

# Worldwide occurrence records reflect a global decline in bee species richness

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## Abstract

Wild and managed bees are key pollinators, providing ecosystem services to a large fraction of the world's flowering plants, including ~85% of all cultivated crops. Recent reports of wild bee decline and its potential consequences are thus worrisome. However, evidence is mostly based on local or regional studies; global status of bee decline has not been assessed yet. To fill this gap, we analyzed publicly available worldwide occurrence records from the Global Biodiversity Information Facility spanning more than a century of specimen collection. We found that after the 1980's the number of collected bee species declines steeply, and approximately 25% fewer species were reported between 2006 and 2015 relative to the number of species counted before the 1990's. These trends are alarming and encourage swift action to avoid further decline of these key pollinators.

## Introduction

Insects are the most specious group of animals and are estimated to encompass a large fraction of the Earth's living biomass<sup>1</sup>. Given their historical abundance and ubiquity, along

25 with the many familiar examples of extreme resilience to natural or intentional extermination,  
26 some insects have been traditionally viewed as the ultimate survivors of most apocalyptic  
27 scenarios. However, in the last two decades, a series of high-profile reports based mostly on  
28 local or regional evidence have repeatedly warned of a significant decline in insect diversity  
29 and biomass and raised the alarm about the potential consequence of this decline for the  
30 delivery of many ecosystem services<sup>2-5</sup>. Among affected ecosystem services is plant  
31 pollination: insects are the main vectors for pollen transfer of most wild and crop flowering  
32 plant species<sup>6-10</sup>. Bees (Hymenoptera: Apoidea: Anthophila), a lineage that includes about  
33 20,000 described species, are the most important group of insect pollinators<sup>11,12</sup>. Wild bee  
34 species are not only key to sexual reproduction of hundreds of thousands of wild plant  
35 species<sup>7</sup>, but also to the yield of about 85% of all cultivated crops<sup>6,13,10</sup>. There is mounting  
36 evidence that a decline in wild bee populations might follow or even be more pronounced  
37 than overall trends of insect decline<sup>12,14-17</sup>. Such differential vulnerability might result from a  
38 high dependence of bees on flowers for food and a diversity of substrates for nesting,  
39 resources that are greatly affected by land conversion to large-scale agriculture, massive  
40 urbanization, and other intensive land uses<sup>18-20</sup>. However, most studies on “bee decline” to  
41 date are based on local-, regional- or country-level datasets, and have a strong bias towards  
42 the Northern Hemisphere, particularly North America and Europe, where most long-term  
43 research projects capable of generating multidecadal datasets have been conducted<sup>4,12,21,22</sup>.

44 To find an alternative approach to assess whether bee decline is a global phenomenon, we  
45 resorted to the data publicly available at the Global Biodiversity Information Facility  
46 (GBIF)<sup>23</sup>. The GBIF collects and provides “data about all types of life on Earth” from  
47 “sources including everything from museum specimens collected in the 18th and 19th century  
48 to geotagged smartphone photos shared by amateur naturalists in recent days and weeks”<sup>23</sup>.  
49 GBIF ingests data from a widely diverse range of data sources, localities, recording

50 strategies, geographic areas, sampling intensities, etc., with each data source potentially  
51 plagued by both systematic and idiosyncratic biases<sup>24–27</sup>. Although usage of GBIF data has  
52 been strongly criticized due to its inherent biases<sup>21,24,28–30</sup>, most criticisms are usually aimed  
53 towards using its occurrence data to reconstruct and model species' distribution ranges.  
54 Reconstructing geographic ranges and abundances from such “messy” datasets is indeed  
55 challenging. However, a binning approach in which a simpler question (“has a species been  
56 recorded anywhere during a given period?”) yields a yes/no answer can potentially be much  
57 more robust to sampling effort heterogeneity and geographic uncertainty<sup>31</sup>. We reasoned that  
58 if bees are experiencing a global decline in the last few decades, then a generalized decrease  
59 in population size and range would result in increased rarity, diminished chance of  
60 observation and collection and, consequently, a diminished number of total species being  
61 observed and recorded worldwide each year.

## 62 Results and Discussion

63 To test our hypothesis of global bee decline, we queried GBIF for all occurrence records  
64 of Hymenoptera prior to 2020 with either “Preserved specimen” or “Human observation”  
65 bases of record<sup>32</sup> (see Methods section below). Records of preserved specimens originate in  
66 vouchered collections such as those from museums and universities, or associated with  
67 biodiversity surveys and molecular barcoding initiatives, among others. Human observations,  
68 on the other hand, are records in which a given species was observed, but no voucher was  
69 collected; this category of records has been growing exponentially since citizen science  
70 initiatives became increasingly popular<sup>33</sup>. Because the preserved specimen records are likely  
71 to represent the most taxonomically traceable source of information within the GBIF  
72 dataset<sup>33,34</sup>, we made parallel analyses for both the full dataset and the specimens-only subset.  
73 We filtered the datasets to six families of the superfamily Apoidea that conform the

74 Anthophila or “true bees”: Melittidae, Andrenidae, Halictidae, Colletidae, Megachilidae and  
75 Apidae (we excluded the small family Stenotritidae from our analysis, since it has only about  
76 21 species restricted to Australia)<sup>11</sup>.

77 Plotting the total number of records per year in both datasets show that the number of  
78 worldwide bee occurrence records follows a mostly monotonic increasing trend that becomes  
79 steeper after 1990 (Fig. 1A). Since the four most recent years (2016-2019, marked with \* in  
80 Fig. 1A) show a noticeable drop in records, likely due to time lags in data entry<sup>35</sup>, we  
81 excluded those years from further analyses to avoid a downward bias in most recent years. In  
82 contrast, while the number of recorded species per year during the same period also increases  
83 initially, it reaches a steady maximum after 1950 but then shows a noticeable decline starting  
84 near the end of the 20th century (Fig. 1B). This negative temporal trend persisted even when  
85 number of records and of contributing collections, institutions and datasets are considered  
86 (generalized least squares estimate  $\pm$  s.e. for the period 1986-2016:  $-31.9 \pm 11.0$ ,  $t$  value:  $-2.9$ ,  
87  $p = 0.008$ ). Thus, fewer species have been reported globally within GBIF records since  
88 approximately the 1990s.

89 To remove potential biases introduced by year-to-year heterogeneity of data sources, we  
90 binned records every 10 years starting from 1946 (after the end of World War II, which  
91 caused a noticeable dip in collection intensity, see Fig. 1A) and until 2015 inclusive; we call  
92 these bins “idecades” and name them by the multiple-of-ten year in the middle. We then used  
93 rarefaction based interpolation/extrapolation curves (iNEXT) and asymptotic richness  
94 estimators<sup>36,37</sup> to compare idecadal changes in richness of species records. In this analysis,  
95 accumulation curves are very similar from the 1950’s to the 1990’s but flatten considerably to  
96 reach lower asymptotes for the 2000’s and 2010’s (Fig. 1C,E), again showing that the number  
97 of species among bee specimens collected worldwide is showing a sharp decline. More

98 specifically, we found a reduction of about 8% during the 2000s in both datasets, and of 22%  
99 and 26% during the 2010s for the full and specimen-only datasets, respectively (Fig. 1D, F).

100 Bee families in our dataset are heterogeneous in term of richness and abundance, and the  
101 observed trends might be driven by just a few bee clades. To make a more phylogenetically-  
102 explicit analysis exploring whether bees show a differential temporal trend compared to their  
103 closest relatives, and whether particular bee families are more endangered than others, we re-  
104 analyzed the specimen dataset, this time retaining also records for two families of carnivorous  
105 apoid wasps, Crabronidae and Sphecidae, that are sister to Anthophila, and for another highly  
106 diverse, non-apoid hymenopteran family, the Formicidae (ants)<sup>38</sup>. The results show different  
107 patterns of species richness in records of each family, with noticeable phylogenetic structure  
108 (Fig. 2). Long-tongued bees (Megachilidae and Apidae) show a steepening decline starting at  
109 2000's, while short-tongued bees show declines starting earlier (Andrenidae and Halictidae)  
110 or later (Colletidae). These declines in richness of recorded species relative to the average  
111 number found between 1950 and 1990 ranged from 17% for Halictidae to over 41% for  
112 Melittidae. Comparisons between Anthophila families and two families of apoid wasps sister  
113 to bees, and to a more distantly related family, the true ants (Formicidae) revealed contrasting  
114 trends (Fig. 2). While both wasp families also show declining trends, they present different  
115 patterns than bees. Record richness of sphecid and crabronid wasps both show a smoother  
116 decrease initiating earlier than the 2000's. In contrast, ants show very little evidence of global  
117 record richness decline, but rather a trend towards an increase in the number of recorded  
118 species. Although the limited number of bee families precludes a formal analysis of  
119 phylogenetic patterning, closely related families (e.g., Apidae and Megachilidae, or  
120 Colletidae and Halictidae) seem to share more similar trends in terms of timing and  
121 magnitude of species richness decline than less related families. This hint of phylogenetic  
122 patterning becomes even more apparent when considering the two apoid wasp families,

123 Crabronidae and Sphecidae (Fig. 2). Interestingly, a very similar pattern – in which bees  
124 show a strong, recent decline, wasps show a gentler decline starting earlier, while ants remain  
125 steady – was recently reported using a quite different analytical approach on a substantially  
126 different and more geographically limited dataset<sup>39</sup>. Altogether, family-specific trends and  
127 asymptotic richness estimates show that the overall decline in global bee record richness is  
128 not driven by any particular family. Instead, a generalized decline seems to be a pervasive  
129 feature within the bee lineage.

