

New indices for rapid assessment of pollination services based on crop yield data: France as a case study

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- 4 -Authors (given name first and family name second): Gabrielle Martin^{1*}, Colin Fontaine¹,
- 5 Francesco Accatino², Emmanuelle Porcher¹
- 6 -Full name(s), affiliation(s) and e-mail address(es) of all author(s):
- 7 Gabrielle Martin¹ gabrielle.martin@mnhn.fr, Colin Fontaine¹ colin.fontaine@mnhn.fr,
- 8 Francesco Accatino² francesco.accatino@inra.fr, Emmanuelle Porcher¹
- 9 emmanuelle.porcher@mnhn.fr
- ¹Centre d'Ecologie et des Sciences de la Conservation (CESCO), Muséum national d'Histoire
- 11 naturelle, Centre National de la Recherche Scientifique, Sorbonne Université, Paris, France
- ²INRA UMR SADAPT Team Concept, 75005 Paris, France.
- 13
- 14 the name and complete mailing address (including telephone and fax numbers and e-mail
- 15 address) of the person to whom correspondence:
- 16 *Corresponding author:
- 17 Gabrielle Martin
- 18 UMR 7204 CESCO CP 135
- 19 Muséum national d'Histoire naturelle
- 20 Département Homme et environnement,
- 21 43 rue Buffon, 75005 Paris, France
- 22 Tel: + 33 1 40 79 81 02 mail: gabrielle.martin@mnhn.fr

24 Abstract

Local studies indicate that animal pollination is essential for crop productivity, but its 25 effectiveness and temporal stability vary broadly across regions. However, there is no simple 26 27 and rapid method to assess the pollination services over large areas. Here, we introduce two new indices to measure pollination services and its temporal stability in farmland, the 28 Pollination Services Index and the index of Temporal Variation in Pollination Services, that 29 30 only require readily available data, namely crop yield and crop pollinator dependence. The philosophy of these indices is to compare at a given site the standardized yield, or the 31 32 temporal variation in yield, among crops that have different levels of dependence on animal 33 pollinators for their production. We expect that where there is a shortage of pollinators, standardized crop yields should decrease, and temporal variation in crop yields should 34 35 increase, with increasing dependence on pollinators. The Pollination Services Index in a given 36 area is thus defined as the slope of the linear regression between standardized crop yield 37 and crop pollinator dependence; the Temporal Variation in Pollination Services is defined as 38 the slope of the linear regression between the inter-annual coefficient of variation of crop yield and crop pollinator dependence. We calculated these two indices in France, where we 39 40 show extensive spatial variation in the estimated pollination services. We further show that this variation in the Pollination Services Index is negatively correlated with the index of 41 42 Temporal Variation in Pollination Services, and positively correlated with habitat quality for 43 pollinators. At a spatial resolution of administrative departments (ca. 5800 km²), the results 44 show that intensive farming is positively correlated with higher Temporal Variation in 45 Pollination Services but is not significantly associated with the Pollination Services Index, probably due to multicollinearity issues. Despite some limitations that deserve further 46 attention, these indices may constitute promising, cost-effective tools to highlight regions of 47

48 pollination deficit over large areas.

49

50 Highlights

- 51 -We introduce indices for rapid assessment of pollination services over large areas.
- 52 -The two new indices only require data on crop yield and crop pollinator dependence.
- -Pollination services correlates positively with habitat quality for pollinators.
- 54 -Pollination stability correlates negatively with intensive farming.
- 55 -The two indices are used to map pollination services for the first time in France.

56

- 57 Keywords: Pollination services; Pollination stability; Relative Pollination Potential; Crop yield;
- 58 Ecosystem services; Intensive farming.

60 **1. Introduction**

There is strong evidence that wild (Biesmeijer et al., 2006) and managed (Potts et al., 2010; 61 vanEngelsdorp et al., 2011) insect pollinators have declined in abundance and diversity over 62 the past few decades in Europe and North America (Potts et al., 2016). The main recognized 63 64 drivers of such a decline include land-use change and the resulting loss and fragmentation of 65 semi-natural habitats, environmental pollution, due to e.g. pesticides, decreasing resource 66 diversity and/or abundance, alien species, spread of pathogens and climate change (see Potts et al., 2016 for a synthesis). Decline in pollinators has raised much attention because 67 animal pollination is essential for the persistence of wild plant communities (Aguilar et al., 68 2006; Ashman et al., 2004; Biesmeijer et al., 2006; Fontaine et al., 2005), and because it is 69 70 considered an important ecosystem service (Millennium Ecosystem Assessment, 2005), 71 defined by Daily (1997) as "the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life". For example, the yield of 72 73 ca. 75% of crop species representing 35% of global food production is improved by animal pollination (Klein et al., 2007). In Europe, the proportion of crop species (partially) 74 75 dependent on pollinators reaches 84% (Williams, 1994).

76

The actual contribution of pollinators to crop yields is however known to vary through space and time depending on the abundance, composition or diversity of pollinator communities (Garibaldi et al., 2011b). Assessing the pollination services over large areas is crucial to quantify the provision of these services, to identify general spatial patterns, temporal trends and potential drivers of pollination services, as well as to inform land-management decisions and to achieve conservation objectives. Moreover, the assessment of the spatial distribution of the pollination services over large spatial extents has become a policy priority in the last

84 years (see e.g. "Action 5" of the EU biodiversity strategy, European Commission, 2011). However, so far there is no simple means to evaluate this variation over large areas. 85 Numerous local scale studies have demonstrated a positive effect of wild pollinator 86 87 abundance or diversity on crop production and its temporal stability (Garibaldi et al., 2016, 88 2013, 2011b). Most of these field-scale studies use data-intensive experimental methods to 89 collect detailed information on flower-visitor richness, visitation rates, and seed or fruit set, 90 thereby providing precise estimates of the pollination services at a local scale. Although they are fundamental for an accurate measure of animal pollination, these methods cannot easily 91 92 be used to assess the pollination services over larger areas, because they are expensive and 93 extremely time-consuming. To our knowledge, a single, indirect measure of the pollination services exists at the 94 95 European scale: Zulian et al. (2013) introduced the Relative Pollination Potential index, 96 defined as the potential of ecosystems to support crop pollination by wild bees. The Relative 97 Pollination Potential combines literature and expert-assessed parameters on the ecology of wild bee species, with spatial information on resource availability for such pollinators (i.e., 98 99 food and nesting sites). The Relative Pollination Potential decreases with the distance to 100 semi-natural habitats (a proxy of the bee visitation rate) and increases with annual 101 temperature (a proxy of wild bee activity). The mapping of this index shows an increase in 102 pollination potential along a North-South gradient following the temperature gradient in 103 Europe (Zulian et al., 2013). However, the indicator only uses a-priori and expert-based assumptions on wild bee ecology, it is not based on observations of pollinators or pollination, 104 105 and has not been validated against data. For this reason, its interpretation as an indicator of 106 the pollination service might be questionable.

107

108 In this study, we introduce and test two new indices based on the direct measure of crop 109 yield, which, although influenced by numerous additional factors, is the measurable final output of pollination services. The general idea of these new indices is to quantify for 110 111 different areas (i) the relative effectiveness in animal pollination, defined here as a 112 quantitative measure of the amount of successful pollen deposition and (ii) the temporal 113 instability in animal pollination. We call these two new indices (i) the Pollination Services 114 Index and (ii) the Temporal Variation in Pollination Services, respectively. Our approach elaborates on that of Garibaldi et al. (2011a), who examined the correlations between (1) 115 116 standardized crop yield or crop yield coefficient of variation and (2) crop pollinator 117 dependence to demonstrate the impact of pollinator limitation on agricultural production at a global scale. Here, we show that this approach can be adapted to assess the spatial 118 119 distribution of pollination services over large areas. 120 We used a dataset reporting the yield of 56 crops between 2000 and 2010, available at the 121 spatial resolution of administrative departments in France and we combined it with information on crop pollinator dependence to produce maps of Pollination Services Index 122 123 and index of Temporal Variation in Pollination Services. We calculate and examine the spatial 124 patterns of these two indices over the French territory. We test their ecological relevance by examining their correlations with two known indicators of drivers of pollinator communities 125 126 and activities: the Relative Pollination Potential (Zulian et al., 2013), an indicator based on habitat and climate suitability for wild bees; the High Nature Value index, an indicator of 127 extensive agricultural practices. We discuss the potential limitations and biases of this new 128 129 approach for the assessment of the pollination services. We conclude that our approach, 130 which is easily transferable to other datasets, could be used to monitor spatial and temporal 131 variation in the pollination services from local to regional scales, depending on availability

132 and spatial resolution of crop yield data.

