 Pollinator populations are known to be sensitive to weather conditions [31] with temperature
322 influencing pollinator phenology [46] as well as plant-pollinator interactions [47]. Our analyses
323 indicated that the crops in the tropics experienced significantly less variation in temperature than
324 those in temperate regions ($t = 6.71$; $df = 34.74$; $p < 0.001$, Supplementary Figure S3) but insufficient

325 climate data across all the datasets (only 28 studies of the 43 recorded temperature), meant this aspect
326 could not be fully explored within this study.

327

328 Of the 43 studies utilised, 25 studies had two years of data, 14 studies three years of data and four
329 studies with four or more years of repeated sampling. With these differences in number of years of
330 sampling, our global synthesis has only provided a first step to looking at temporal dynamics.

331 Estimates of temporal dynamics may vary with the number of years sampled and every effort has
332 been made to account for these differences by analysing changes in observed in every two years of
333 each study. It is to be noted that results of the models with the pairwise year calculations were
334 consistent with the model using data across all the years, but further measures to account for any
335 differences caused by varying number of sampling years, and are beyond the scope of this manuscript.
336 Also, the diversity-stability effect identified, may be linked to sampling effort with lower sampling
337 leading to leading to high CV values and low diversity between years. As this is a collated dataset
338 consisting of various studies that have taken place across several geographic regions across multiple
339 years and we cannot retrospectively change the sampling effort, we acknowledge that the CV may be
340 sensitive to these underlying effects and raise this as a point to be considered in future studies.

341

342 Many studies to date, have focused on spatial variations observed between crops, fields and across
343 different landscapes [29, 48, 49], while relatively few studies have considered temporal variation
344 caused by differences in crop flowering times [31, 40, 50] and even these focussed only on within
345 season variation. To the best of our knowledge, our study is the first to explore temporal variation
346 in pollinator communities across different crops. Our results highlight the importance of
347 considering both wider pollinator diversity as well as abundance of dominant species in understanding
348 inter-annual stability of crop pollinators. Temporal stability of ecosystem functioning increases the
349 predictability and reliability of ecosystem services and understanding the drivers of stability across
350 spatial scales is important for land management and policy decisions [25]. Stability in the availability
351 of pollinators is also important from an agro-ecological resilience perspective as increased variation in

352 animal pollination could reduce average yield and yield stability [51]. We further propose that the
353 stability and ecological resilience brought about by enhancing the diversity of pollinator communities
354 will contribute beyond agriculture and should be considered alongside longer-term conservation
355 targets focussed on maintaining and enhancing wider biodiversity.

356

357 Data Accessibility: The data supporting the analyses are available from University of Reading
358 Research Data Archive <http://dx.doi.org/10.17864/1947.291> [52].

359

360 **Acknowledgements:** The authors wish to thank Riccardo Bommarco for his data contribution. This
361 study was supported EU COST Action Super-B project (STSM-FA1307-150416-070296) and DS by
362 the University of Reading Research Endowment Trust Fund (E3530600). JF by DFG grant FR
363 3364/4-1; LGC funded by FCT and EU project EUCLIPO-028360 and by CNPq 421668/2018-0; PQ
364 305157/2018-3; MPDG by an Insect Pollinators Initiative grant BB/I000348/1; DK by the Dutch
365 Ministry of Agriculture, Nature and Food Quality (BO-11-011.01-011); AJ & HZ by the Bee
366 resources research funds (CAAS-ASTIP-IAR; NSFC31672500) in China; BMF by a Productivity in
367 Research Sponsorship (#308948/16-5), Brasilia-Brazil; MM and DW funded by Waitrose & Partners,
368 Fruition PO, and the University of Worcester; and CW funded by the DFG grant 405945293.