130 To rule out the possibility that the method we used to estimate richness does not correlate  
131 with actual bee diversity, we compared the asymptotic estimator of total richness for each  
132 family based on GBIF records with the total known number of species and found a linear  
133 correlation between both estimates across families (Fig. S1). Another potential artifact  
134 causing a decline in recorded bee diversity in the last two decades could be an increasing  
135 loss in taxonomic expertise during that period<sup>40–42</sup>. Under such scenario, we would expect  
136 the fraction of records unidentified to the species level – a reasonable proxy for lack of  
137 expertise<sup>33</sup> – should have stayed approximately constant until the last two decades and then  
138 increased noticeably. While the fraction of records missing species' identification shows an  
139 overall increase in the last 120 years, this trend has actually reversed since the 2000's (Fig.  
140 S2). This result is consistent with previous analyses of the GBIF dataset<sup>33</sup>, and shows that  
141 potential loss of taxonomic expertise cannot explain the decline in bee record diversity seen  
142 at the last two decades.

143 Next, we explored the geographic distribution of the dataset, by sub-setting the data by  
144 continent and repeating the analyses. Overall, GBIF has a strong bias towards North  
145 American and European records<sup>35</sup>, and this bias results in a very uneven contribution of each  
146 continent to decadal number of records (Fig. S3). North America (including Central America  
147 and the Caribbean) has the largest and most even representation of records across decades

148 (between 46 and 75% of global records) and shows its steepest decline in species richness  
149 between the 1990's and the 2010's (Fig. S4). In contrast, Europe shows two separate periods  
150 of decline, one between the 1960's and the 1970's and a more recent drop between the 1980's  
151 and 1990's but stabilizes afterwards (Fig. S4). Africa shows a sustained fall in species  
152 richness since the 1980's, whereas in Asia the decline seems to have started two or three  
153 decades earlier (Fig. S4). The trend in South America is less clear, although estimated  
154 richness also decreases in the last ten years of the dataset (Fig. S4). Overall, analyses of the  
155 dataset at a continental scale show heterogeneity in both the proportional and absolute  
156 contributions to the records, and in the timing and magnitude of the decline in species  
157 richness. However, despite large differences in data availability and, perhaps, except for  
158 Oceania, a decline in species richness of bee records seems to be common to all continents.

159 A global decline in bee record diversity could relate to a proportional decrease in bee  
160 abundance, so that rare species become rarer or even extinct, and abundant species become  
161 less abundant. Alternatively, the less abundant species could be declining strongly, whereas  
162 abundant species might be declining at a lower rate or even thriving. These different  
163 scenarios are expected to leave a distinctive signature in the temporal pattern of relative  
164 record abundances. Under the first scenario, the sharp decrease in species richness estimates  
165 should not be accompanied by a decrease in evenness, a measure of how equally total record  
166 abundance is partitioned among species, whereas under the second scenario there should be a  
167 parallel decrease in record evenness. As expected from the hypothesis of an abundance-  
168 related differential species decline, plotting Pielou's index (a common measure of  
169 evenness<sup>43</sup>) per year of bee records shows a strong decreasing trend since the 1990's for both  
170 datasets (Fig. 3). Therefore, this decline in species richness of records can relate to either a  
171 global change in how an invariant bee diversity is sampled, leading to more infrequent  
172 reporting of many species and much more frequent reporting of a few other species, or to a

173 global phenomenon by which thousands of species are becoming too rare to be sampled while  
174 fewer species are becoming dominant and perhaps even increasing in abundance. These two  
175 alternatives are not mutually exclusive, and both increased sampling and reporting bias and  
176 declining bee biodiversity should be a matter of concern.

177 Our results support a hypothesis of overall decline in bee diversity at a global scale. If  
178 trends in species richness of GBIF records are reflecting an actual trend in bee diversity, then  
179 this decline seems to be occurring with distinctive characteristics in every bee family and in  
180 most continents. Interestingly, this trend appears to be a relatively recent phenomenon that  
181 accentuated in the nineties, at the beginning of the globalization era, and continues to the  
182 present. The globalization era has not only been a period of major economic, political and  
183 social change, but also of accelerated land-use transformation<sup>44</sup>. Bees thrive in  
184 heterogeneous habitats, even those driven by man<sup>18,45</sup>, where they find a diversity of floral  
185 and nesting resources. However, land devoted to agriculture, particularly to monoculture, has  
186 expanded in several regions of the world since the 1990s<sup>44</sup>. This has led not only to higher  
187 habitat homogeneity, which can relate by itself to more impoverished and spatially  
188 homogeneous bee assemblages<sup>18,46</sup>, but also to higher use of pesticides and other agriculture  
189 chemical inputs that have direct and indirect lethal and sub-lethal effects on bee health<sup>47</sup>.  
190 Effects of climate change on shrinking bee geographical ranges have been also documented  
191 in Europe and North America<sup>4</sup>. Lastly, a booming international bee trade has involved the  
192 co-introduction of bee pathogens, that may cause bee decline, like the emblematic case of the  
193 giant Patagonian bumble bee, *Bombus dahlbomii*<sup>48</sup>. These drivers can act synergistically,  
194 which can have accelerated a process of bee decline. Phylogenetic patterning in the trend of  
195 recorded species diversity among the different bee families (Fig. 2) suggests that different  
196 lineages can be differentially affected by different drivers, likely based both on their common  
197 geographical distribution and shared clade-specific biological and ecological traits<sup>21,49,50</sup>.



198 Associated with the declining trend of richness of species records is a trend of increasing  
199 dominance of records by a few species. Increasing dominance by one or a few species can be  
200 observed at the regional scale, like the case of invasive *Bombus terrestris* in southern South  
201 America<sup>51</sup> or the western honeybee *Apis mellifera* in the Mediterranean<sup>52</sup>. The western  
202 honeybee has been introduced in every single continent from its original geographical range  
203 in Europe and Africa. Although both domesticated and wild populations of the western  
204 honeybee seem to be declining in several countries, this species is still thriving globally<sup>53</sup>.  
205 Correspondingly, an increasing fraction of the total global bee records is composed by *Apis*  
206 *mellifera* occurrences (Fig. S5). A consequence of increasingly less diverse and uneven bee  
207 assemblages could be an increase in pollination deficits, causing a reduction in the quantity  
208 and quality of the fruits and seeds produced by both wild and cultivated plants. Less diverse  
209 bee assemblages at both local and regional scales have been associated with lower and less  
210 stable yields of most pollinator-dependent crops<sup>13</sup>.

211 GBIF is certainly not a source of systematically collected data, and this should be borne in  
212 mind when interpreting the results of our analyses<sup>21,27,35,54,55</sup>. Spatial and temporal biases in  
213 collection intensity (e.g., targeted programs might enrich the abundance of specific  
214 species/groups at specific spans and regions) can generate spurious trends. In our analysis, we  
215 counted every species only once per year regardless of how many records it had for a given  
216 year; this filters out biases due to sporadic intensive sampling campaigns. Biases introduced  
217 due to targeted collection efforts or local/regional events (e.g., changes in research and  
218 conservation policies, economic downturns, social unrest, etc.) are likely, yet most such  
219 biases tend to be spatially and temporally restricted, and are less likely to systematically  
220 affect trends at the global, multi-decadal scale of this analysis. Indeed, several potential  
221 biases would be expected to deflate, rather than inflate our results. For example, collectors

222 targeting rare species would be expected to enrich the number of species (unless many  
223 species are becoming so scarce that they just cannot be found).

224 Nonetheless, our continent-level analysis showed that regions with the best temporal and  
225 spatial coverage (i.e., Europe and North America, Fig. S3) are the ones showing the clearest  
226 signal for decline (Fig. S4); our results agree with several existing reports at local, national  
227 and subcontinental level<sup>14,16,17,39,56–61</sup>. Furthermore, none of those biases can explain the  
228 noticeable phylogenetic contagion seen in the trends (Fig. 2) better than the fact that the  
229 hymenopteran groups we analyzed have a considerable phylogenetic signal in their ecology  
230 and life history traits and would be expected to show phylogenetic clustering in their response  
231 to drivers of decline<sup>50</sup>.

232 Unsurprisingly, when data is disaggregated by country, agreement between country-level  
233 results and existing reports improves as the number of records increases. For example, our  
234 data reflects a clear and continuous decline in bee diversity in the USA<sup>56,57,60</sup> (with over 1  
235 million records), a decline in Brazil<sup>61</sup> during the last two decades (~190k records), but shows  
236 no clear loss of richness in Great Britain (~25k records), or much uncertainty in an apparent  
237 trend in bee species loss in Panama (~9k records), despite reports of bee decline in all those  
238 countries<sup>14,16,17,62</sup> (Fig. S6). Interestingly, reports on decline of British bees are based on  
239 occurrence data that is not publicly available – i.e. ~300k records from the Bees, Wasps and  
240 Ants Recording Society (BWARS: <http://www.bwars.com/>). This suggests that, besides data  
241 source heterogeneity, a major source of bias and inaccuracy of results derived from GBIF  
242 data result from obstacles to data mobilization, and highlights the need to increase efforts to  
243 remove barriers to data sharing and discourage funding agencies from allowing data  
244 sequestration.

245 Thus, while the inherent heterogeneity and biases of aggregated datasets as those offered  
246 by GBIF make them unreliable as a direct (i.e., unfiltered, uncorrected) data source of

247 predictive models, they can still be used within a hypothesis-driven framework to test  
248 whether bees (or any other taxon) as a group are declining worldwide. In this context, our  
249 results largely agree with the hypothesis that current regional reports of declining bee  
250 diversity reflect a global phenomenon.