133

134 **2.** Materials and methods

Countless definitions of the pollination services exist (see e.g. Liss et al., 2013). In the
following, pollination services are defined as the relative increase in crop yield resulting from
pollen deposition by animal pollinators.

138

139 2.1. Crop dataset and pollinator dependence

140 Annual yields of 133 crops were retrieved from the Service de la Statistique et de la

141 *Prospective* of the French ministry of agriculture

142 (<u>http://acces.agriculture.gouv.fr/disar/faces/</u>) for each of the 95 administrative departments 143 of France (mean area = 5770 km²), except Paris, and for the years 2000 to 2010. We selected 59 crops that produce fruits or seeds for direct human consumption, therefore excluding 144 crops for which seeds are only used for breeding purposes or to grow vegetative parts for 145 direct human use or for fodder. We also excluded greenhouse production. These crops were 146 147 grown in a minimum of two departments (Avocados) and a maximum of 93 departments 148 (Apples) between 2000 and 2010, with an average of 64 departments. The annual area grown with these crops varied between 8 ha (Avocados) and above 4 million ha (Bread 149 150 wheat) with an average of 242,676 ha (see Appendix A Table A1 in Supplementary data for 151 details). Following Klein et al. (2007), we classified crops on the basis of their level of 152 pollinator dependence, defined as the percentage of yield reduction resulting from an 153 absence of pollinators. The dependence categories were: none (0% yield reduction), little 154 (<10% yield reduction), modest (10 to 39 % yield reduction), great (40 to 89% yield 155 reduction), and essential (≥90% yield reduction). The level of pollinator dependence was

156	unknown for three of 59 crop classes (Oleaginous, Proteaginous, Other oleaginous), which
157	were excluded from the analysis. The levels of pollinator dependence contained between 5
158	("essential") and 21 ("none") crops, representing respectively 20,000 ha and 9 million ha
159	each year in France (Table 1; see Appendix A Table A1 in Supplementary data).
160	
161	2.2. Calculation of the Pollination Services and the Temporal Variation in
162	Pollination Services indices
163	As a preliminary step common to both indices, we performed for each crop a linear
164	regression of crop yield against years to account for annual yield increases due to genetic
165	progress and improvement of agricultural practices. We then extracted the residual yields
166	from the regression.
167	
168	Pollination Services Index
169	For the Pollination Services Index, residual yields were standardized within each crop (i.e. z-
170	transformed) across the 95 departments to allow comparisons among crops. For each crop,
171	the z-transformed residual can be interpreted as the yield surplus or deficit in a department
172	with respect to the national mean. For each department, we then performed a linear mixed-
173	effects regression of standardized residual yields against the level of pollinator dependence
174	to describe the relative change in yield along a pollinator dependence gradient (Fig. 1). The
175	mixed-effect model also included a random effect of year, to account for non-independence
176	of crop yield data within a year. We chose a linear regression over more flexible models
177	because each crop pollinator dependence class is expected to be impacted by pollinator
178	shortage in direct proportion to its pollinator dependence, by definition of the latter. We
179	defined the Pollination Services Index as the slope of this linear regression. The use of z- 8

180 transformed residuals has two important implications for the interpretation of the index. First, our approach does not compare absolute yields, but instead the position of crop yields 181 with respect to the national mean (for a given crop), across levels of pollinator dependence. 182 183 In other words, a positive slope in a department indicates that the pollinator-dependent 184 crops fare better than the national mean, while pollinator-independent crops have yield 185 equivalent to, or below, the national mean (Fig. 1, Bouches-du-Rhône department). Hence in 186 such department, pollination does not appear as a major limitation for crop yield. In 187 contrast, a negative slope in a department (e.g. Fig. 1, Eure department) tends to suggest 188 that pollinator-dependent crops fare worse there than the national mean, while pollinator-189 independent crop yields are at or above the national mean. This could be interpreted as a 190 sign of pollination deficit (but see next paragraph for a more careful interpretation). 191 Second, the z-transformation of the residual yields of each crop at the national level implies by definition that the distribution of z-transformed residual yields is centered on zero, with 192 193 95% of the distribution between -2 and 2 for each crop. Hence, when all z-transformed residual crop yields, from all departments, are plotted together against pollinator 194 195 dependence (Fig. 1), the collection of points is centered on zero throughout the range of 196 pollination dependence values. If pollination services are equally effective across the study 197 area, i.e. with all departments experiencing the same levels of pollination, the yield of a 198 given crop in a given department should not depend on the pollinator-dependence of the crop, but mostly on local environmental conditions and farming practices. As a result, the 199 200 slope of the linear regression of z-transformed residual crop yields against pollinator 201 dependence for a given department is expected to be zero on average, i.e. with small values 202 that do not differ significantly more zero more often than 5% of the time. In contrast, when 203 pollination services are variable through space, we expect frequent (>>5%) significant

204 positive and negative slopes for the linear regression between residual yields and pollinator 205 dependence. Because the z-transformed residual crop yield dataset is constrained mostly 206 between -2 and 2 throughout the whole range of pollinator dependence, by symmetry any positive slope in one department will be compensated by a negative slope in another 207 208 department, and vice versa (Fig. 1). Hence the Pollination Services Index only provides a 209 relative, not an absolute, indicator of pollination services. It ranks the study area from sub-210 areas (here departments) in which pollination is most limiting (departments with highly 211 negative slopes) to sub-areas in which pollination is less limiting (departments with highly 212 positive slopes). In the latter departments where pollination is less limiting, crop yield might 213 still be pollinator-limited, but to a lesser extent than in other departments.

214

215 Temporal Variation in Pollination Services

216 For the Temporal Variation in Pollination Services, we also worked with residual yields 217 obtained from the linear regression against years, but we added the mean yield in 2005 (the 218 median year for our dataset) to residual yields for each crop, to work with positive values 219 only. We then calculated for each crop and department the coefficient of variation of these 220 values, which provided a standardized measure of yield variation. We performed a linear regression of the coefficient of variation of residuals yields against level of pollinator 221 222 dependence for each department. We retained the slope of the linear relationship between yield variability and crop pollinator dependence as the departmental index of Temporal 223 224 Variation in Pollination Services. Positive relationships between yield variability and 225 pollinator dependence in a department indicate temporal instability of the pollination 226 services, i.e. the temporal variability of yield is larger for pollinator-dependent vs. pollinator-227 independent crops during the study period. In contrast, a slope of zero suggests comparable

stability of the pollination services for pollinator-dependent and independent crops.

229

230 2.3. Correlations with the Relative Pollination Potential, another index of231 pollination services, and the High Nature Value index

We examined, using the Spearman's rank correlation coefficient, all the pairwise correlations between the Pollination Services Index, the Temporal Variation in Pollination Services, and the Relative Pollination Potential of Zulian et al. (2013). For each department, the Relative Pollination Potential is provided at a 100m x 100m pixel resolution; we calculated the average Relative Pollination Potential in agricultural areas as the mean over all farmland pixels of a department.