369

370 **References:**

371

- 372 1. IPBES. 2016 The assessment report on pollinators, pollination and food production. p. 810.
373 Bonn, Germany, Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and
374 Ecosystem Services.
- 375 2. Ollerton J., Winfree R., Tarrant S. 2011 How many flowering plants are pollinated by
376 animals? *Oikos* **120**, 321-326. (doi:10.1111/j.1600-0706.2010.18644.x).
- 377 3. Klein A.-M., Vaissière B.E., Cane J.H., Steffan-Dewenter I., Cunningham S.A., Kremen C.,
378 Tscharntke T. 2007 Importance of pollinators in changing landscapes for world crops. *Proc Roy Soc B*
379 **274**, 303-313. (doi:10.1098/rspb.2006.3721).
- 380 4. Aizen M.A., Garibaldi L.A., Cunningham S.A., Klein A.M. 2008 Long-Term Global Trends
381 in Crop Yield and Production Reveal No Current Pollination Shortage but Increasing Pollinator
382 Dependency. *Current Biology* **18**, 1572-1575. (doi:<https://doi.org/10.1016/j.cub.2008.08.066>).
- 383 5. Carnevalheiro L.G., Kunin W.E., Keil P., Aguirre-Gutierrez J., Ellis W.N., Fox R., Groom Q.,
384 Hennekens S., Van Landuyt W., Maes D., Van de Meutter F., Michez D., et al. 2013 Species richness
385 declines and biotic homogenisation have slowed down for NW-European pollinators and plants. *Ecol*
386 *Lett* **16**, 870-878. (doi:10.1111/ele.12121).