## 251 Conclusions

252 One of the most important pieces of missing information of the global report on  
253 Pollinators, Pollination and Food Production of IPBES <sup>63</sup> was the lack of data on global bee  
254 decline, despite the many local and few regional reports pointing out that this decline could  
255 add to a global phenomenon. Despite all its shortcomings, GBIF still is probably the best  
256 global data source available on long-term species occurrence and has the potential to  
257 contribute in filling this critical knowledge gap. Its analysis supports the hypothesis that we  
258 are undergoing a global decline in bee diversity that needs the immediate attention of  
259 governments and international institutions. Under the most optimistic interpretation – that  
260 bees are not declining, and the trends we find are an artifact of data collection - our results  
261 would indicate that global efforts to record and monitor bee biodiversity are decreasing over  
262 time. However, and given the current outlook of global biodiversity <sup>4,5,10,12</sup>, it is more likely  
263 that these trends reflect existing scenarios of declining bee diversity. In the best scenario, this  
264 can indicate that thousands of bee species have become too rare; under the worst scenario,  
265 they may have already gone locally or globally extinct. In any case, a decline in bee diversity  
266 driven by either increasing rarity or irreversible extinction will affect the pollination of wild  
267 plants and crops, with broader ecological and economic consequences. Slowing down and  
268 even reversing habitat destruction and land-conversion to intensive uses, implementation of  
269 environmentally friendly schemes in agricultural and urban settings, and programs to re-  
270 flower our world are urgently required. Bees cannot wait.

## 271 Methods

### 272 Datasets

273 An initial query at the database of occurrence records at the Global Biodiversity  
274 Information Facility ([www.gbif.org](http://www.gbif.org)) using the filters [Scientific Name = “Hymenoptera”,  
275 Basis of Record = “PRESERVED\_SPECIMEN” | “HUMAN\_OBSERVATION”, Year  
276 <2020] resulted on 9,176,688 total records involving 2,374 datasets<sup>32</sup>. Data were  
277 downloaded as a text file and filtered for records identified to species levels and belonging to  
278 Anthophila (defined as the families Melittidae, Andrenidae, Halictidae, Colletidae,  
279 Megachilidae and Apidae; 3,459,086 records). We also retrieved records for two closely  
280 related families of apoid wasps (Crabronidae and Sphecidae; 283,331 records), or the true  
281 ants (Formicidae; 1,121,857 records). Phylogenetic relations between all these nine families  
282 follow recent phylogenomic results<sup>38</sup>.

### 283 Analyses

284 All datasets were analyzed using a customized script written and executed within the R  
285 computing environment<sup>64</sup>. The complete annotated script is available as Supplementary  
286 Materials, and can be used to fully reproduce all results, or adapted to re-run the analyses on  
287 other datasets. Data was processed using the `tidyr`<sup>65</sup>, `dplyr`<sup>66</sup> and `data.table`<sup>67</sup>  
288 packages.

289 After removing records without “year” data, yearly counts of records and species were  
290 plotted using `ggplot2`<sup>68</sup>. Significance of a negative trend was tested by fitting yearly counts  
291 of records, species, collections, institutions and datasets a generalized least squares model  
292 with the formula `sp ~ year + records + collections + institutions +`  
293 `datasets`, with an autoregressive-moving average autocorrelation structure of order (1,0).  
294 Then, each year was assigned to a 10-year period termed “idecade” (for inter-decade),

295 corresponding to a regular decade shifted four years into the past (e.g, the 1990's idecade  
296 spans 1986 to 1995). Records by species and idecade were counted and stored in a matrix of  
297  $m$  species  $\times$  7 idecades (1950's to 2010's). This matrix was used as abundance data input for  
298 the `iNEXT` function of the `iNEXT` package<sup>37</sup> to estimate rarefaction-based  
299 interpolation/extrapolation (`iNEXT`) curves and Chao1 asymptotic estimators of species  
300 richness<sup>36</sup>. We also compared the asymptotic estimator for species richness for each family  
301 with the total number of species listed for each family in the taxonomic framework of the  
302 Integrated Taxonomic Information System ([www.itis.gov](http://www.itis.gov)).

303 To estimate potential biases caused by changes of taxonomic expertise over time, we re-  
304 filtered the initial GBIF query without excluding records without a species ID, then counted  
305 the number of records with or without a species id per year<sup>33</sup>. To analyze trends at  
306 continental level, we added a "Continent" field to the base dataset via table joining to a list of  
307 countries, country codes and continents from [https://datahub.io/JohnSnowLabs/country-and-](https://datahub.io/JohnSnowLabs/country-and-continent-codes-list)  
308 [continent-codes-list](https://datahub.io/JohnSnowLabs/country-and-continent-codes-list). We then repeated the analyses splitting the dataset by continent.  
309 Continent and country-specific shapes were taken from <https://github.com/djaiss/mapsicon>.  
310 To show trends in equitability of species abundance across records over time, we calculated  
311 Pielou's evenness index<sup>43</sup>,  $J = \sum p_i \ln(p_i) / \log(S)$  for  $i=1$  to  $S$ , the total number of species, for  
312 each year between 1900 and 2018, using the diversity functions from the package `vegan`<sup>69</sup>.  
313 The contribution of a given species (e.g., *Apis mellifera*) was calculated as yearly number of  
314 the species records divided the total number of records for that year and plotted as a function  
315 of year.

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## 326 Footnotes

327 **Author contributions:** Conceptualization, E.E.Z. and M.A.A.; Data Curation: E.E.Z.;  
328 Formal analysis: E.E.Z. and M.A.A.; Visualization: E.E.Z.; Writing – original draft, E.E.Z.  
329 and M.A.A., Writing – review & editing, E.E.Z. and M.A.A.

330 **Competing interests:** Authors declare no competing interests.

331 **Data and materials availability:** Occurrence record data used in this paper can be  
332 downloaded from <https://doi.org/10.15468/dl.ysjm4x>; original sources traceable via  
333 GBIF.org. The R language script used to analyze the data and generate the plots is available  
334 at <https://github.com/ezattara/global-bee-decline>.

## 335 References

- 336 1. Bar-On, Y.M., Phillips, R., and Milo, R. (2018). The biomass distribution on Earth. *Proc.*  
337 *Natl. Acad. Sci.* *115*, 6506.
- 338 2. Hallmann, C.A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N., Schwan, H., Stenmans,  
339 W., Müller, A., Sumser, H., Hörren, T., et al. (2017). More than 75 percent decline over  
340 27 years in total flying insect biomass in protected areas. *PLOS ONE* *12*, e0185809.
- 341 3. Leather, S.R. (2017). “Ecological Armageddon” - more evidence for the drastic decline in  
342 insect numbers. *Ann. Appl. Biol.* *172*, 1–3.
- 343 4. Sánchez-Bayo, F., and Wyckhuys, K.A.G. (2019). Worldwide decline of the  
344 entomofauna: A review of its drivers. *Biol. Conserv.* *232*, 8–27.

- 345 5. Klink, R. van, Bowler, D.E., Gongalsky, K.B., Swengel, A.B., Gentile, A., and Chase,  
346 J.M. (2020). Meta-analysis reveals declines in terrestrial but increases in freshwater  
347 insect abundances. *Science* 368, 417–420.
- 348 6. Gallai, N., Salles, J.-M., Settele, J., and Vaissière, B.E. (2009). Economic valuation of the  
349 vulnerability of world agriculture confronted with pollinator decline. *Ecol. Econ.* 68,  
350 810–821.
- 351 7. Ollerton, J., Winfree, R., and Tarrant, S. (2011). How many flowering plants are  
352 pollinated by animals? *Oikos* 120, 321–326.
- 353 8. Vanbergen, A.J., and the Insect Pollinators Initiative (2013). Threats to an ecosystem  
354 service: pressures on pollinators. *Front. Ecol. Environ.* 11, 251–259.
- 355 9. Dirzo, R., Young, H.S., Galetti, M., Ceballos, G., Isaac, N.J.B., and Collen, B. (2014).  
356 Defaunation in the anthropocene. *Science* 345, 401–406.
- 357 10. IPBES (2019). Summary for policymakers of the global assessment report on biodiversity  
358 and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity  
359 and Ecosystem Services S. Díaz, J. Settele, E. Brondízio, H. Ngo, M. Guèze, J. Agard, A.  
360 Arneth, P. Balvanera, K. Brauman, S. Butchart, et al., eds. (IPBES secretariat).
- 361 11. Michener, C.D. (2007). *The bees of the world* 2nd ed. (The Johns Hopkins University  
362 Press).
- 363 12. Potts, S.G., Biesmeijer, J.C., Kremen, C., Neumann, P., Schweiger, O., and Kunin, W.E.  
364 (2010). Global pollinator declines: trends, impacts and drivers. *Trends Ecol. Evol.* 25,  
365 345–353.
- 366 13. Garibaldi, L.A., Steffan-Dewenter, I., Winfree, R., Aizen, M.A., Bommarco, R.,  
367 Cunningham, S.A., Kremen, C., Carvalheiro, L.G., Harder, L.D., Afik, O., et al. (2013).  
368 Wild pollinators enhance fruit set of crops regardless of honey bee abundance. *Science*  
369 339, 1608–1611.
- 370 14. Biesmeijer, J.C., Roberts, S.P.M., Reemer, M., Ohlemüller, R., Edwards, M., Peeters, T.,  
371 Schaffers, A.P., Potts, S.G., Kleukers, R., Thomas, C.D., et al. (2006). Parallel declines in  
372 pollinators and insect-pollinated plants in Britain and the Netherlands. *Science* 313, 351–  
373 354.
- 374 15. Goulson, D., Lye, G.C., and Darvill, B. (2008). Decline and conservation of bumble bees.  
375 *Annu. Rev. Entomol.* 53, 191–208.
- 376 16. Ollerton, J., Erenler, H., Edwards, M., and Crockett, R. (2014). Extinctions of aculeate  
377 pollinators in Britain and the role of large-scale agricultural changes. *Science* 346, 1360–  
378 1362.
- 379 17. Powney, G.D., Carvell, C., Edwards, M., Morris, R.K.A., Roy, H.E., Woodcock, B.A.,  
380 and Isaac, N.J.B. (2019). Widespread losses of pollinating insects in Britain. *Nat.*  
381 *Commun.* 10, 1–6.