Both the Relative Pollination Potential and the Pollination Services Index exhibit a strong 238 239 latitudinal gradient (see below). To examine the spatial patterns in both Pollination Services 240 Index and Temporal Variation in Pollination Services, as well as their environmental 241 correlates, while checking for biases due to the latitudinal gradient and particularly for a strong spatial autocorrelation in the data, we then used linear mixed models (Pinheiro and 242 243 Bates, 2000). These models included three fixed explanatory variables that are likely to drive 244 most of the latitudinal gradient, namely the Relative Pollination Potential (habitat 245 availability), agricultural intensity and temperature (climate). We also included administrative 246 regions (n = 22, i.e. administrative regions group about 4-5 neighboring administrative departments) as a random variable in the model, to further account for unidentified drivers 247 of the latitudinal gradient. We then checked that the residuals of both models were spatially 248 249 uncorrelated using Moran's Index with inverse-distance weighting. 250 We used the High Nature Value index (Andersen et al., 2004; Pointereau et al., 2010, 2007)

to characterize agricultural intensity. The High Nature Value index is defined in areas where

252 agriculture is a major land use. It aggregates three components at the municipality level 253 (average area = 15 km²). The first component quantifies crop diversity and share of permanent grasslands, a proxy for the rotation system and the diversity of agricultural 254 255 landscape. The second component characterizes extensive farming practices, defined by low 256 pesticide and mineral fertilizer inputs, as well as low irrigation; it includes permanent 257 grasslands and annual crops but not permanent crops. The third component estimates semi-258 natural habitat availability in agricultural areas, via a combination of number of traditional 259 fruit trees, length of hedges and wood edges and number of farm ponds. All these 260 components are likely to influence habitat quality and availability for pollinators and we 261 expect the High Nature Value index to be positively related with the Pollination Services Index and negatively related with the Temporal Variation in Pollination Services. In each 262 263 department, we calculated the average High Nature Value across all municipalities weighted by their farmland area (Agreste, 2016), for each of the three components of the High Nature 264 265 Value index. Because the three components are strongly correlated with one another, we performed a principal component analysis (PCA) on these three components. We retained 266 267 the first axis of the PCA only, which represents 69% of all variance and can be interpreted as 268 a South-North gradient of increasing agricultural intensity (see Appendix A Fig. A1 in 269 Supplementary data).

We calculated the mean annual temperature, a variable with major influence on insect
activity and their pollination potential (Corbet et al., 1993) and potentially contributing
strongly to the latitudinal gradient in pollination. For each department, we collected daily
mean temperature between 2000 and 2010 from the ENSEMBLES dataset (Haylock et al.,
2008), using data from the nearest E-OBS station in France on a 0.25 degree grid.

275

276	All analyses were performed using R version 3.2.4 (R Development Core Team, 2008). Indices
277	were calculated and mapped using R packages ggplot2 version 2.1.0 (Wickham, 2009), sp
278	version 1.2.2 (Bivand et al., 2013; Pebesma and Bivand, 2005), maptools version 0.8.39
279	(Bivand and Lewin-Koh, 2016), classInt version 0.1.23 (Bivand, 2015), RColorBrewer version
280	1.1.2 (Neuwirth, 2014), maps version 3.1.0 (Becker and Wilks, 2016), rgdal version 1.1.3
281	(Bivand et al., 2015), rgeos version 0.3.17 (Bivand and Rundel, 2016), rje version 1.9.0 (Evans,
282	2014), gridExtra version 2.3.0 (Auguie, 2017), nlme version 3.1-131.1 (Pinheiro et al., 2017),
283	geo version 1.4-3 (Hoskuldur et al., 2015), car version 2.1-6 (Fox and Weisberg, 2011), gstat
284	version 1.1-5 (Pebesma, 2004) and <i>ape</i> version 5.1 (Paradis et al., 2004). Climate data were
285	extracted using the R package <i>climateExtract</i> (Schmucki, 2018), and <i>devtools</i> (Wickham and
286	Chang, 2016).
287	
288	3. Results
289	3.1. Latitudinal gradient in the pollination services
290	We found a strong latitudinal gradient in the Pollination Services Index, with higher values in
291	southern vs. northern France (Spearman correlation with latitude $ ho$ = -0.64, <i>n</i> = 95, <i>P</i> <
292	0.001). Overall, the Pollination Services Index, i.e. the slope of the linear regression between
293	standardized mean yield and level of pollinator dependence, varied between –1.78 \pm 0.19
294	and 2.39± 0.16, with significant negative values in 38 departments, most of them in northern

France, and significant positive values in 31 departments (Fig. 2a). Individual relationships

between standardized mean yield and level of pollinator dependence for all departments are

297 plotted in Appendix A Fig. A2 in Supplementary data.

298

299 3.2. Negative correlation between the pollination services and their temporal

300 variation

We found a significant negative but weak correlation between the Pollination Services Index 301 302 and the Temporal Variation in Pollination Services (Spearman's $\rho = -0.31$, n = 95, P = 0.002, 303 Fig. 3a), i.e. departments with higher pollination services also tended to exhibit more stable 304 pollination. The Temporal Variation in Pollination Services, i.e. the slope of the regression 305 between yield variation and level of pollinator dependence, was significantly positive in 16 departments (Fig. 2b, and see Appendix A Fig. A3 in Supplementary data for individual 306 307 relationships in each department). Such positive relationships suggest that in those 308 departments an appreciable fraction of the temporal variability in the yield of pollinatordependent crops is caused by temporal variation in pollinator availability or effectiveness. In 309 78 departments, the relationship was not significantly different from 0, indicating that 310 311 pollinators do not appear to contribute much to yield temporal variation. The relationship 312 between yield variability and level of pollinator dependence was significantly negative in a 313 single department (Haute-Pyrénées). Departments with strong pollination instability tended 314 to be located in northern France, as indicated by a weak latitudinal gradient (Spearman's ρ = 315 0.19, n = 95, P = 0.059) that was however not significant.

316

317 3.3. Relationships with the Relative Pollination Potential and the index of318 agricultural intensity

319 We found a strong positive correlation between our Pollination Services Index and the

Relative Pollination Potential of Zulian et al. (2013), (Spearman's $\rho = 0.65$, n = 95, P < 0.001,

321 Fig. 3b): both indices therefore appear to convey consistent information, and exhibit a strong

- 322 latitudinal gradient with larger pollination potential and pollination services in southern
- 323 France. In contrast, the Temporal Variation in Pollination Services and the Relative Pollination

Potential were not significantly related at the national scale, although there was a tendency for more variable pollination services in departments with a lower Relative Pollination Potential (Spearman's $\rho = -0.19$, n = 95, P = 0.06, Fig. 3c).

When all drivers of pollination were assessed within a single model accounting for spatial 327 328 autocorrelation, the Pollination Services Index was significantly correlated with the Relative 329 Pollination Potential only, but not with agricultural intensity nor with temperature (Table 2). Note however that the Relative Pollination Potential encapsulates information on 330 331 temperatures and some components of the High Nature Value index (namely habitat 332 quality). When the Relative Pollination Potential was removed from the linear model, the Pollination Services Index was significantly related negatively with agricultural intensity and 333 positively with temperature (not shown). In contrast, the Temporal Variation in Pollination 334 335 Services was not related with the Relative Pollination Potential, but was positively correlated 336 with the index of agricultural intensity and negatively with mean annual temperature (Table 2). 337

338

4. Discussion

This study is the first to our knowledge to provide spatial indices of the pollination services and their temporal variation nationwide directly on the basis of crop yields and pollinator dependence. Both indices exhibit strong geographical patterns, as indicated by appreciable differences among departments. Below we discuss the extent to which such differences among departments are indicative of true differences in the pollination services, and we outline future research directions to validate further these two indices.