- 387 6. Powney G.D., Carvell C., Edwards M., Morris R.K.A., Roy H.E., Woodcock B.A., Isaac
388 N.J.B. 2019 Widespread losses of pollinating insects in Britain. *Nat Comms* **10**, 1018-1018.
389 (doi:10.1038/s41467-019-08974-9).
- 390 7. Garibaldi L.A., Carvalheiro L.G., Vaissière B.E., Gemmill-Herren B., Hipólito J., Freitas
391 B.M., Ngo H.T., Azzu N., Sáez A., Åström J., An J., Blochtein B., et al. 2016 Mutually beneficial
392 pollinator diversity and crop yield outcomes in small and large farms. *Science* **351**, 388-391.
393 (doi:10.1126/science.aac7287).
- 394 8. Dainese M., Martin E.A., Aizen M.A., Albrecht M., Bartomeus I., Bommarco R., Carvalheiro
395 L.G., Chaplin-Kramer R., Gagic V., Garibaldi L.A., Ghazoul J., Grab H., et al. 2019 A global
396 synthesis reveals biodiversity-mediated benefits for crop production. *Sci Adv* **5**, eaax0121.
397 (doi:10.1126/sciadv.aax0121).
- 398 9. Bommarco R., Lundin O., Smith H.G., Rundlöf M. 2012 Drastic historic shifts in bumble-bee
399 community composition in Sweden. *Proc Roy Soc B* **279**, 309-315. (doi:10.1098/rspb.2011.0647).
- 400 10. Klein A.M., Cunningham S.A., Bos M., Steffan-Dewenter I. 2008 Advances in pollination
401 ecology from tropical plantation crops. *Ecology* **89**, 935-943. (doi:10.1890/07-0088.1).
- 402 11. Albrecht M., Schmid B., Hautier Y., Müller C.B. 2012 Diverse pollinator communities
403 enhance plant reproductive success. *Proc Biol Sci* **279**, 4845-4852. (doi:10.1098/rspb.2012.1621).
- 404 12. Winfree R., Kremen C. 2009 Are ecosystem services stabilized by differences among
405 species? A test using crop pollination. *Proceedings of the Royal Society of London B: Biological
406 Sciences* **276**, 229-237. (doi:10.1098/rspb.2008.0709).
- 407 13. Isbell F., Craven D., Connolly J., Loreau M., Schmid B., Beierkuhnlein C., Bezemer T.M.,
408 Bonin C., Bruelheide H., de Luca E., Ebeling A., Griffin J.N., et al. 2015 Biodiversity increases the
409 resistance of ecosystem productivity to climate extremes. *Nature* **526**, 574.
410 (doi:10.1038/nature15374).
- 411 14. Ives A.R., Carpenter S.R. 2007 Stability and diversity of ecosystems. *Science* **317**, 58-62.
412 (doi:10.1126/science.1133258).
- 413 15. McGill B.J., Etienne R.S., Gray J.S., Alonso D., Anderson M.J., Benecha H.K., Dornelas M.,
414 Enquist B.J., Green J.L., He F., Hurlbert A.H., Magurran A.E., et al. 2007 Species abundance
415 distributions: moving beyond single prediction theories to integration within an ecological framework.
416 *Ecol Lett* **10**, 995-1015. (doi:10.1111/j.1461-0248.2007.01094.x).
- 417 16. Vázquez D.P., Morris W.F., Jordano P. 2005 Interaction frequency as a surrogate for the total
418 effect of animal mutualists on plants. *Ecol Lett* **8**, 1088-1094. (doi:10.1111/j.1461-
419 0248.2005.00810.x).
- 420 17. Kleijn D., Winfree R., Bartomeus I., Carvalheiro L.G., Henry M., Isaacs R., Klein A.-M.,
421 Kremen C., M'Gonigle L.K., Rader R., Ricketts T.H., Williams N.M., et al. 2015 Delivery of crop
422 pollination services is an insufficient argument for wild pollinator conservation. *Nat Commun* **6**, 7414.
423 (doi:10.1038/ncomms8414).
- 424 18. Winfree R., Reilly J.R., Bartomeus I., Cariveau D.P., Williams N.M., Gibbs J. 2018 Species
425 turnover promotes the importance of bee diversity for crop pollination at regional scales. *Science* **359**,
426 791-793. (doi:10.1126/science.aao2117).
- 427 19. Grman E., Lau J.A., Schoolmaster Jr. D.R., Gross K.L. 2010 Mechanisms contributing to
428 stability in ecosystem function depend on the environmental context. *Ecol Lett* **13**, 1400-1410.
429 (doi:10.1111/j.1461-0248.2010.01533.x).
- 430 20. Clarence L. Lehman, David Tilman. 2000 Biodiversity, stability, and productivity in
431 competitive communities. *Am Nat* **156**, 534-552. (doi:10.1086/303402).
- 432 21. Sasaki T., Lauenroth W.K. 2011 Dominant species, rather than diversity, regulates temporal
433 stability of plant communities. *Oecologia* **166**, 761-768. (doi:10.1007/s00442-011-1916-1).
- 434 22. Allan E., Weisser W., Weigelt A., Roscher C., Fischer M., Hillebrand H. 2011 More diverse
435 plant communities have higher functioning over time due to turnover in complementary dominant
436 species. *PNAS* **108**, 17034-17039. (doi:10.1073/pnas.1104015108).
- 437 23. Bartomeus I., Park M.G., Gibbs J., Danforth B.N., Lakso A.N., Winfree R. 2013 Biodiversity
438 ensures plant–pollinator phenological synchrony against climate change. *Ecol Lett* **16**, 1331-1338.
439 (doi:10.1111/ele.12170).