- 382 18. Williams, N.M., and Kremen, C. (2007). Resource distributions among habitats  
383 determine solitary bee offspring production in a mosaic landscape. *Ecol. Appl.* *17*, 910–  
384 921.
- 385 19. Belsky, J., and Joshi, N.K. (2019). Impact of biotic and abiotic stressors on managed and  
386 feral bees. *Insects* *10*, 233.
- 387 20. Aizen, M.A., Aguiar, S., Biesmeijer, J.C., Garibaldi, L.A., Inouye, D.W., Jung, C.,  
388 Martins, D.J., Medel, R., Morales, C.L., Ngo, H., et al. (2019). Global agricultural  
389 productivity is threatened by increasing pollinator dependence without a parallel increase  
390 in crop diversification. *Glob. Change Biol.* *25*, 3516–3527.
- 391 21. Bartomeus I., Stavert J. R., Ward D., and Aguado O. (2018). Historical collections as a  
392 tool for assessing the global pollination crisis. *Philos. Trans. R. Soc. B Biol. Sci.* *374*,  
393 20170389.
- 394 22. Thomas, C.D., Jones, T.H., and Hartley, S.E. (2019). “Insectageddon”: A call for more  
395 robust data and rigorous analyses. *Glob. Change Biol.* *25*, 1891–1892.
- 396 23. GBIF Secretariat (2019). What is GBIF? <https://www.gbif.org/what-is-gbif>.
- 397 24. Boakes, E.H., McGowan, P.J.K., Fuller, R.A., Chang-qing, D., Clark, N.E., O’Connor,  
398 K., and Mace, G.M. (2010). Distorted views of biodiversity: spatial and temporal bias in  
399 species occurrence data. *PLOS Biol.* *8*, e1000385.
- 400 25. Isaac, N.J.B., and Pocock, M.J.O. (2015). Bias and information in biological records.  
401 *Biol. J. Linn. Soc.* *115*, 522–531.
- 402 26. Maldonado, C., Molina, C.I., Zizka, A., Persson, C., Taylor, C.M., Albán, J., Chilquillo,  
403 E., Rønsted, N., and Antonelli, A. (2015). Estimating species diversity and distribution in  
404 the era of Big Data: to what extent can we trust public databases? *Glob. Ecol. Biogeogr.*  
405 *24*, 973–984.
- 406 27. Troudet, J., Grandcolas, P., Blin, A., Vignes-Lebbe, R., and Legendre, F. (2017).  
407 Taxonomic bias in biodiversity data and societal preferences. *Sci. Rep.* *7*, 9132.
- 408 28. Hortal, J., Jiménez-Valverde, A., Gómez, J.F., Lobo, J.M., and Baselga, A. (2008).  
409 Historical bias in biodiversity inventories affects the observed environmental niche of the  
410 species. *Oikos* *117*, 847–858.
- 411 29. Beck, J., Ballesteros-Mejia, L., Nagel, P., and Kitching, I.J. (2013). Online solutions and  
412 the ‘Wallacean shortfall’: what does GBIF contribute to our knowledge of species’  
413 ranges? *Divers. Distrib.* *19*, 1043–1050.
- 414 30. Beck, J., Böller, M., Erhardt, A., and Schwanghart, W. (2014). Spatial bias in the GBIF  
415 database and its effect on modeling species’ geographic distributions. *Ecol. Inform.* *19*,  
416 10–15.
- 417 31. Telfer, M.G., Preston, C.D., and Rothery, P. (2002). A general method for measuring  
418 relative change in range size from biological atlas data. *Biol. Conserv.* *107*, 99–109.

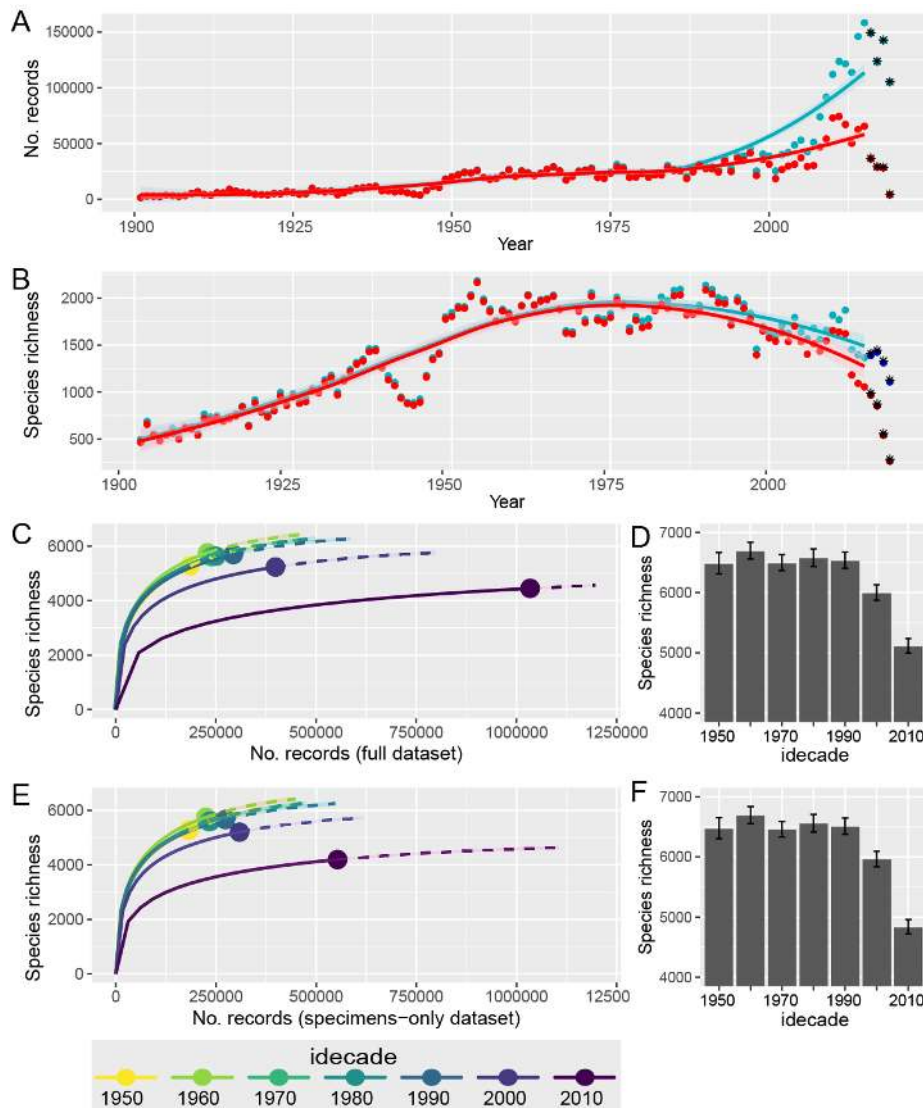


- 419 32. GBIF.org (2020). (07 May 2020) GBIF occurrence download.  
420 <https://doi.org/10.15468/dl.ysjm4x>. <https://doi.org/10.15468/dl.ysjm4x>.
- 421 33. Troudet, J., Vignes-Lebbe, R., Grandcolas, P., and Legendre, F. (2018). The increasing  
422 disconnection of primary biodiversity data from specimens: how does it happen and how  
423 to handle it? *Syst. Biol.* *67*, 1110–1119.
- 424 34. Speed, J.D.M., Bendiksby, M., Finstad, A.G., Hassel, K., Kolstad, A.L., and Prestø, T.  
425 (2018). Contrasting spatial, temporal and environmental patterns in observation and  
426 specimen based species occurrence data. *PLOS ONE* *13*, e0196417.
- 427 35. Gaiji, S., Chavan, V., Ariño, A.H., Otegui, J., Hobern, D., Sood, R., and Robles, E.  
428 (2013). Content assessment of the primary biodiversity data published through GBIF  
429 network: Status, challenges and potentials. *Biodivers. Inform.* *8*.
- 430 36. Chao, A., Gotelli, N.J., Hsieh, T.C., Sander, E.L., Ma, K.H., Colwell, R.K., and Ellison,  
431 A.M. (2014). Rarefaction and extrapolation with Hill numbers: a framework for sampling  
432 and estimation in species diversity studies. *Ecol. Monogr.* *84*, 45–67.
- 433 37. Hsieh, T.C., Ma, K.H., and Chao, A. (2016). iNEXT: an R package for rarefaction and  
434 extrapolation of species diversity (Hill numbers). *Methods Ecol. Evol.* *7*, 1451–1456.
- 435 38. Johnson, B.R., Borowiec, M.L., Chiu, J.C., Lee, E.K., Atallah, J., and Ward, P.S. (2013).  
436 Phylogenomics resolves evolutionary relationships among ants, bees, and wasps. *Curr.*  
437 *Biol.* *23*, 2058–2062.
- 438 39. Outhwaite, C.L., Gregory, R.D., Chandler, R.E., Collen, B., and Isaac, N.J.B. (2020).  
439 Complex long-term biodiversity change among invertebrates, bryophytes and lichens.  
440 *Nat. Ecol. Evol.* *4*, 384–392.
- 441 40. Wilson, E.O. (1971). The plight of taxonomy. *Ecology* *52*, 741–741.
- 442 41. Agnarsson, I., and Kuntner, M. (2007). Taxonomy in a changing world: seeking solutions  
443 for a science in crisis. *Syst. Biol.* *56*, 531–539.
- 444 42. Carvalho, M.R. de, Ebach, M.C., Williams, D.M., Nihei, S.S., Rodrigues, M.T., Grant,  
445 T., Silveira, L.F., Zaher, H., Gill, A.C., Schelly, R.C., et al. (2014). Does counting  
446 species count as taxonomy? On misrepresenting systematics, yet again. *Cladistics* *30*,  
447 322–329.
- 448 43. Pielou, E.C. (1969). *An introduction to mathematical ecology* (Wiley-Interscience).
- 449 44. Lambin, E.F., and Meyfroidt, P. (2011). Global land use change, economic globalization,  
450 and the looming land scarcity. *Proc. Natl. Acad. Sci. U. S. A.* *108*, 3465–3472.
- 451 45. Normandin, É., Vereecken, N.J., Buddle, C.M., and Fournier, V. (2017). Taxonomic and  
452 functional trait diversity of wild bees in different urban settings. *PeerJ* *5*, e3051.
- 453 46. Quintero, C., Morales, C.L., and Aizen, M.A. (2010). Effects of anthropogenic habitat  
454 disturbance on local pollinator diversity and species turnover across a precipitation  
455 gradient. *Biodivers. Conserv.* *19*, 257–274.