346

3474.1.Two independent indices show consistent patterns in the pollination services

348 The Pollination Services Index and the Relative Pollination Potential (Zulian et al., 2013), 349 although they were obtained from fully independent datasets and methods, exhibited a significant positive correlation, partly driven by a strong latitudinal gradient. The Pollination 350 351 Services Index developed in this study is based on the measurable and final output of 352 pollination services provided by all types of pollinators, crop yields. In contrast, the Relative 353 Pollination Potential combines literature and expert-assessment on the ecology of wild bee 354 species only. As its name indicates, it only characterizes a *potential* for one type of pollination 355 and has not been validated by data on pollinators or pollination so far. The most intuitive 356 explanation for their positive correlation is a causal one: the Relative Pollination Potential is a 357 proxy for the abundance and/or diversity of pollinator communities, which in turn controls 358 the rate of pollen delivery to crops (Garibaldi et al., 2013; Kleijn et al., 2015). With this 359 interpretation, both indices validate each other by producing consistent information from 360 independent datasets. The causal role of pollinators is further supported by the latitudinal 361 gradient in species richness observed in wild bees in Europe (Nieto et al., 2014). However, cross-validation and the congruence of spatial gradients are only circumstantial evidence, 362 363 and a formal validation of all indices would require comparison with more direct 364 measurements of pollination services at the plant level. 365 Despite the congruence of these independent pollination services proxies, i.e. the Pollination 366 Services Index and the Relative Pollination Potential, our analysis remains correlative. Therefore, we cannot exclude that the observed pattern is driven by other factors, among 367 which the latitudinal gradient in environmental conditions, without an underlying causality. 368 369 One important question is whether the numerous other environmental factors that have 370 recognized key impacts on crop yield (weather, soil type, farming practices including e.g. use 371 of pesticides or fertilizers, or fruit culling...) could bias the Pollination Services Index and for

372 example create a latitudinal gradient in crop yield of pollinator-dependent crops that is not due to pollinators. The latitudinal gradient in the Pollination Services Index implies that 373 pollinator-dependent crops tend to have higher yields in southern vs. northern France, 374 375 whereas the opposite is true for pollinator-independent crops. Climate/weather, soil type or 376 farming practices can only drive such pattern if their effects on crop yield were related to 377 pollinator-dependence through mechanisms that do not involve pollination. For sake of 378 illustration, one can imagine a situation in which pollinator-dependent crops were more 379 likely to be trees than pollinator-independent crops, and in which trees in general would 380 grow better in warmer climates (two highly unlikely hypotheses). In this case, the yield of 381 pollinator-dependent crops would be higher than the national mean in warm departments (southern France) and lower than the mean in northern France, which would create the 382 383 same signal as the one we observe. However, we cannot think of an obvious mechanism, other than pollination, that would cause the effects of environmental factors on crop yield to 384 385 vary systematically with the pollinator dependence of crops. In summary, we detect patterns 386 of local adaptation such that pollinator-dependent crop have higher yields in southern vs. 387 northern France. The most likely explanation for this pattern remains a gradient in pollination 388 services, but we do not have the data here to make firm conclusions. 389 With these limitations in mind, the two pollination indices introduced here still show 390 patterns consistent with some of the known effects of landscape on pollinators. Analyzes controlling for spatial autocorrelation patterns showed that the Relative Pollination Potential 391 392 was a significant correlate of the Pollination Services Index, while the index of agricultural 393 intensity, as measured by a combination of in-field practices, crop diversity and landscape 394 simplification, was not. This result suggests that the quality and diversity of landscapes may 395 prevail over agricultural practices to explain pollination of pollinator-dependent crops. This

396 absence of a relationship between pollination services and agriculture is at odds with numerous studies demonstrating negative effects of intensive agriculture on pollinators, 397 particularly wild bees (Hendrickx et al., 2007; Le Féon et al., 2010; Koh et al., 2016) and the 398 399 service they provide (Deguines et al., 2014). This somewhat surprising result should be 400 tempered by several considerations. (1) The strong latitudinal gradient influencing all indices 401 and their environmental correlates makes it difficult to isolate individual correlations. Indeed, 402 the RPP emerges as the main correlate of the Pollination Services Index when both agricultural 403 intensification and RPP are included in the analysis, but agricultural intensification is significantly 404 negatively correlated with the Pollination Services Index when analysed in a one-way ANOVA. (2) 405 Although pollination services were not correlated with agricultural intensity on average, their temporal variability increased with the index of agricultural intensity, in agreement with 406 407 most earlier results showing negative impacts of agriculture on pollinators and pollination. 408 (3) Drivers not included in the Relative Pollination Potential (Zulian et al., 2013) or in the High 409 Nature Value index may also influence pollinator communities. Among these drivers, other pollinator groups such as flies that are not accounted for in the Relative Pollination Potential 410 411 could have a stronger functional role as they are known to be adapted to cooler climates 412 (Elberling and Olesen, 1999). Pesticide use could also play an important role as it has been 413 increasing steadily in France (Hossard et al., 2017), especially in northern France ("EuroStat," 2011). Pesticides are known to have strong effects on pollinators, particularly on wild bees 414 (e.g. Brittain et al., 2010; Gill et al., 2012; Laycock et al., 2012) or in simplified landscapes 415 416 such as those encountered in northern France (Park et al., 2015). (5) Finally, both indices may 417 have been calculated at a spatial resolution too coarse to detect the local effects of within-418 field agricultural practices (see below).

419

420 4.2. Caveats for interpretation of the index values

421 It is important to keep in mind that the Pollination Services Index does not provide an absolute, but only a relative assessment of the pollination services. This limitation is not a 422 major one, but one should be careful that a positive value of the Pollination Services Index 423 424 does not necessarily indicate sufficient pollination, but only a better pollination than in the 425 other sampling units. With spatial variation in the pollination services, the analysis 426 introduced here will produce values of the pollination services ranging from negative values 427 that are significantly different from zero to positive values that are significantly different from 428 zero, regardless of the average effectiveness of pollination across the study area. Hence, the 429 Pollination Services Index should only be used to compare areas, not to assess pollination in an absolute manner. 430

431 The quality of the assessment of crop pollinator dependence may also influence the two 432 indices. Here, we have used available data, which are coarse: the classes of pollinator 433 dependence can span up to 30%. In addition, within a given crop species, pollinator dependence is known to vary across varieties. For example in oilseed rape, plant breeders 434 435 seek to develop less pollinator-dependent varieties to cope with pollinator declines 436 (Hudewenz et al., 2014). As a result, farmers may grow less pollinator dependent varieties in 437 areas with pollination deficit. This phenomenon, if it exists, should however make our 438 Pollination Services Index conservative, i.e. the standardized crop yield should decrease less with increasing crop pollinator dependence than with an accurate measurement of crop 439 pollinator dependence. In any case, both indices would benefit from more precise estimates 440 441 of crop pollinator dependence.

The value of the Pollination Services Index may further be changed by our choice to work on
residual crop yields, thereby removing any linear temporal trend in yield. This choice was

444 made to avoid the confounding effects of genetic progress and improvement of agricultural 445 practices and is justified when the temporal trend in crop yield is positive. However, for several crops, such as almonds or kiwis, the temporal trend in crop yield between 2000 and 446 2010 was negative. For pollinator-dependent crops, a decline in pollination services is one 447 448 likely cause of this decline in productivity. Our Pollination Services Index does not include this 449 temporal decrease in crop yield and is therefore again conservative. The index was designed 450 to detect differences in pollination services in space, but may have limited power to detect 451 temporal trends in pollination services. To address temporal changes in the pollination services, we recommend calculating the index without the initial step of linear regression of 452 453 crop yield on years.