- 440 24. Rader R., Howlett B.G., Cunningham S.A., Westcott D.A., Edwards W. 2012 Spatial and
441 temporal variation in pollinator effectiveness: do unmanaged insects provide consistent pollination
442 services to mass flowering crops? *J App Ecol* **49**, 126-134. (doi:10.1111/j.1365-2664.2011.02066.x).
- 443 25. Wilcox K.R., Tredennick A.T., Koerner S.E., Grman E., Hallett L.M., Avolio M.L., La Pierre
444 K.J., Houseman G.R., Isbell F., Johnson D.S., Alatalo J.M., Baldwin A.H., et al. 2017 Asynchrony
445 among local communities stabilises ecosystem function of metacommunities. *Ecol Lett* **20**, 1534-
446 1545. (doi:10.1111/ele.12861).
- 447 26. Garibaldi L.A., Bartomeus I., Bommarco R., Klein A.M., Cunningham S.A., Aizen M.A.,
448 Boreux V., Garratt M.P.D., Carvalheiro L.G., Kremen C., Morales C.L., Schüepp C., et al. 2015 Trait
449 matching of flower visitors and crops predicts fruit set better than trait diversity. *J App Ecol* **52**, 1436-
450 1444. (doi:10.1111/1365-2664.12530).
- 451 27. Westphal C., Steffan-Dewenter I., Tschardt T. 2003 Mass flowering crops enhance
452 pollinator densities at a landscape scale. *Ecol Lett* **6**, 961-965. (doi:10.1046/j.1461-
453 0248.2003.00523.x).
- 454 28. Klein A.-M., Brittain C., Hendrix S.D., Thorp R., Williams N., Kremen C. 2012 Wild
455 pollination services to California almond rely on semi-natural habitat. *J App Ecol* **49**, 723-732.
456 (doi:10.1111/j.1365-2664.2012.02144.x).
- 457 29. Hanley M.E., Franco M., Dean C.E., Franklin E.L., Harris H.R., Haynes A.G., Rapson S.R.,
458 Rowse G., Thomas K.C., Waterhouse B.R., Knight M.E. 2011 Increased bumblebee abundance along
459 the margins of a mass flowering crop: evidence for pollinator spill-over. *Oikos* **120**, 1618-1624.
460 (doi:10.1111/j.1600-0706.2011.19233.x).
- 461 30. Rader R., Howlett B.G., Cunningham S.A., Westcott D.A., Newstrom-Lloyd L.E., Walker
462 M.K., Teulon D.A.J., Edwards W. 2009 Alternative pollinator taxa are equally efficient but not as
463 effective as the honeybee in a mass flowering crop. *J App Ecol* **46**, 1080-1087. (doi:10.1111/j.1365-
464 2664.2009.01700.x).
- 465 31. Kallioniemi E., Åström J., Rusch G.M., Dahle S., Åström S., Gjershaug J.O. 2017 Local
466 resources, linear elements and mass-flowering crops determine bumblebee occurrences in moderately
467 intensified farmlands. *Agric Ecosyst Environ* **239**, 90-100.
468 (doi:<https://doi.org/10.1016/j.agee.2016.12.039>).
- 469 32. Krebs C.J. 1999 *Ecological methodology*. 2nd ed ed, Addison-Wesley Educational Publishers,
470 Inc.
- 471 33. Jost L. 2006 Entropy and diversity. *Oikos* **113**, 363-375.
472 (doi:<https://doi.org/10.1111/j.2006.0030-1299.14714.x>).
- 473 34. Bates D., Maechler M. 2009 lme4: Linear mixed-effects models using Eigen and S4 classes. R package,
474 version 0.999375-31. Available at: <http://CRAN.R-project.org/package=lme4>.
- 475 35. Burnham K.P., Anderson D.R. 2002 Model selection and multimodel inference: a practical
476 information-theoretic approach. New York, Springer-Verlag.
- 477 36. R Development Core Team. 2019 R: A language and environment for statistical computing.
478 3.6.3 ed. Vienna, R Foundation for Statistical Computing.
- 479 37. Ecology Letters Proceedings of the National Academy of Sciences Blüthgen N., Simons N.K.,
480 Jung K., Prati D., Renner S.C., Boch S., Fischer M., Hölzel N., Klaus V.H., Kleinebecker T.,
481 Tschapka M., Weisser W.W., et al. 2016 Land use imperils plant and animal community stability
482 through changes in asynchrony rather than diversity. *Nat Comms* **7**, 10697.
483 (doi:10.1038/ncomms10697).
- 484 38. Garibaldi L.A., Steffan-Dewenter I., Winfree R., Aizen M.A., Bommarco R., Cunningham
485 S.A., Kremen C., Carvalheiro L.G., Harder L.D., Afik O., Bartomeus I., Benjamin F., et al. 2013 Wild
486 pollinators enhance fruit set of crops regardless of honey bee abundance. *Science* **339**, 1608-1611.
487 (doi:10.1126/science.1230200).
- 488 39. Lindström S.A.M., Herbertsson L., Rundlöf M., Bommarco R., Smith H.G. 2016
489 Experimental evidence that honeybees depress wild insect densities in a flowering crop. *Proc Roy Soc*
490 *B* **283**, 20161641. (doi:<https://doi.org/10.1098/rspb.2016.1641>).
- 491 40. Garratt M.P.D., Brown R., Hartfield C., Hart A., Potts S.G. 2018 Integrated crop pollination
492 to buffer spatial and temporal variability in pollinator activity. *Basic Appl Ecol* **32**, 77-85.
493 (doi:<https://doi.org/10.1016/j.baae.2018.06.005>).

