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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 biomass¹. 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 services²⁻⁵. Among affected ecosystem services is plant
31 pollination: insects are the main vectors for pollen transfer of most wild and crop flowering
32 plant species⁶⁻¹⁰. Bees (Hymenoptera: Apoidea: Anthophila), a lineage that includes about
33 20,000 described species, are the most important group of insect pollinators^{11,12}. Wild bee
34 species are not only key to sexual reproduction of hundreds of thousands of wild plant
35 species⁷, but also to the yield of about 85% of all cultivated crops^{6,13,10}. 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^{12,14-17}. 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 uses¹⁸⁻²⁰. 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^{4,12,21,22}.

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)²³. 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”²³.
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^{24–27}. Although usage of GBIF data has
52 been strongly criticized due to its inherent biases^{21,24,28–30}, 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 uncertainty³¹. 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 record³² (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 popular³³. Because the preserved specimen records are likely
71 to represent the most taxonomically traceable source of information within the GBIF
72 dataset^{33,34}, 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)¹¹.

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 entry³⁵, 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 ± 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^{36,37} 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)³⁸. 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 dataset³⁹. 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^{40–42}. Under such scenario, we would expect
136 the fraction of records unidentified to the species level – a reasonable proxy for lack of
137 expertise³³ – 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 dataset³³, 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 records³⁵, 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 evenness⁴³) 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 transformation⁴⁴. Bees thrive in
184 heterogeneous habitats, even those driven by man^{18,45}, 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 1990s⁴⁴. This has led not only to higher
187 habitat homogeneity, which can relate by itself to more impoverished and spatially
188 homogeneous bee assemblages^{18,46}, 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 health⁴⁷.
190 Effects of climate change on shrinking bee geographical ranges have been also documented
191 in Europe and North America⁴. 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*⁴⁸. 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^{21,49,50}.

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 America⁵¹ or the western honeybee *Apis mellifera* in the Mediterranean⁵². 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 globally⁵³.
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 crops¹³.

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^{21,27,35,54,55}. 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^{14,16,17,39,56–61}. 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 decline⁵⁰.

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^{56,57,60} (with over 1
235 million records), a decline in Brazil⁶¹ 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^{14,16,17,62} (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 ⁶³ 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 ^{4,5,10,12}, 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) 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 datasets³². 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 results³⁸.

283 Analyses

284 All datasets were analyzed using a customized script written and executed within the R
285 computing environment⁶⁴. 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`⁶⁵, `dplyr`⁶⁶ and `data.table`⁶⁷
288 packages.

289 After removing records without “year” data, yearly counts of records and species were
290 plotted using `ggplot2`⁶⁸. 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` package³⁷ to estimate rarefaction-based
299 interpolation/extrapolation (`iNEXT`) curves and Chao1 asymptotic estimators of species
300 richness³⁶. 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).

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 year³³. 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 index⁴³, $J = \sum p_i \ln(p_i) / \log(S)$ 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`⁶⁹.
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>.