454 The index of Temporal Variation in Pollination Services may also be biased by standardization 455 issues although it does not require z-transformation of yield. This index is calculated as the slope of the relationship between the coefficient of variation of the yield and crop pollinator 456 457 dependence. Since the coefficient of variation is inversely proportional to mean yield, its variation may reflect variation in the mean, rather than in the variance of crop yields. In 458 459 other words, departments with instable pollination may in fact be departments with low 460 pollination services on average, an interpretation that is partly supported by the negative relationship between the Temporal Variation in Pollination Services and the Pollination 461 462 Services Index. However, the alternative explanation, that departments with low services and high instability are characterized by poor and variable pollinator communities, is equally 463 likely. 464

465

466 4.3. Perspectives

467 To go further in determining the causal link between our indices and the pollination services,

468 several perspectives could be explored. First, the two indices and the Relative Pollination Potential should be compared with variables describing the structure and composition of 469 pollinator communities. Quantitative data on wild pollinators are few, especially on large 470 471 spatial scales and for taxonomic groups beyond bees. However, recent initiatives to monitor 472 pollinator communities via participatory science schemes may produce useful data in the 473 short term (see e.g. the French photographic survey of pollinators, Deguines et al., 2012). 474 Second, the ultimate test for these indices would be a comparison with proper estimates of 475 pollinator limitation using caging and pollen supplementation experiments (e.g. Hudewenz et 476 al., 2014). Third, a more accurate examination of the relationship between pollination 477 services indices and its potential drivers, particularly agricultural intensity may require finer 478 spatial resolutions of the indices. For example, there may be a mismatch in the departmental 479 resolution at which the indices were calculated, and the spatial resolution at which agricultural practices or landscape structures influence pollinator population dynamics and 480 481 behavior (Steffan-Dewenter et al., 2002). However, the spatial resolution of both pollination services indices depends solely on the spatial resolution of data and there is no obstacle to 482 483 obtaining them at much finer spatial resolution should crop yield data be available.

484

485 **5. Conclusion**

The Pollination Services Index and the Temporal Variation in Pollination Services are correlated in a consistent way, and their correlation with the Relative Pollination Potential and the index of agricultural intensity, respectively, are in line with the known influence of habitat quality and agricultural practices on pollinator communities. Despite the need for further work to ascertain causality, our indices pave the way to quantify and map pollination services at any spatial resolution in a cost-effective way over large areas. Such maps could

help identifying areas suffering from deficit in pollination services and related drivers. They
could also contribute to evaluate agricultural and conservation practices. Last but not least,
they provide easy-to-grasp communication tools to raise awareness of stakeholders on
pollination issues.

496

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507 Authors' contributions

- 508 EP and CF conceived the ideas and designed methodology; GM, FA and EP collected the data;
- 509 GM, CF and EP analyzed the data; GM, CF, FA and EP led the writing of the manuscript. All
- authors contributed critically to the drafts and gave final approval for publication.

511

512 Appendix A. Supplementary data

- 513 Supplementary data associated with this article can be found in the online version.
- 514
- 515 References

- 516 Agreste, 2016. Agreste [WWW Document]. URL http://agreste.agriculture.gouv.fr/
- Aguilar, R., Ashworth, L., Galetto, L., Aizen, M.A., 2006. Plant reproductive susceptibility to habitat
 fragmentation: review and synthesis through a meta-analysis. Ecology Letters 9, 968–980.
 https://doi.org/10.1111/j.1461-0248.2006.00927.x
- Andersen, E., Baldock, D., Bennett, H., Beaufoy, G., Bignal, E., Brouwer, F., Elbersen, B., Eiden, G.,
 Godeschalk, F., Jones, G., McCracken, D., Nieuwenhuizen, W., van Eupen, M., Hennekens, S.,
 Zervas, G., 2004. Developping a High Nature Value Farming area indicator.
- Ashman, T.-L., Knight, T.M., Steets, J.A., Amarasekare, P., Burd, M., Campbell, D.R., Dudash, M.R.,
 Johnston, M.O., Mazer, S.J., Mitchell, R.J., Morgan, M.T., Wilson, W.G., 2004. Pollen
 limitation of plant reproduction: ecological and evolutionary causes and consequences.
 Ecology 85, 2408–2421. https://doi.org/10.1890/03-8024
- 527 Auguie, B., 2017. gridExtra: Miscellaneous Functions for "Grid" Graphics.
- 528 Becker, R.A., Wilks, A.R., 2016. maps: Draw Geographical Maps.
- Biesmeijer, J.C., Roberts, S.P.M., Reemer, M., Ohlemüller, R., Edwards, M., Peeters, T., Schaffers, A.P.,
 Potts, S.G., Kleukers, R., Thomas, C.D., Settele, J., Kunin, W.E., 2006. Parallel Declines in
 Pollinators and Insect-Pollinated Plants in Britain and the Netherlands. Science 313, 351–354.
 https://doi.org/10.1126/science.1127863
- Bivand, R.S., Pebesma, E.J., Gomez-Rubio, V., 2013. Applied spatial data analysis with R, Second
 edition.
- 535 Bivand, R.S., 2015. classInt: Choose Univariate Class Intervals.
- Bivand, R.S., Keitt, T., Rowlingson, B., 2015. rgdal: Bindings for the Geospatial Data Abstraction
 Library.
- 538 Bivand, R.S., Lewin-Koh, N., 2016. maptools: Tools for Reading and Handling Spatial Objects.
- 539 Bivand, R.S., Rundel, C., 2016. rgeos: Interface to Geometry Engine Open Source (GEOS).
- Brittain, C.A., Vighi, M., Bommarco, R., Settele, J., Potts, S.G., 2010. Impacts of a pesticide on
 pollinator species richness at different spatial scales. Basic and Applied Ecology 11, 106–115.
 https://doi.org/10.1016/j.baae.2009.11.007
- 543 Corbet, S.A., Fussell, M., Ake, R., Fraser, A., Gunson, C., Savage, A., Smith, K., 1993. Temperature and
 544 the pollinating activity of social bees. Ecological Entomology 18, 17–30.
 545 https://doi.org/10.1111/j.1365-2311.1993.tb01075.x
- 546 Daily, G., 1997. Nature's Services. Island Press, Washington, DC.
- 547 Deguines, N., Julliard, R., de Flores, M., Fontaine, C., 2012. The Whereabouts of Flower Visitors:
 548 Contrasting Land-Use Preferences Revealed by a Country-Wide Survey Based on Citizen
 549 Science. PLoS ONE 7, e45822. https://doi.org/10.1371/journal.pone.0045822
- Deguines, N., Jono, C., Baude, M., Henry, M., Julliard, R., Fontaine, C., 2014. Large-scale trade-off
 between agricultural intensification and crop pollination services. Frontiers in Ecology and
 the Environment 12, 212–217. https://doi.org/10.1890/130054
- Elberling, H., Olesen, J.M., 1999. The structure of a high latitude plant-flower visitor system: the
 dominance of flies. Ecography 22, 314–323. https://doi.org/10.1111/j.16000587.1999.tb00507.x
- European Commission, 2011. Our Life Insurance, Our Natural Capital: An EU Biodiversity Strategy to
 2020.
- 558 EuroStat, 2011.
- 559 Evans, R., 2014. rje: Miscellaneous useful functions.
- Fontaine, C., Dajoz, I., Meriguet, J., Loreau, M., 2005. Functional Diversity of Plant–Pollinator
 Interaction Webs Enhances the Persistence of Plant Communities. PLoS Biology 4, e1.
 https://doi.org/10.1371/journal.pbio.0040001
- 563 Fox, J., Weisberg, S., 2011. An {R} Companion to Applied Regression, Second Edition.
- Garibaldi, L.A., Aizen, M.A., Klein, A.M., Cunningham, S.A., Harder, L.D., 2011a. Global growth and
 stability of agricultural yield decrease with pollinator dependence. Proceedings of the
 National Academy of Sciences 108, 5909–5914. https://doi.org/10.1073/pnas.1012431108