- 456 47. Goulson, D., Nicholls, E., Botías, C., and Rotheray, E.L. (2015). Bee declines driven by  
457 combined stress from parasites, pesticides, and lack of flowers. *Science* 347, 1255957.
- 458 48. Aizen, M.A., Smith-Ramírez, C., Morales, C.L., Vieli, L., Sáez, A., Barahona-Segovia,  
459 R.M., Arbetman, M.P., Montalva, J., Garibaldi, L.A., Inouye, D.W., et al. (2019).  
460 Coordinated species importation policies are needed to reduce serious invasions globally:  
461 The case of alien bumblebees in South America. *J. Appl. Ecol.* 56, 100–106.
- 462 49. De Palma, A., Abrahamczyk, S., Aizen, M.A., Albrecht, M., Basset, Y., Bates, A., Blake,  
463 R.J., Boutin, C., Bugter, R., Connop, S., et al. (2016). Predicting bee community  
464 responses to land-use changes: Effects of geographic and taxonomic biases. *Sci. Rep.* 6,  
465 31153.
- 466 50. Bartomeus, I., Ascher, J.S., Gibbs, J., Danforth, B.N., Wagner, D.L., Hedtke, S.M., and  
467 Winfree, R. (2013). Historical changes in northeastern US bee pollinators related to  
468 shared ecological traits. *Proc. Natl. Acad. Sci.* 110, 4656–4660.
- 469 51. Geslin, B., and Morales, C.L. (2015). New records reveal rapid geographic expansion of  
470 *Bombus terrestris* Linnaeus, 1758 (Hymenoptera: Apidae), an invasive species in  
471 Argentina. *Check List* 11, 1620.
- 472 52. Herrera, C.M. (2019). Gradual replacement of wild bees by honeybees in flowers of the  
473 Mediterranean Basin over the last 50 years. *bioRxiv*, 828160.
- 474 53. Aizen, M.A., and Harder, L.D. (2009). The global stock of domesticated honey bees Is  
475 growing slower than agricultural demand for pollination. *Curr. Biol.* 19, 915–918.
- 476 54. García-Roselló, E., Guisande, C., Manjarrés-Hernández, A., González-Dacosta, J., Heine,  
477 J., Pelayo-Villamil, P., González-Vilas, L., Vari, R.P., Vaamonde, A., Granado-Lorencio,  
478 C., et al. (2015). Can we derive macroecological patterns from primary Global  
479 Biodiversity Information Facility data? *Glob. Ecol. Biogeogr.* 24, 335–347.
- 480 55. Lobo, J.M., Hortal, J., Yela, J.L., Millán, A., Sánchez-Fernández, D., García-Roselló, E.,  
481 González-Dacosta, J., Heine, J., González-Vilas, L., and Guisande, C. (2018). KnowBR:  
482 An application to map the geographical variation of survey effort and identify well-  
483 surveyed areas from biodiversity databases. *Ecol. Indic.* 91, 241–248.
- 484 56. Marlin, J.C., and LaBerge, W.E. (2001). The native bee fauna of Carlinville, Illinois,  
485 revisited after 75 Years: a case for persistence. *Conserv. Ecol.* 5.
- 486 57. Koh, I., Lonsdorf, E.V., Williams, N.M., Brittain, C., Isaacs, R., Gibbs, J., and Ricketts,  
487 T.H. (2016). Modeling the status, trends, and impacts of wild bee abundance in the  
488 United States. *Proc. Natl. Acad. Sci.* 113, 140.
- 489 58. Frankie, G.W., Rizzardi, M., Vinson, S.B., and Griswold, T.L. (2009). Decline in bee  
490 diversity and abundance from 1972–2004 on a flowering leguminous tree, *Andira inermis*  
491 in Costa Rica at the interface of disturbed dry forest and the urban environment. *J. Kans.*  
492 *Entomol. Soc.* 82, 1–20.
- 493 59. Nieto, A., Roberts, S.P., Kemp, J., Rasmont, P., Kuhlmann, M., García Criado, M.,  
494 Biesmeijer, J.C., Bogusch, P., Dathe, H.H., De la Rúa, P., et al. (2014). European red list  
495 of bees (Publication Office of the European Union).

- 496 60. Gardner, J.D., and Spivak, M. (2014). A survey and historical comparison of the  
497 Megachilidae (Hymenoptera: Apoidea) of Itasca State Park, Minnesota. *Ann. Entomol.*  
498 *Soc. Am.* *107*, 983–993.
- 499 61. Nemésio, A. (2013). Are orchid bees at risk? First comparative survey suggests declining  
500 populations of forest-dependent species. *Braz. J. Biol.* *73*, 367–374.
- 501 62. Vega-Hildago, Á., Añino, Y., Krichilsky, E., Smith, A.R., Santos-Murgas, A., and  
502 Gálvez, D. (2020). Decline of native bees (Apidae: Euglossa) in a tropical forest of  
503 Panama. *Apidologie*.
- 504 63. Potts, S.G., Ngo, H.T., Biesmeijer, J.C., Breeze, T.D., Dicks, L.V., Garibaldi, L.A., Hill,  
505 R., Settele, J., and Vanbergen, A. (2016). The assessment report of the Intergovernmental  
506 Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators,  
507 pollination and food production (Secretariat of the Intergovernmental Science-Policy  
508 Platform on Biodiversity and Ecosystem Services).
- 509 64. R Development Core Team (2011). R: A Language and Environment for Statistical  
510 Computing.
- 511 65. Wickham, H., and Henry, L. (2020). *tidyr*: Tidy messy data.
- 512 66. Wickham, H., François, R., Henry, L., and Müller, K. (2020). *dplyr*: A grammar of data  
513 manipulation.
- 514 67. Dowle, M., and Srinivasan, A. (2019). *data.table*: Extension of `data.frame`.
- 515 68. Wickham, H. (2016). *ggplot2*: Elegant graphics for data analysis (Springer-Verlag).
- 516 69. Oksanen, J., Blanchet, F.G., Friendly, M., Kindt, R., Legendre, P., McGlenn, D., Minchin,  
517 P.R., O’Hara, R.B., Simpson, G.L., Solymos, P., et al. (2019). *vegan*: Community  
518 ecology package.