- 494 41. Isaacs R., Williams N., Ellis J., Pitts-Singer T.L., Bommarco R., Vaughan M. 2017 Integrated
495 crop pollination: Combining strategies to ensure stable and sustainable yields of pollination-dependent
496 crops. *Basic Appl Ecol* **22**, 44-60. (doi:<https://doi.org/10.1016/j.baae.2017.07.003>).
- 497 42. Rollin O., Garibaldi L.A. 2019 Impacts of honeybee density on crop yield: A meta-analysis. *J*
498 *App Ecol* **56**, 1152-1163. (doi:10.1111/1365-2664.13355).
- 499 43. Fijen T.P.M., Scheper J.A., Boom T.M., Janssen N., Raemakers I., Kleijn D. 2018 Insect
500 pollination is at least as important for marketable crop yield as plant quality in a seed crop. *Ecol Lett*
501 **21**, 1704-1713. (doi:10.1111/ele.13150).
- 502 44. Garratt M.P., Coston D.J., Truslove C.L., Lappage M.G., Polce C., Dean R., Biesmeijer J.C.,
503 Potts S.G. 2014 The identity of crop pollinators helps target conservation for improved ecosystem
504 services. *Biol Conserv* **169**, 128-135. (doi:10.1016/j.biocon.2013.11.001).
- 505 45. Marzinzig B., Brünjes L., Biagioni S., Behling H., Link W., Westphal C. 2018 Bee pollinators
506 of faba bean (*Vicia faba* L.) differ in their foraging behaviour and pollination efficiency. *Agric*
507 *Ecosyst Environ* **264**, 24-33. (doi:<https://doi.org/10.1016/j.agee.2018.05.003>).
- 508 46. Duchenne F., Thebault E., Michez D., Elias M., Drake M., Persson M., Rousseau-Piot J.S.,
509 Pollet M., Vanormelingen P., Fontaine C. 2020 Phenological shifts alter the seasonal structure of
510 pollinator assemblages in Europe. *Nat Ecol Evol* **4**. (doi:10.1038/s41559-019-1062-4).
- 511 47. Classen A., Eardley C.D., Hemp A., Peters M.K., Peters R.S., Ssymank A., Steffan-Dewenter
512 I. 2020 Specialization of plant-pollinator interactions increases with temperature at Mt. Kilimanjaro.
513 *Ecol Evol* **10**, 2182-2195. (doi:10.1002/ece3.6056).
- 514 48. Beduschi T., Kormann U.G., Tschardt T., Scherber C. 2018 Spatial community turnover of
515 pollinators is relaxed by semi-natural habitats, but not by mass-flowering crops in agricultural
516 landscapes. *Biol Conserv* **221**, 59-66. (doi:<https://doi.org/10.1016/j.biocon.2018.01.016>).
- 517 49. De Palma A., Kuhlmann M., Roberts S.P.M., Potts S.G., Börger L., Hudson L.N., Lysenko I.,
518 Newbold T., Purvis A. 2015 Ecological traits affect the sensitivity of bees to land-use pressures in
519 European agricultural landscapes. *J App Ecol* **52**, 1567-1577. (doi:10.1111/1365-2664.12524).
- 520 50. Grab H., Blitzer E.J., Danforth B., Loeb G., Poveda K. 2017 Temporally dependent pollinator
521 competition and facilitation with mass flowering crops affects yield in co-blooming crops. *Scientific*
522 *reports* **7**, 45296-45296. (doi:10.1038/srep45296).
- 523 51. Garibaldi L.A., Aizen M.A., Klein A.M., Cunningham S.A., Harder L.D. 2011 Global growth
524 and stability of agricultural yield decrease with pollinator dependence. *PNAS* **108**, 5909-5914.
525 (doi:10.1073/pnas.1012431108).
- 526 52. Author. 2021 Temporal variation in global crop pollinator communities. *Reading U.o.*
527 Dataset. (doi:<http://dx.doi.org/10.17864/1947.291>).