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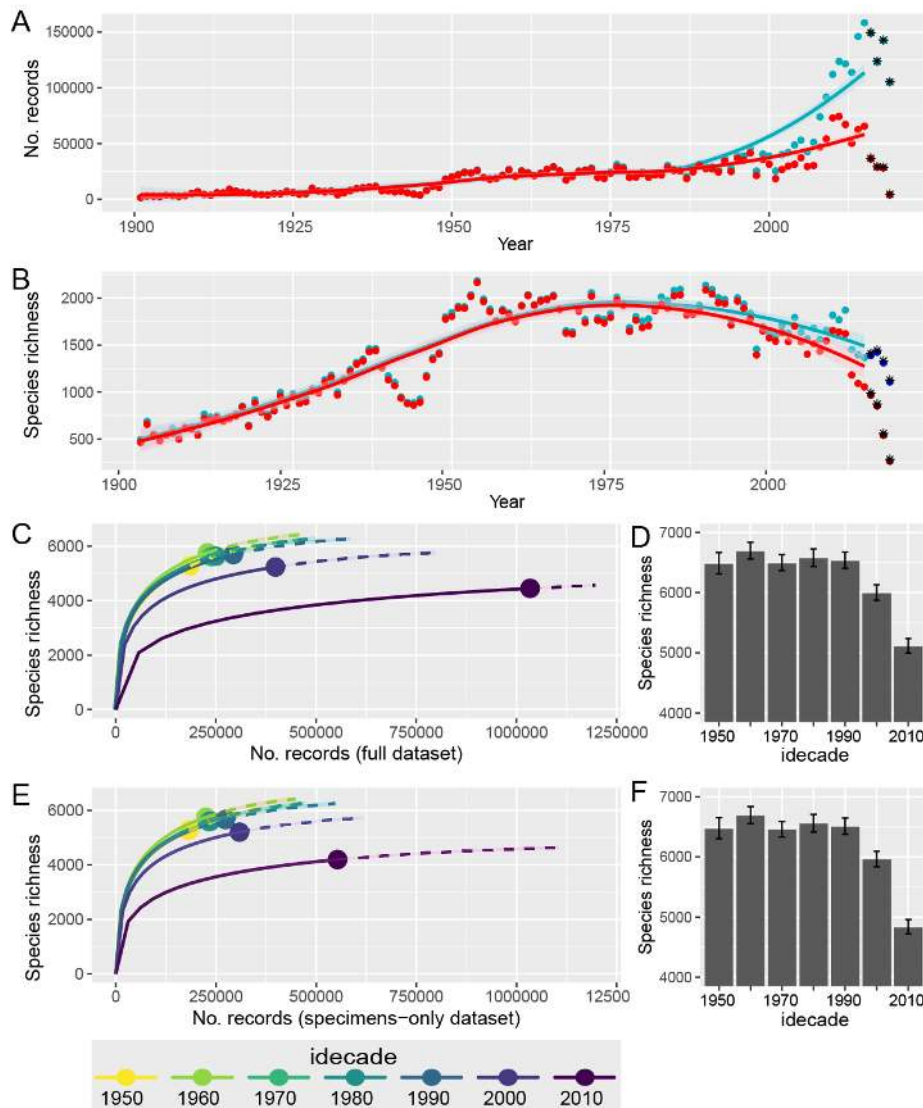
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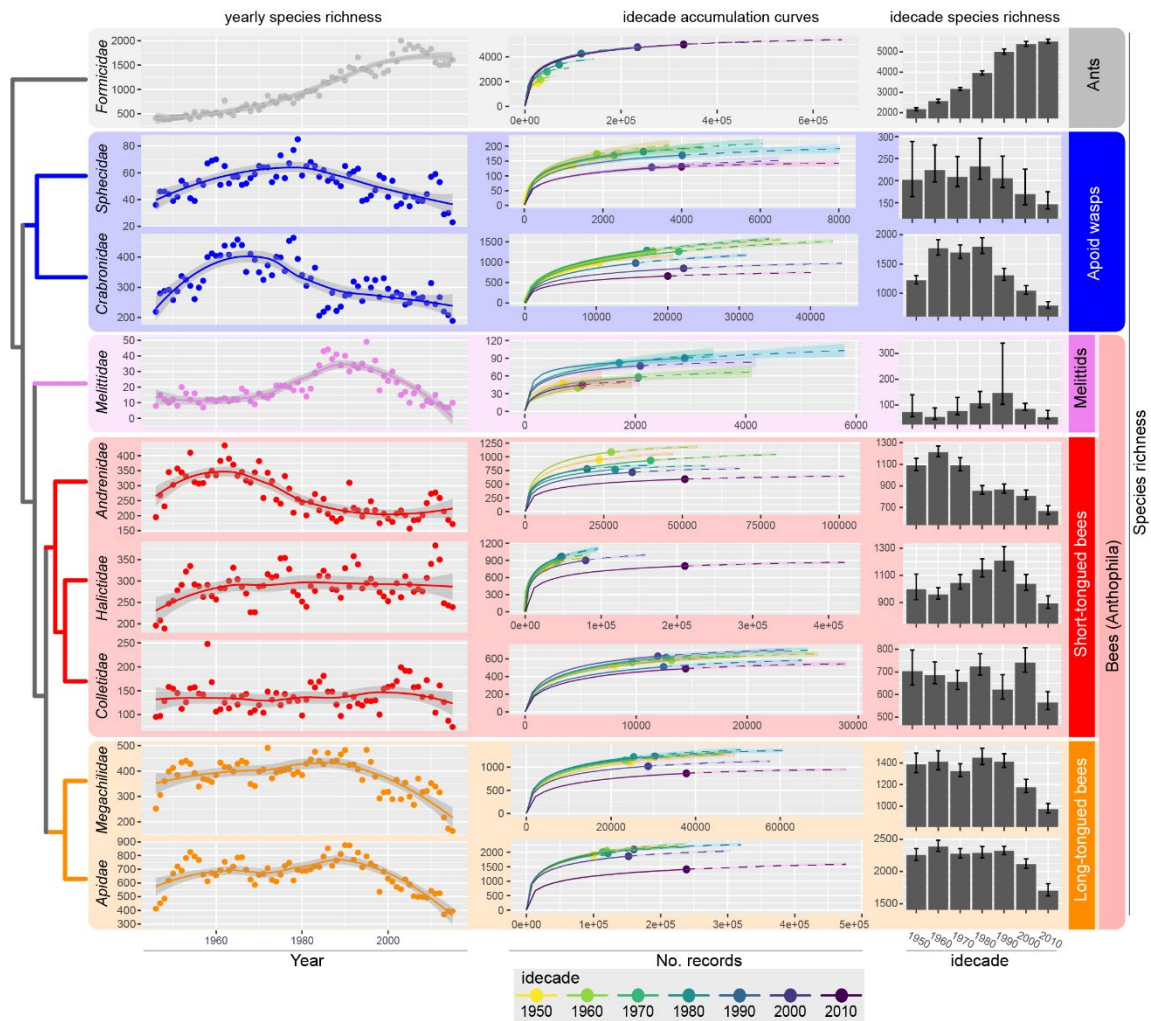
519 Figures and figure legends