- Garibaldi, L.A., Steffan-Dewenter, I., Kremen, C., Morales, J.M., Bommarco, R., Cunningham, S.A.,
 Carvalheiro, L.G., Chacoff, N.P., Dudenhöffer, J.H., Greenleaf, S.S., Holzschuh, A., Isaacs, R.,
 Krewenka, K., Mandelik, Y., Mayfield, M.M., Morandin, L.A., Potts, S.G., Ricketts, T.H.,
 Szentgyörgyi, H., Viana, B.F., Westphal, C., Winfree, R., Klein, A.M., 2011b. Stability of
 pollination services decreases with isolation from natural areas despite honey bee visits:
 Habitat isolation and pollination stability. Ecology Letters 14, 1062–1072.
- 573 https://doi.org/10.1111/j.1461-0248.2011.01669.x
- 574 Garibaldi, L.A., Steffan-Dewenter, I., Winfree, R., Aizen, M.A., Bommarco, R., Cunningham, S.A., 575 Kremen, C., Carvalheiro, L.G., Harder, L.D., Afik, O., Bartomeus, I., Benjamin, F., Boreux, V., 576 Cariveau, D., Chacoff, N.P., Dudenhoffer, J.H., Freitas, B.M., Ghazoul, J., Greenleaf, S., 577 Hipolito, J., Holzschuh, A., Howlett, B., Isaacs, R., Javorek, S.K., Kennedy, C.M., Krewenka, 578 K.M., Krishnan, S., Mandelik, Y., Mayfield, M.M., Motzke, I., Munyuli, T., Nault, B.A., Otieno, 579 M., Petersen, J., Pisanty, G., Potts, S.G., Rader, R., Ricketts, T.H., Rundlof, M., Seymour, C.L., 580 Schuepp, C., Szentgyorgyi, H., Taki, H., Tscharntke, T., Vergara, C.H., Viana, B.F., Wanger, T.C., 581 Westphal, C., Williams, N., Klein, A.M., 2013. Wild Pollinators Enhance Fruit Set of Crops 582 Regardless of Honey Bee Abundance. Science 339, 1608–1611.
- 583 https://doi.org/10.1126/science.1230200
- Garibaldi, L.A., Carvalheiro, L.G., Vaissiere, B.E., Gemmill-Herren, B., Hipolito, J., Freitas, B.M., Ngo,
 H.T., Azzu, N., Saez, A., Astrom, J., An, J., Blochtein, B., Buchori, D., Garcia, F.J.C., Oliveira da
 Silva, F., Devkota, K., Ribeiro, M. d. F., Freitas, L., Gaglianone, M.C., Goss, M., Irshad, M.,
 Kasina, M., Filho, A.J.S.P., Kiill, L.H.P., Kwapong, P., Parra, G.N., Pires, C., Pires, V., Rawal, R.S.,
 Rizali, A., Saraiva, A.M., Veldtman, R., Viana, B.F., Witter, S., Zhang, H., 2016. Mutually
 beneficial pollinator diversity and crop yield outcomes in small and large farms. Science 351,
 388–391. https://doi.org/10.1126/science.aac7287
- Gill, R.J., Ramos-Rodriguez, O., Raine, N.E., 2012. Combined pesticide exposure severely affects
 individual- and colony-level traits in bees. Nature 491, 105–108.
 https://doi.org/10.1038/nature11585
- Haylock, M.R., Hofstra, N., Klein Tank, A.M.G., Klok, E.J., Jones, P.D., New, M., 2008. A European daily
 high-resolution gridded data set of surface temperature and precipitation for 1950–2006.
 Journal of Geophysical Research 113. https://doi.org/10.1029/2008JD010201
- Hendrickx, F., Maelfait, J.-P., Van Wingerden, W., Schweiger, O., Speelmans, M., Aviron, S.,
 Augenstein, I., Billeter, R., Bailey, D., Bukacek, R., Burel, F., DieköTter, T., Dirksen, J., Herzog,
 F., Liira, J., Roubalova, M., Vandomme, V., Bugter, R., 2007. How landscape structure, landuse intensity and habitat diversity affect components of total arthropod diversity in
 agricultural landscapes: Agricultural factors and arthropod biodiversity. Journal of Applied
 Ecology 44, 340–351. https://doi.org/10.1111/j.1365-2664.2006.01270.x
- Hoskuldur, B., Sigurdur Thor, J., Arni, M., Bjarki Thor, E., 2015. geo: Draw and Annotate Maps,
 Especially Charts of the North Atlantic.
- Hossard, L., Guichard, L., Pelosi, C., Makowski, D., 2017. Lack of evidence for a decrease in synthetic
 pesticide use on the main arable crops in France. Science of The Total Environment 575, 152–
 161. https://doi.org/10.1016/j.scitotenv.2016.10.008
- Hudewenz, A., Pufal, G., BöGeholz, A.-L., Klein, A.-M., 2014. Cross-pollination benefits differ among
 oilseed rape varieties. The Journal of Agricultural Science 152, 770–778.
 https://doi.org/10.1017/S0021859613000440
- Kleijn, D., Winfree, R., Bartomeus, I., Carvalheiro, L.G., Henry, M., Isaacs, R., Klein, A.-M., Kremen, C.,
 M'Gonigle, L.K., Rader, R., Ricketts, T.H., Williams, N.M., Lee Adamson, N., Ascher, J.S., Báldi,
 A., Batáry, P., Benjamin, F., Biesmeijer, J.C., Blitzer, E.J., Bommarco, R., Brand, M.R.,
 Bretagnolle, V., Button, L., Cariveau, D.P., Chifflet, R., Colville, J.F., Danforth, B.N., Elle, E.,
 Garratt, M.P.D., Herzog, F., Holzschuh, A., Howlett, B.G., Jauker, F., Jha, S., Knop, E.,
- 616 Krewenka, K.M., Le Féon, V., Mandelik, Y., May, E.A., Park, M.G., Pisanty, G., Reemer, M.,
- 617 Riedinger, V., Rollin, O., Rundlöf, M., Sardiñas, H.S., Scheper, J., Sciligo, A.R., Smith, H.G.,