Table 1: The proportion of studies and sites showing inter-annual changes in the dominant taxonomic groups and species of crop pollinators; actual no. of studies and sites shown within parentheses.

Note: One study with five sites (Pisa01) had only morphospecies level data

	Study Level		Site Level	
	Change	No change	Change	No Change
Taxonomic Group	27.9% (12)	72.1% (31)	31.2% (117)	68.8% (258)
Species (excl Pisa01)	48.1% (20)	51.2% (22)	50.8% (188)	49.2% (182)

Table 2: Results of model averaging of candidate models that were within AICc $\Delta 7$ of the model with the lowest AICc value.

Response variable	Fixed effects remaining in the averaged model	Estimate	Adjusted SE	z value	p value
CV total pollinator abundance	Models with CV calculated across all years of the studies Conditional R ² = 0.33; Marginal R ² = 0.09				
	Same dominant species	-0.08482	0.03802	2.231	0.0257 *
	H' index	-0.15584	0.03932	3.964	7.38e-05 ***
	Climatic region	0.08302	0.09064	0.916	0.3598
	MFC	-0.08627	0.08326	1.036	0.3001
	Models with CV calculated for every two years of the studies Conditional R ² = 0.35; Marginal R ² = 0.06				
	Same dominant species	-0.05286	0.03726	1.418	0.15607
	H' index	-0.10368	0.03792	2.734	0.00626**
	Climatic region	0.11703	0.08691	1.347	0.17812
	MFC	-0.10889	0.03726	1.322	0.18609
CV of pollinator species richness	Models with CV calculated across all years of the studies Conditional R ² = 0.56; Marginal R ² = 0.19				
	Climatic region	0.16877	0.08576	1.968	0.049096 *
	CV of most dominant species [^]	0.09774	0.02957	3.305	0.000951 ***
	H' index	-0.16173	0.02879	5.616	< 2e-16 ***
	MFC	0.00435	0.11645	0.037	0.970190
	Models with CV calculated for every two years of the studies Conditional R ² = 0.37; Marginal R ² = 0.09				
	Climatic region	0.111412	0.079390	2.138	0.032545*
	CV of most dominant species [^]	0.121180	0.032136	3.771	0.000163 ***
	H' index	-	0.037559	2.242	0.024961 *
	MFC	0.002177	0.051874	0.073	0.942094

[^] CV of most dominant species remained significant when it was the single most dominant, two most dominant as well as three most dominant species.