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

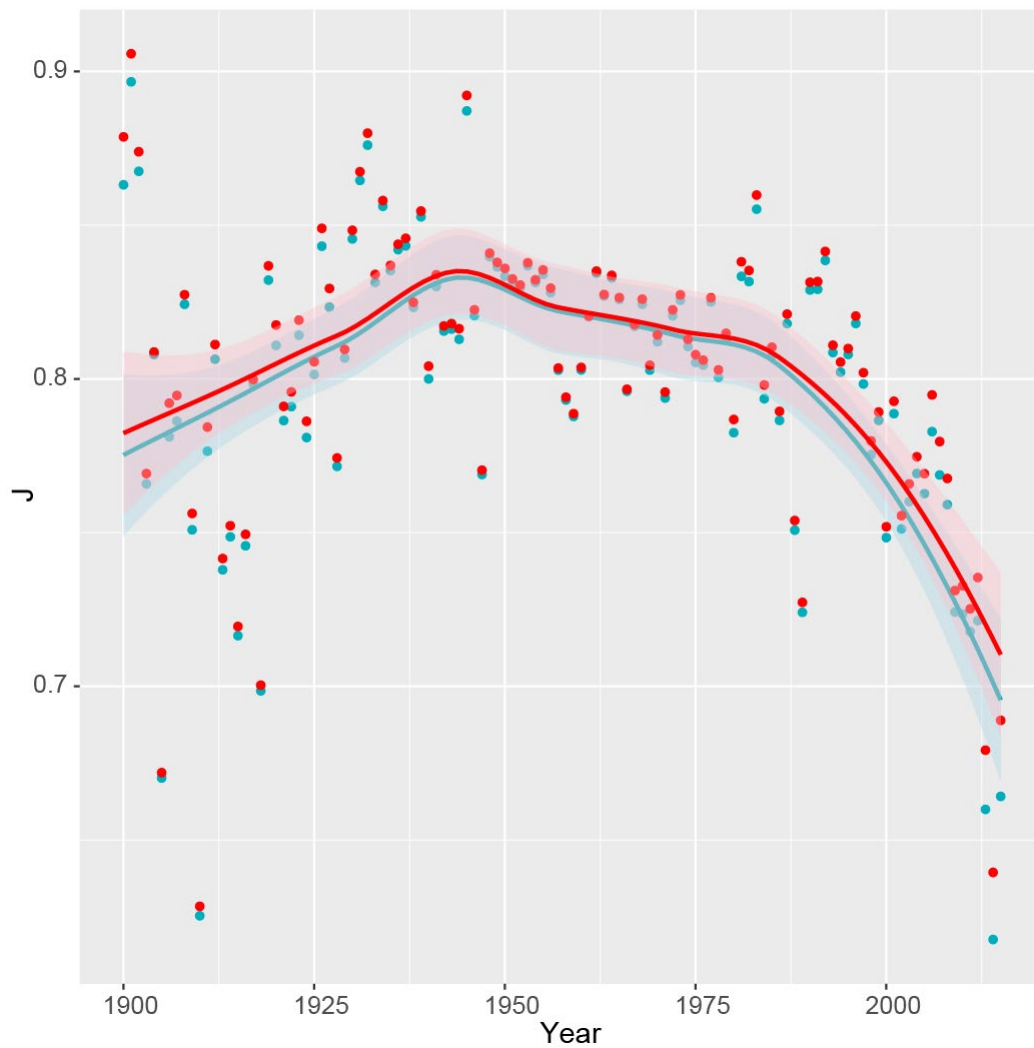
529 specimen records and separate interpolated (left, full line) from extrapolated (right, dashed
530 line) regions of each curve. (D) Values of the asymptotic richness estimator by idecade (see
531 main text) for the full dataset (error bars mark upper and lower 95% confidence intervals).
532 (E) Chao's 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).