Steffan-Dewenter, I., Thorp, R., Tscharntke, T., Verhulst, J., Viana, B.F., Vaissière, B.E., 618 619 Veldtman, R., Westphal, C., Potts, S.G., 2015. Delivery of crop pollination services is an 620 insufficient argument for wild pollinator conservation. Nature Communications 6, 7414. 621 https://doi.org/10.1038/ncomms8414 Klein, A.-M., Vaissiere, B.E., Cane, J.H., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C., 622 623 Tscharntke, T., 2007. Importance of pollinators in changing landscapes for world crops. 624 Proceedings of the Royal Society B: Biological Sciences 274, 303–313. https://doi.org/10.1098/rspb.2006.3721 625 Koh, I., Lonsdorf, E.V., Williams, N.M., Brittain, C., Isaacs, R., Gibbs, J., Ricketts, T.H., 2016. Modeling 626 627 the status, trends, and impacts of wild bee abundance in the United States. Proceedings of 628 the National Academy of Sciences 113, 140–145. https://doi.org/10.1073/pnas.1517685113 629 Laycock, I., Lenthall, K.M., Barratt, A.T., Cresswell, J.E., 2012. Erratum to: Effects of imidacloprid, a 630 neonicotinoid pesticide, on reproduction in worker bumble bees (Bombus terrestris). 631 Ecotoxicology 21, 1946–1946. https://doi.org/10.1007/s10646-012-0974-4 632 Le Féon, V., Schermann-Legionnet, A., Delettre, Y., Aviron, S., Billeter, R., Bugter, R., Hendrickx, F., 633 Burel, F., 2010. Intensification of agriculture, landscape composition and wild bee 634 communities: A large scale study in four European countries. Agriculture, Ecosystems & 635 Environment 137, 143–150. https://doi.org/10.1016/j.agee.2010.01.015 636 Liss, K.N., Mitchell, M.G., MacDonald, G.K., Mahajan, S.L., Méthot, J., Jacob, A.L., Maguire, D.Y., 637 Metson, G.S., Ziter, C., Dancose, K., Martins, K., Terrado, M., Bennett, E.M., 2013. Variability 638 in ecosystem service measurement: a pollination service case study. Frontiers in Ecology and 639 the Environment 11, 414-422. https://doi.org/10.1890/120189 640 Millennium Ecosystem Assessment (MA), 2005. Ecosystems and Human Well-being: Synthesis. Island 641 Press, Washington, DC. 642 Neuwirth, E., 2014. RColorBrewer: ColorBrewer Palettes. 643 Nieto, A., Roberts, S.P.M., Kemp, J., Rasmont, P., Kuhlmann, M., García Criado, M., Biesmeijer, J.C., 644 Bogusch, P., Dathe, H.H., de la Rua, P., 2014. European Red List of bees, Luxembourg: 645 Publication Office of the European Union. ed. Luxembourg. 646 Paradis, E., Claude, J., Strimmer, K., 2004. APE: Analyses of Phylogenetics and Evolution in R 647 language. Bioinformatics 20, 289–290. https://doi.org/10.1093/bioinformatics/btg412 648 Park, M.G., Blitzer, E.J., Gibbs, J., Losey, J.E., Danforth, B.N., 2015. Negative effects of pesticides on 649 wild bee communities can be buffered by landscape context. Proceedings of the Royal 650 Society B: Biological Sciences 282, 20150299. https://doi.org/10.1098/rspb.2015.0299 651 Pebesma, E.J., 2004. Multivariable geostatistics in S: the gstat package. Computers & Geosciences 30, 652 683-691. https://doi.org/10.1016/j.cageo.2004.03.012 653 Pebesma, E.J., Bivand, R.S., 2005. Classes and methods for spatial data: the sp Package. 654 Pinheiro, J.C., Bates, D.M., 2000. Mixed-Effects Models in S and S-PLUS. Springer, New York. 655 Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., R Development Core Team, 2017. nlme: Linear and 656 Nonlinear Mixed Effects Models. 657 Pointereau, P., Paracchini, M.L., Terres, J.-M., Jiguet, F., Bas, Y., Biala, K., 2007. Identification of High 658 Nature Value farmland in France through statistical information and farm practice surveys. 659 Pointereau, P., Doxa, A., Coulon, F., Jiguet, F., Paracchini, M.L., 2010. Analysis of spatial and temporal 660 variations of High Nature Value farmland and links with changes in bird populations: a study 661 on France. 662 Potts, S.G., Roberts, S.P.M., Dean, R., Marris, G., Brown, M.A., Jones, R., Neumann, P., Settele, J., 663 2010. Declines of managed honey bees and beekeepers in Europe. Journal of Apicultural 664 Research 49, 15–22. https://doi.org/10.3896/IBRA.1.49.1.02 665 Potts, S.G., Imperatriz-Fonseca, V., Ngo, H.T., Biesmeijer, J.C., Breeze, T.D., Dicks, L.V., Garibaldi, L.A., Hill, R., Settele, J., Vanbergen, A.J., 2016. IPBES (2016). The assessment report of the 666 Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on 667

- 668 pollinators, pollination and food production. Secretariat of the Intergovernmental Science-669 Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany.
- 670 R Development Core Team, 2008. R: A language and environment for statistical computing.
- Schmucki, R., accessed 2018. climateExtract: Extract Climate Data From a Local NETCDF File.
 https://github.com/RetoSchmucki/climateExtract
- 673 Steffan-Dewenter, I., Münzenberg, U., Bürger, C., Thies, C., Tscharntke, T., 2002. Scale-dependent 674 effects of landscape context on three pollinator guilds. Ecology 83, 1421–1432.
- 675 https://doi.org/10.1890/0012-9658(2002)083[1421:SDEOLC]2.0.CO;2
- vanEngelsdorp, D., Hayes, J., Underwood, R.M., Caron, D., Pettis, J., 2011. A survey of managed
 honey bee colony losses in the USA, fall 2009 to winter 2010. Journal of Apicultural Research
 50, 1–10. https://doi.org/10.3896/IBRA.1.50.1.01
- 679 Wickham, H., 2009. Ggplot2: Elegant Graphics for Data Analysis.
- 680 Wickham, H., Chang, W., 2016. devtools: Tools to Make Developing R Packages Easier.
- Williams, I.H., 1994. The dependence of crop production within the European Union on pollination by
 honey bees. Agricultural Zoology Reviews (United Kingdom) 6: 229-257.
- Zulian, G., Maes, J., Paracchini, M.L., 2013. Linking Land Cover Data and Crop Yields for Mapping and
 Assessment of Pollination Services in Europe. Land 2, 472–492.
- 685 https://doi.org/10.3390/land2030472

686

688 TABLES AND FIGURES

689 Color should be used for figures 1, 2 and 3.

690

Table 1 Levels of pollinator dependence and spatial coverage of 56 crops in France between
2000 and 2010. "Average total area" is the total annual area sown with a given type of crop,
averaged over the 11 years.

694

Table 2 Correlations between the Pollination Services Index (PSI) or the Temporal Variation
in Pollination Services (TVPS) and environmental variables, as inferred from a linear mixed
model with administrative regions as random effect.

698

Fig. 1. Z-transformed residual crop yields as a function of crop pollinator dependence for the 699 700 full dataset. Each point corresponds to a crop from a department. The colors highlight data from two examples of departments with extreme values of the Pollination Services Index: in 701 702 orange, Bouches-du-Rhône, a department where residual yields are positively related with pollinator dependence (slope = 2.42 + - 0.16); in blue, Eure, a department where residual 703 yields are negatively related with pollinator dependence (slope = -1.69 + -0.14). The grey 704 705 horizontal line is the regression over the full dataset (slope = 0). For sake of readability, the xcoordinate of each crop has been slightly shifted such that crops within a given class of 706 pollinator dependence are not plotted on top of each other. 707

708

Fig. 2. Maps of the Pollination Services Index (a) and the Temporal Variation in Pollination
Services (b) across France, at the spatial resolution of departments. Colors indicate the slope
of the relationship between relative mean yield (a) or the coefficient of variation of the yield
(b) and the level of crop pollinator dependence. Stars indicate departments with a significant

713 relationship.

714

- **Fig. 3.** Relationships among three pollination indices in France: (a) Pollination Services Index
- vs. Temporal Variation of Pollination Services; (b) Pollination Services Index vs. Relative
- 717 Pollination Potential; (c), Temporal Variation in Pollination Services vs. Relative Pollination
- 718 Potential. Each point represents a department; colors indicate the latitude of the centroid of
- the department.

721 TABLES AND FIGURES

Median level o pollinator dependence (%)	f Positive impact of anim pollination on productio	al Number on of crops	Mean number of departments	Average total area per year (ha)	
0	No increase	21	95.0	9,753,839	
5	Little	8	92.2	57,721	
25	Modest	10	93.6	1,998,652	
65	Great	12	93.1	129,423	
95	Essential	5	84.8	21,488	

722

Table 1 Levels of pollinator dependence and spatial coverage of 56 crops in France between

2000 and 2010. "Average total area" is the total annual area sown with a given type of crop,

averaged over the 11 years.

Response Variable	Independent variables	Estimate	df	Chisq	P value
PSI	Relative Pollination Potential	8.33	1,70	8.22	0.004**
	Index of agricultural intensity	-0.03	1,70	0.11	0.743
	Mean annual temperature	0.07	1,70	0.92	0.338
TVPS	Relative Pollination Potential	1.04	1,70	1.97	0.161
	Index of agricultural intensity	0.05	1,70	5.49	0.019*
	Mean annual temperature	-0.04	1,70	4.21	0.040*

Table 2 Correlations between the Pollination Services Index (PSI) or the Temporal Variation

in Pollination Services (TVPS) and environmental variables, as inferred from a linear mixed

730 model with administrative regions as random effect.