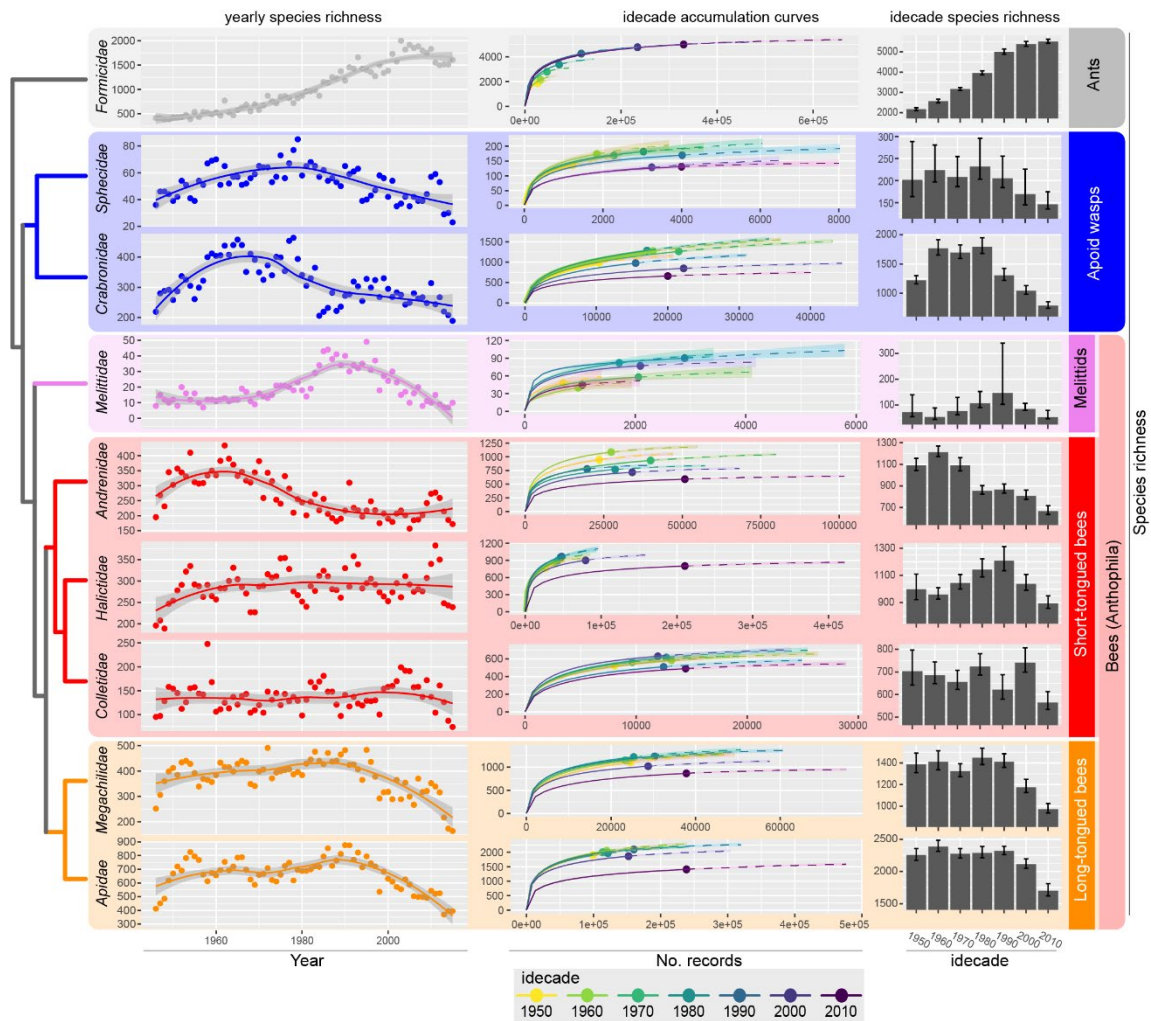
519 Figures and figure legends



520

521 **Fig. 1.** Despite increasing number of specimen records, the number of worldwide recorded  
522 bee species is sharply decreasing. (A) Number of worldwide GBIF records of Anthophila  
523 (bees) occurrences per year in the full (blue) and specimens-only (red) datasets. The curves  
524 represent loess fits with a smoothing parameter  $\alpha = 0.75$  up to 2015. The four most recent  
525 years (2016-2019, labeled with \*) were excluded from further analysis. (B) Number of bee  
526 species found each year in the full (blue) and specimens-only (red) datasets. (C) Chao's  
527 interpolation/extrapolation (iNEXT) curves based on the full dataset. Data were binned into  
528 ten-year periods (*idecades*) from 1946 to 2015. The symbols show actual number of

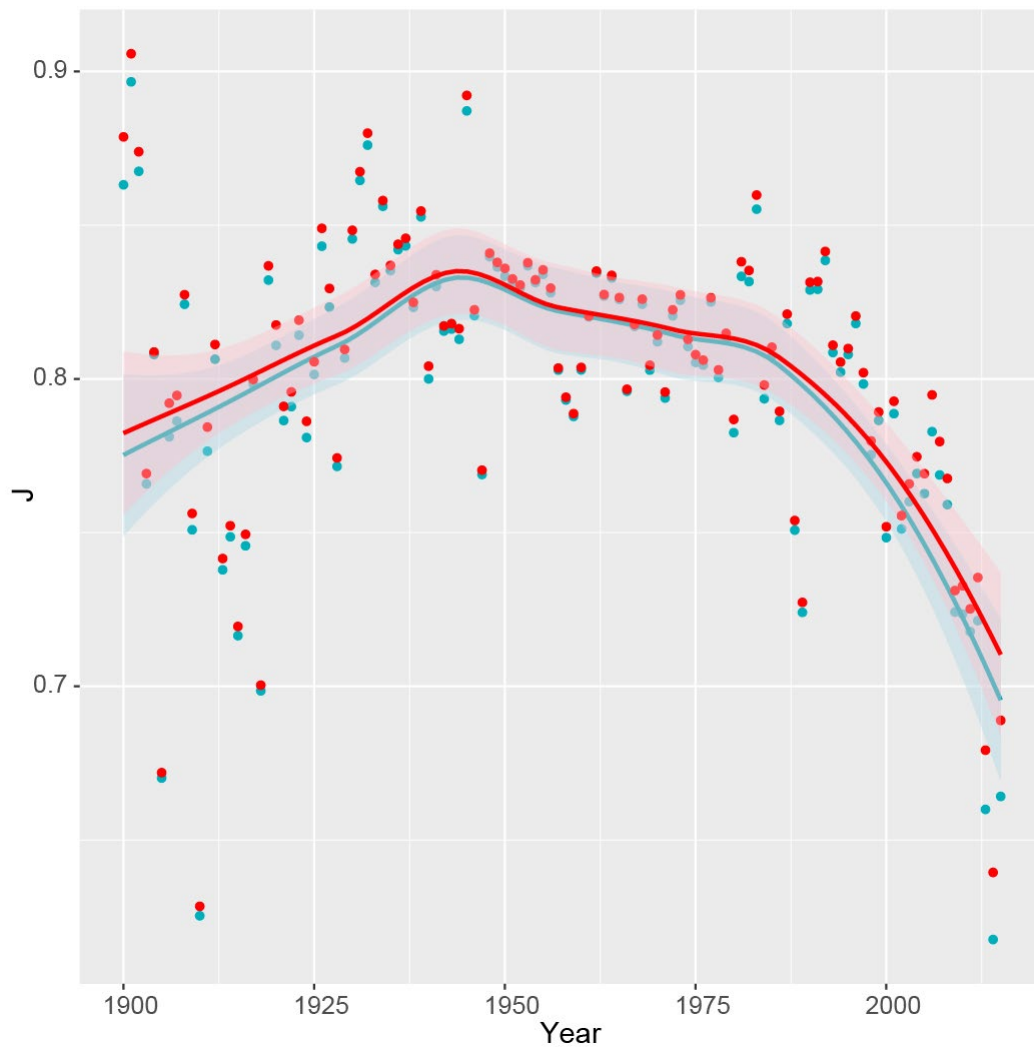
529 specimen records and separate interpolated (left, full line) from extrapolated (right, dashed  
530 line) regions of each curve. (D) Values of the asymptotic richness estimator by idecade (see  
531 main text) for the full dataset (error bars mark upper and lower 95% confidence intervals).  
532 (E) Chao's interpolation/extrapolation (iNEXT) curves based on the specimens-only dataset.  
533 (F) Values of the asymptotic richness estimator by idecade for the specimens-only dataset.  
534



535

536 **Fig. 2.** Decline patterns in worldwide records of bees are generalized but phylogenetically  
 537 structured. Phylogenetic relationships among each of the six families of bees (Anthophila,  
 538 lower six rows), two related families of non-flower associated apoid wasps (2nd and 3rd  
 539 rows), and the less related, highly specious ant family (top row). The left row shows number  
 540 of species per year in GBIF records from 1946 to 2015 based on the preserved specimen  
 541 dataset – the curves represent loess fits with a smoothing parameter  $\alpha = 0.75$ ; the middle row  
 542 shows Chao's interpolation/extrapolation curves based on GBIF records, grouped by idecade  
 543 for the period 1946-2015; the right row show the asymptotic estimates of richness by idecade  
 544 for the same period (error bars mark upper and lower 95% confidence intervals).