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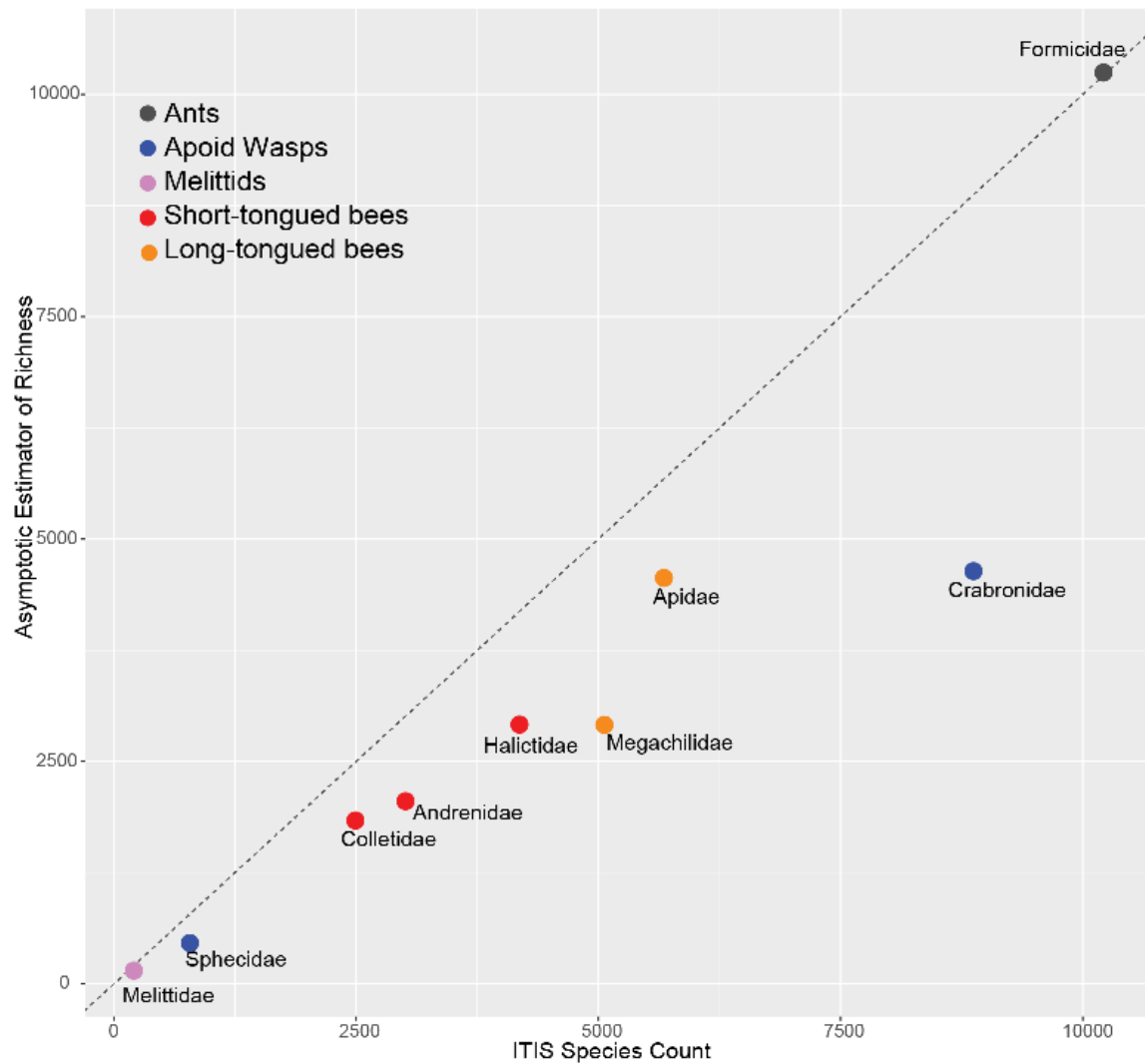
546