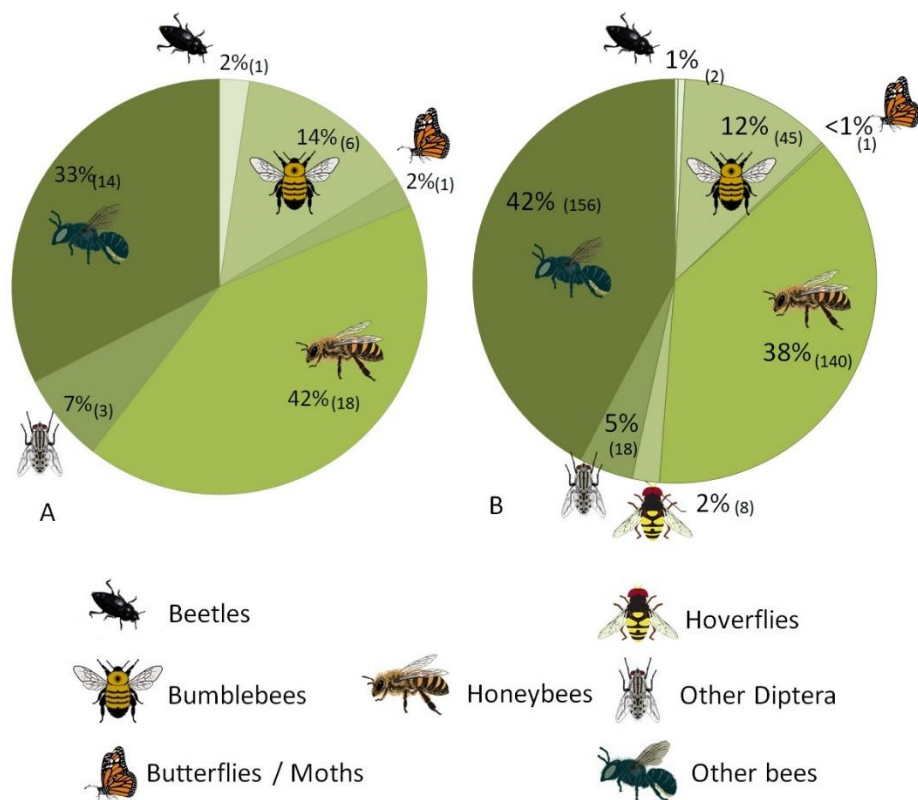


Figure 1: Most dominant taxonomic group of crop pollinators across years at (A) study and (B) site levels with number of studies and number of sites in parentheses.

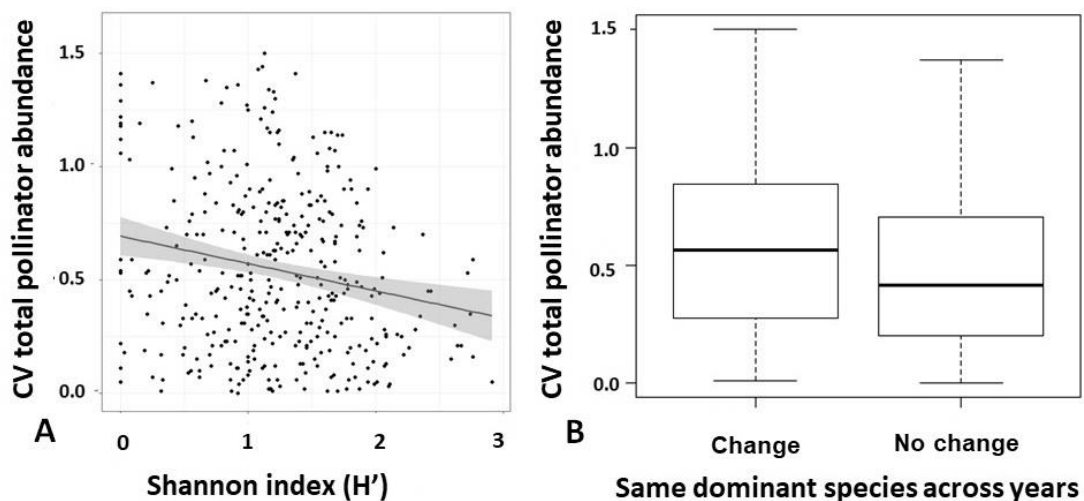


Figure 2: The relative change in total abundance of crop pollinators between years are driven by (A) species diversity (Shannon index) with 95% CI, and (B) the change in dominant species.