545



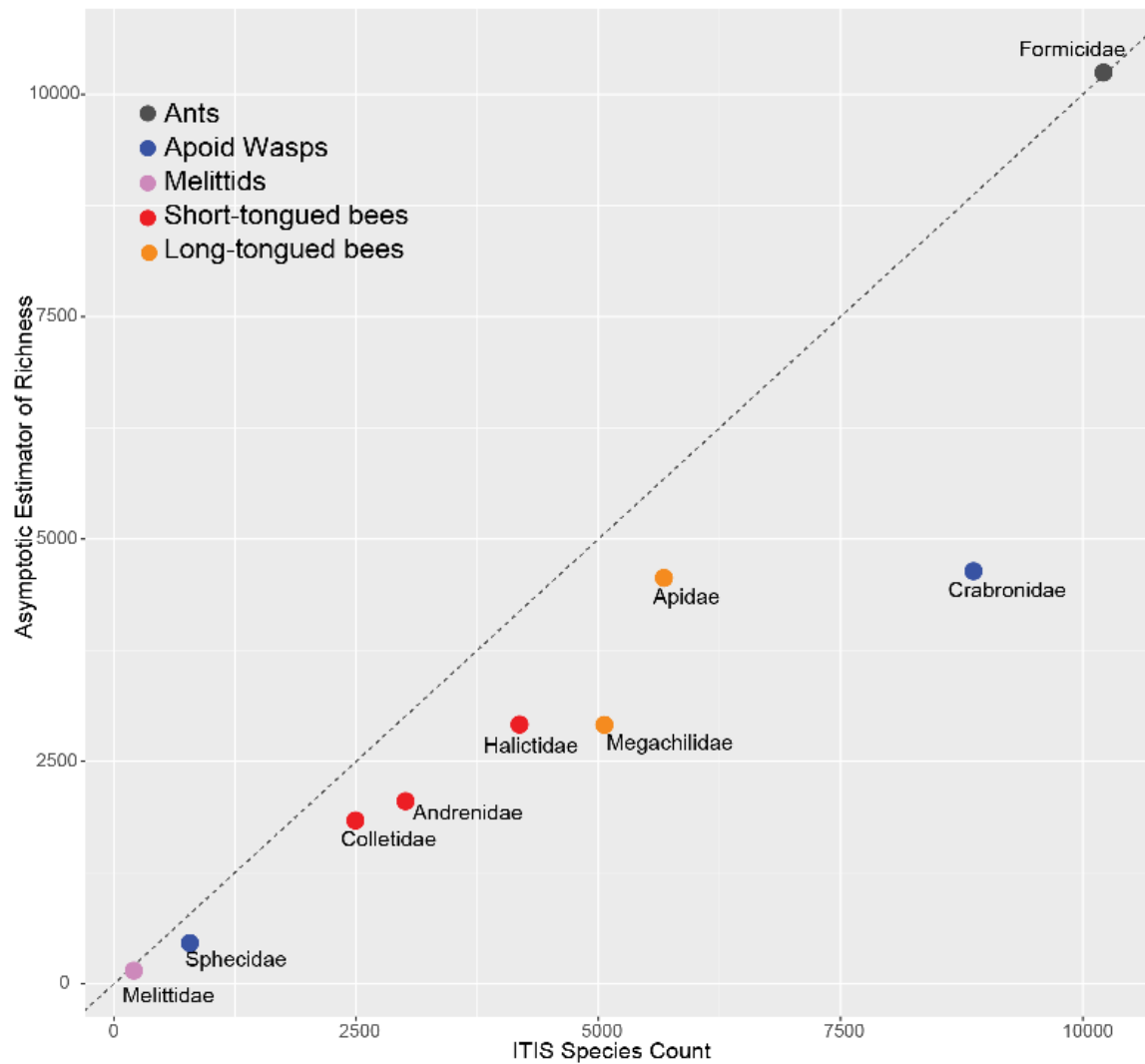
546

547 **Fig. 3.** Overall representation of worldwide bee species based on global records is becoming  
548 increasingly uneven over time. Estimate of Pielou's index of sample evenness per year in the  
549 full (blue) and specimens-only (red) datasets from 1900 to 2016. The lines show respective  
550 loess fit curves with a smoothing parameter  $\alpha = 0.75$ .

551

552

553 **Supplementary Figures**

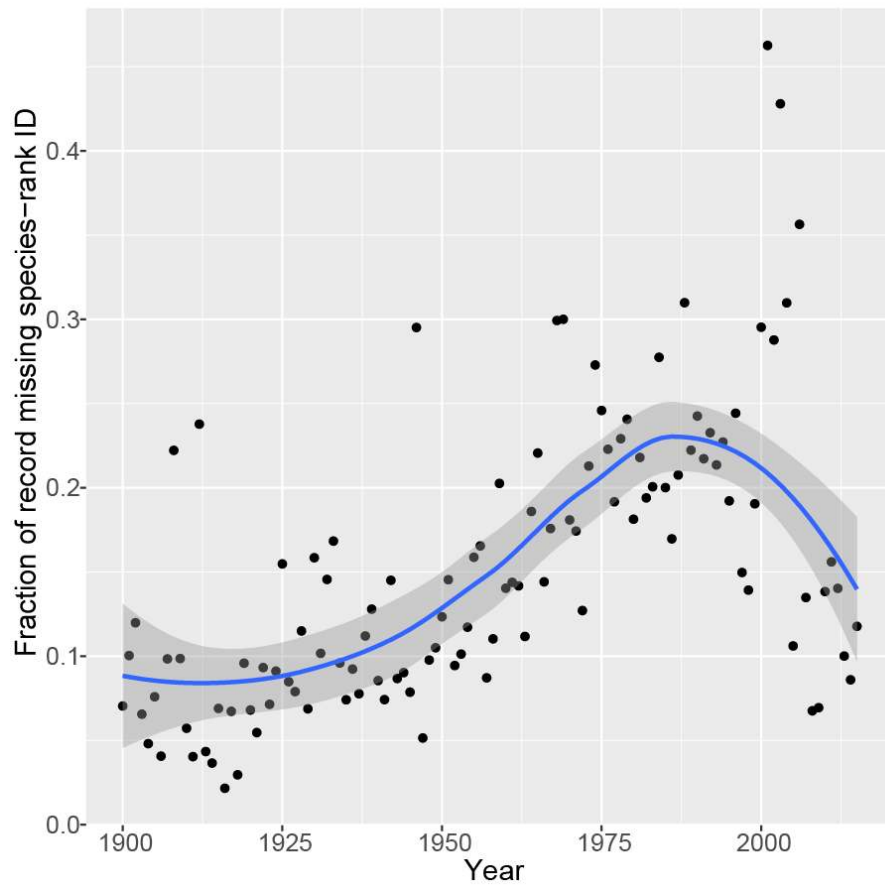


554

555 **Figure S1:** While often underestimating the known richness of each family, Chao's  
556 asymptotic estimators of species richness based on all-times GBIF global records of  
557 preserved specimens show a linear correlation with actual species diversity. The dotted line  
558 shows the identity diagonal. ITIS stands for Integrated Taxonomic Information System  
559 ([www.itis.gov](http://www.itis.gov)).

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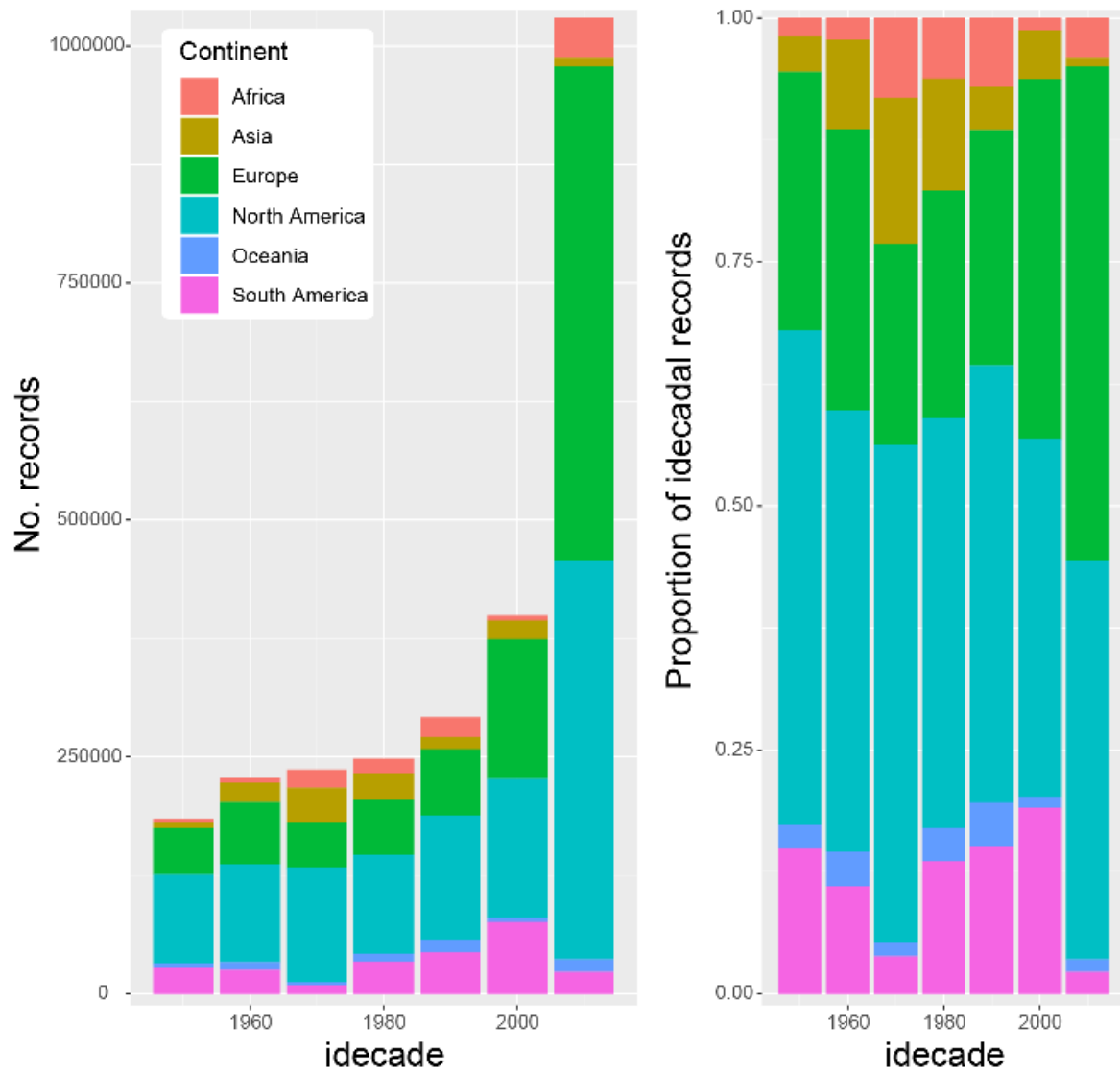




561

562 **Figure S2:** Fraction of the dataset records that lack a species ID. Points show the proportion  
563 of records unidentified at the species level in a given year, relative to the total number of  
564 records for that year, and the curve shows a loess-smoothed trend line with a smoothing  
565 parameter  $\alpha = 0.75$ .