Fig. 1. Z-transformed residual crop yields as a function of crop pollinator dependence for the 732 full dataset. Each point corresponds to a crop from a department. The colors highlight data 733 from two examples of departments with extreme values of the Pollination Services Index: in 734 735 orange, Bouches-du-Rhône, a department where residual yields are positively related with pollinator dependence (slope = 2.39 + - 0.16); in blue, Eure, a department where residual 736 yields are negatively related with pollinator dependence (slope = -1.78 + -0.19). The grey 737 horizontal line is the regression over the full dataset (slope = 0). For sake of readability, the x-738 739 coordinate of each crop has been slightly shifted such that crops within a given class of pollinator dependence are not plotted on top of each other. 740



Fig. 2. Maps of the Pollination Services Index (a) and the Temporal Variation in Pollination
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of the relationship between relative mean yield (a) or the coefficient of variation of the yield
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Fig. 3. Relationships among three pollination indices in France: (a) Pollination Services Index
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Potential. Each point represents a department; colors indicate the latitude of the centroid of
the department.





757 Appendix A. Supplementary Data

758 Color should be used for figures A1, A3, A4.

759

Table A1. List of the 56 crops grown in 95 departments during the 2000-2010 period.

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Fig. A1. PCA on the three High Nature Value components. The ordination diagram is plottedfor axes 1 and 2 (a). The distribution of eigenvalues is shown in (b).

764

Fig. A2. Changes in standardized mean yield with increasing level of crop pollinator

dependence for each of the 95 departments. Dots represent crop yield and the line indicates

the estimate from the linear regression model described in the main text. Colors indicate the

sign and slope of the relationship between relative mean yield and the level of crop

pollinator dependence, as for Fig. 1.

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Fig. A3. Changes in yield stability with increasing level of crop pollinator dependence for each
of the 95 departments. Dots represent crop yield and the line indicates the estimate from
the linear regression model described in the main text. Colors indicate the slope of the
relationship between the coefficient of variation of the yield and the level of crop pollinator
dependence, as for Fig. 1.

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Table A1. List of the 56 crops grown in 95 departments during the 2000-2010 period.

Crop name	Taxonomic group	Level of pollinator dependence	Positive impact of animal pollination on	Number of departments growing the crop	Average total area per year (ha)	Average yield per ha (100 kg/ha)
		05	production	42	44.64	5077.40
Kiwifruits	Actinidia deliciosa	95	essential	42	4161	5377.18
l otal oat	Avena sativa	0	no increase	88	100993.36	3572.45
Other rapeseeds	Brassica napus and Brassica rapa subsp. oleifera	25	modest	85	1239754.45	2469.55
Peppers	Capsicum annuum	5	little	56	520.64	14705.36
Chestnuts	Castanea sativa	25	modest	44	7030.09	527.73
Watermelons	Citrullus lanatus	95	essential	24	156.18	5269.82
Clementines and mandarins	Citrus clementina and Citrus nobilis	5	little	4	1650.91	403.09
Grapefruits	Citrus paradisi	5	little	4	216.27	340.45
Hazelnuts	Corylus avellana var. grandis	0	no increase	53	2919.18	722.45
Muskmelons	Cucumis melo	95	essential	64	12504.36	9385.27
Cucumbers	Cucumis sativus	65	great	80	546.73	123404.45
Gherkins	Cucumis sativus	65	great	47	227.73	5222.36
Zucchinis	Cucurbita pepo	95	essential	87	2539.82	26212.09
Squashes	Cucurbitaceae	95	essential	86	2126.36	18566.91
Figs	Ficus carica	25	modest	19	415	915.45
Strawberries	Fragaria x ananassa	25	modest	92	3498.36	10864.36
Soybean	Glycine max	25	modest	68	59235.45	1411
Sunflower seeds	Helianthus annuus	25	modest	80	611718.55	1837.55
Total barley	Hordeum vulgare and Hordeum hexasticon	0	no increase	89	1630336.82	4870.64
Nuts	Jualans reaia	0	no increase	69	16420.45	1044.45
Lentils	Lens culinaris	0	no increase	56	8195	456 45
Flaxseeds	Linum usitatissimum	5	little	69	10352 45	1007.82
Sweet Lunines		0	no increase	73	4864 36	1349 91
Tomatoes	Lyconersicon esculentum	5	little	88	4736 55	92174 45
Cider annles	Malus domestica	65	great	64	11251 36	7818.09
Table annles	Malus domestica	65	great	93	11251.50	28771 18
Other unmixed cereals	NA	0	no increase	61	28786.64	1/07 18
Melanges of cereals	NA	0	no increase	82	49438.18	2345.91
(excluding metell)				4.5		107.64
Olives	Olea europaea	0	no increase	16	16535.45	187.64
Rice	Oriza sativa	0	no increase	3	18643.45	161.45
Avocados	Persea americana	65	great	2	8.45	98.27
Shelled beans	Phaseolus vulgaris	5	little	/3	/003.09	3305.55
Dry beans	Phaseolus vulgaris	5	little	50	2871.18	999.36
Green beans	Phaseolus vulgaris	5	little	92	30369.64	8746.36
Protein peas	Pisum sativum	0	no increase	87	262965.64	3000.18
Green peas	Pisum sativum subsp. sativum var. sativum	0	no increase	86	33349.64	4817.64
Dried peas	Pisum sativum subsp. sativum var. sativum	0	no increase	21	1044.27	386.18
Apricots	Prunus armeniaca	65	great	39	14456.18	1805.64
Cherries	Prunus avium	65	great	79	11016.45	3231.18
Plums	Prunus domestica	65	great	72	18680.82	5578.64
Almonds	Prunus dulcis	65	great	18	1360.723	224.45
Peaches and nectarines	Prunus spp	65	great	60	16863.64	6599.82
Pears	Pyrus communis	65	great	85	8103.18	15934.09
Blackcurrants and blueberries	Ribes nigrum and Vaccinum	25	modest	80	2642.82	2174.64
Redcurrants	Ribes rubrum	25	modest	74	364	2809.45
Raspberries	Rubus idaeus	65	great	89	943.27	3652.73
Rve	Secale cereale	0	no increase	87	27067 82	3856.36
Eggnlants	Solanum melongeng	25	modest	73	461	18528 73
Sorghum	Sorahom hicolor	0	no increase	73	51877 82	2809 18
Triticale	Triticosecale	0	no increase	86	276058 55	4420.00
Total bread wheat	Triticum aestivum	0	no increase	89	4435083.45	5404.36

Т	otal durum wheat	Triticum durum	0	no increase	68	376115.09	2423
В	road beans	Vicia faba	25	modest	85	73532.36	2291.45
V	ine	Vitis vinifera	0	no increase	74	896643.36	4955.45
N	1aize (grain and seed)	Zea mays	0	no increase	89	1581688.27	7234.36
N	1aize (sweetcorn)	Zea mays	0	no increase	35	24360.27	3542.27

780 Fig. A1. PCA on the three High Nature Value components. The ordination diagram is plotted



for axes 1 and 2 (a). The distribution of eigenvalues is shown in (b).

Fig. A2. Changes in standardized mean yield with increasing level of crop pollinator
dependence for each of the 95 departments. Dots represent crop yield and the line indicates
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788 pollinator dependence, as for Fig. 1.



Fig. A3. Changes in yield stability with increasing level of crop pollinator dependence for each of the 95 departments. Dots represent crop yield and the line indicates the estimate from the linear regression model described in the main text. Colors indicate the slope of the relationship between the coefficient of variation of the yield and the level of crop pollinator dependence, as for Fig. 1.