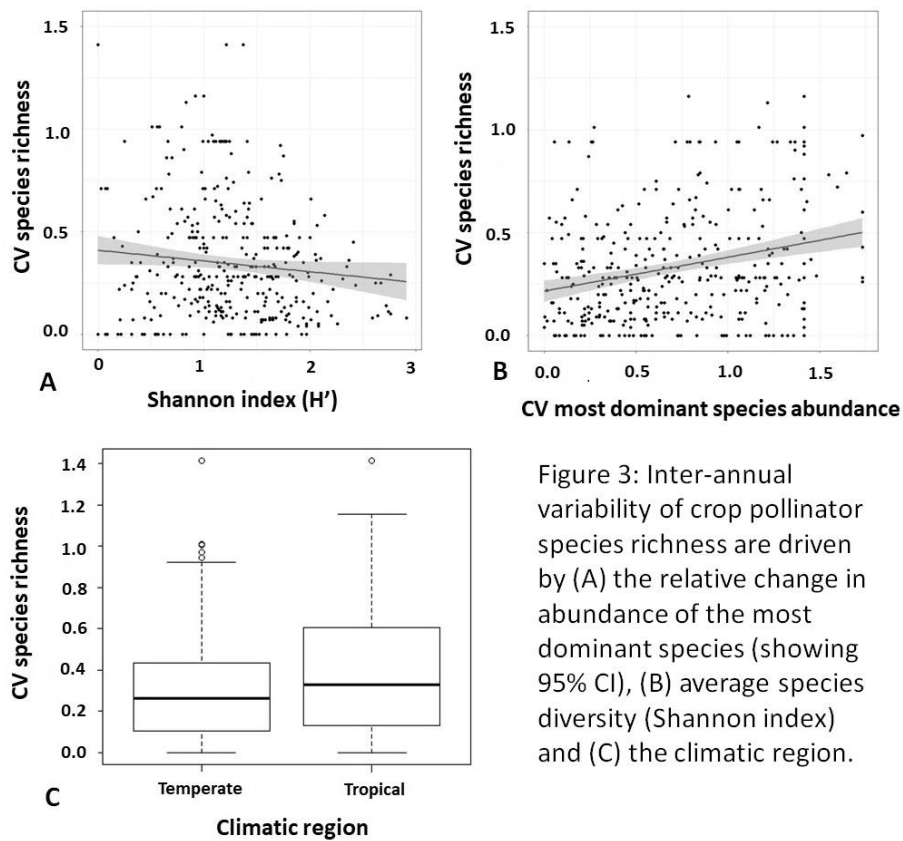


Figure 3: Inter-annual variability of crop pollinator species richness are driven by (A) the relative change in abundance of the most dominant species (showing 95% CI), (B) average species diversity (Shannon index) and (C) the climatic region.

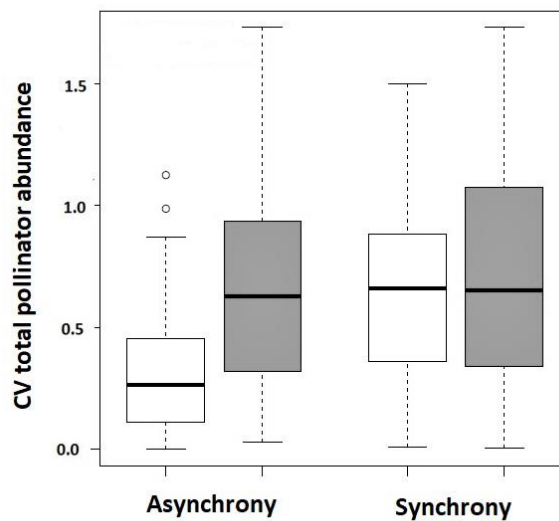


Figure 4: Relative change in single most dominant species (grey) compared to relative change in overall abundance (white) when split into asynchronous (left side) and synchronous (right side) pollinator communities.