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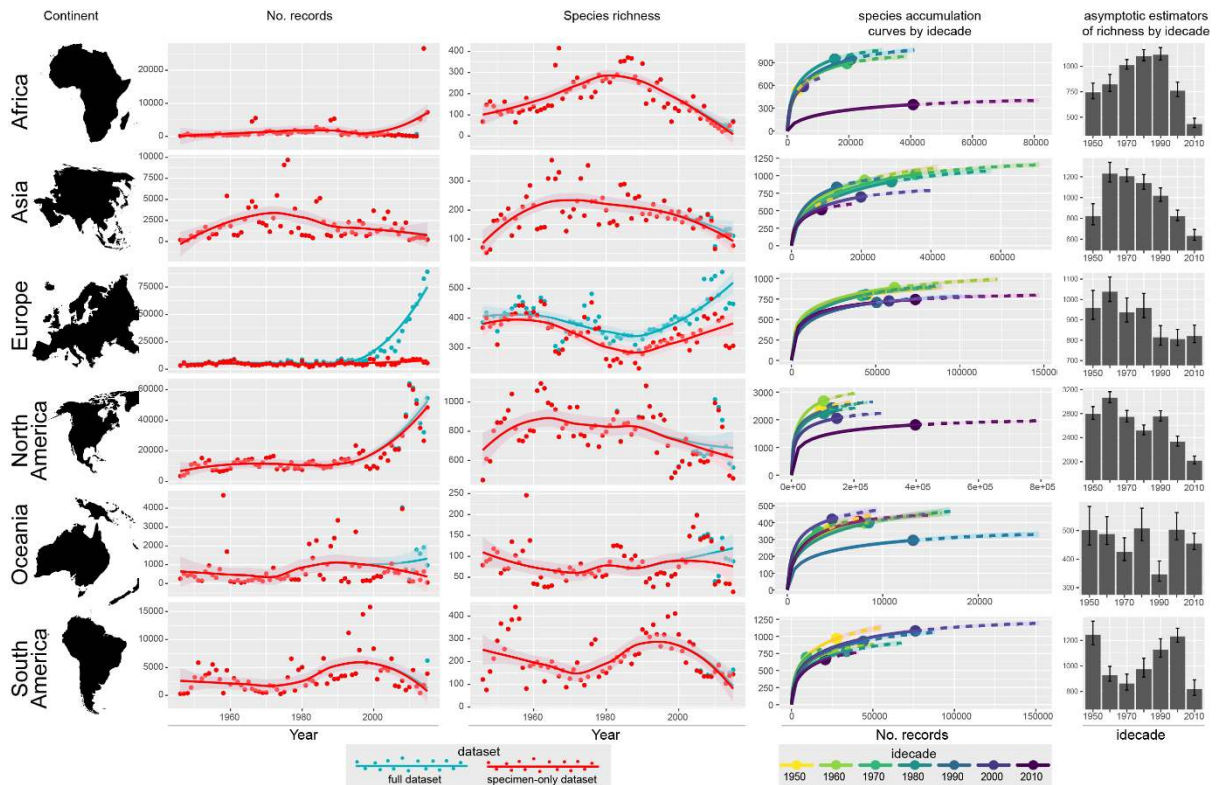
568 **Figure S3:** Contribution by decade of each continent (Antarctica excluded) to the full bee

569 record dataset. (A) Absolute number of GBIF records with a species ID for each continent,

570 grouped by decade since the 1950's. (B) Relative contribution of each continent to

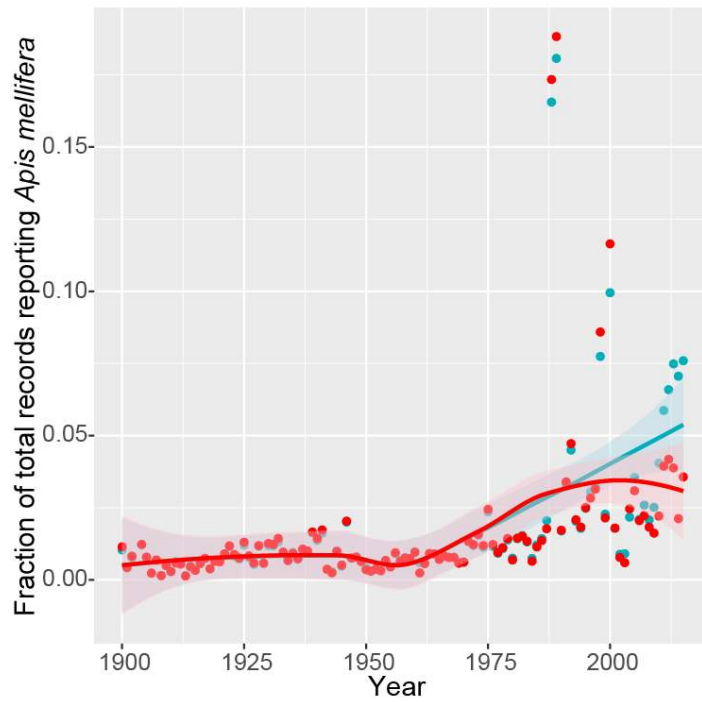
571 worldwide idecadal GBIF records with a species ID.

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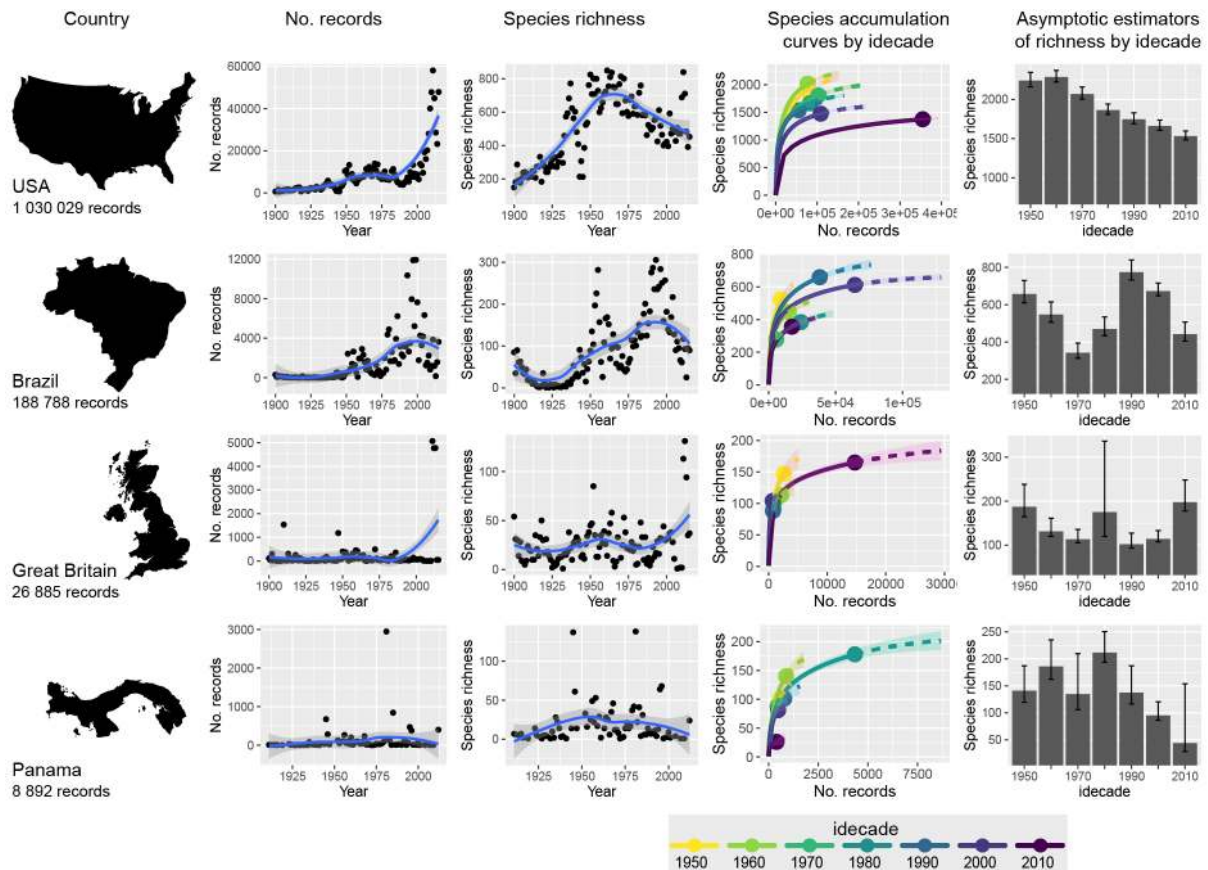
573

574 **Figure S4:** Trends shown in GBIF records for each continent. The left two rows of plots  
 575 show number of yearly bee records and species in GBIF (blue: full dataset; red: specims-  
 576 only dataset); the right two rows show Chao's interpolation/extrapolation curves based on the  
 577 specimens-only dataset grouped every ten years (idecades) for the period 1946-2015 and bar  
 578 plots of the asymptotic estimates of richness by idecade for the same period (error bars mark  
 579 upper and lower 95% confidence intervals).



580

581 **Figure S5:** Increase in the fraction of global records of preserved specimens at GBIF  
582 represented by the honeybee *Apis mellifera* since the year 1900 (blue: full dataset; red:  
583 specimens-only dataset). Points represent yearly proportion of total records belonging to *A.*  
584 *mellifera*; lines show respective loess fit curves with a smoothing parameter  $\alpha = 0.75$ .



585

586 Figure S6: Reliability of trends shown in records of GBIF preserved specimens for specific  
587 countries increases with the number of records. The left two rows of plots show number of  
588 yearly bee records and species in GBIF for each country – fitted trends are loess curves with  
589 a smoothing parameter  $\alpha = 0.75$ ; the right two rows show Chao's interpolation/extrapolation  
590 curves based on records grouped every ten years (idecades) for the period 1946-2015 and bar  
591 plots of the asymptotic estimates of richness by idecade for the same period (error bars mark  
592 upper and lower 95% confidence intervals).

593