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 $\alpha = 0.75$.

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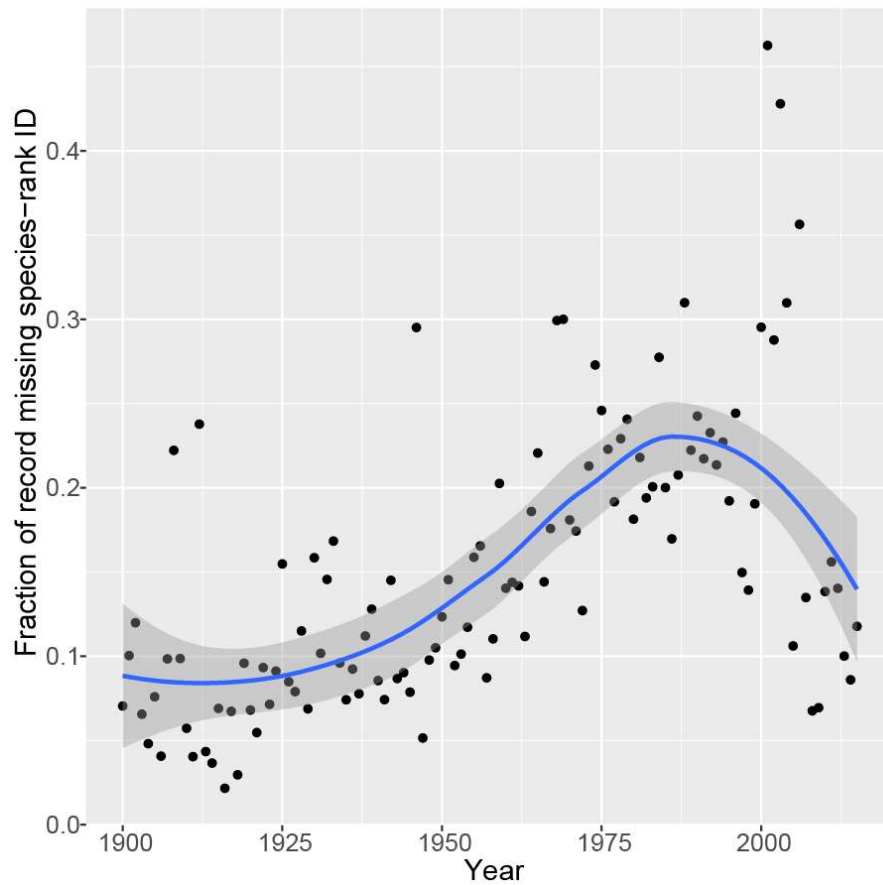
553 Supplementary Figures



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).

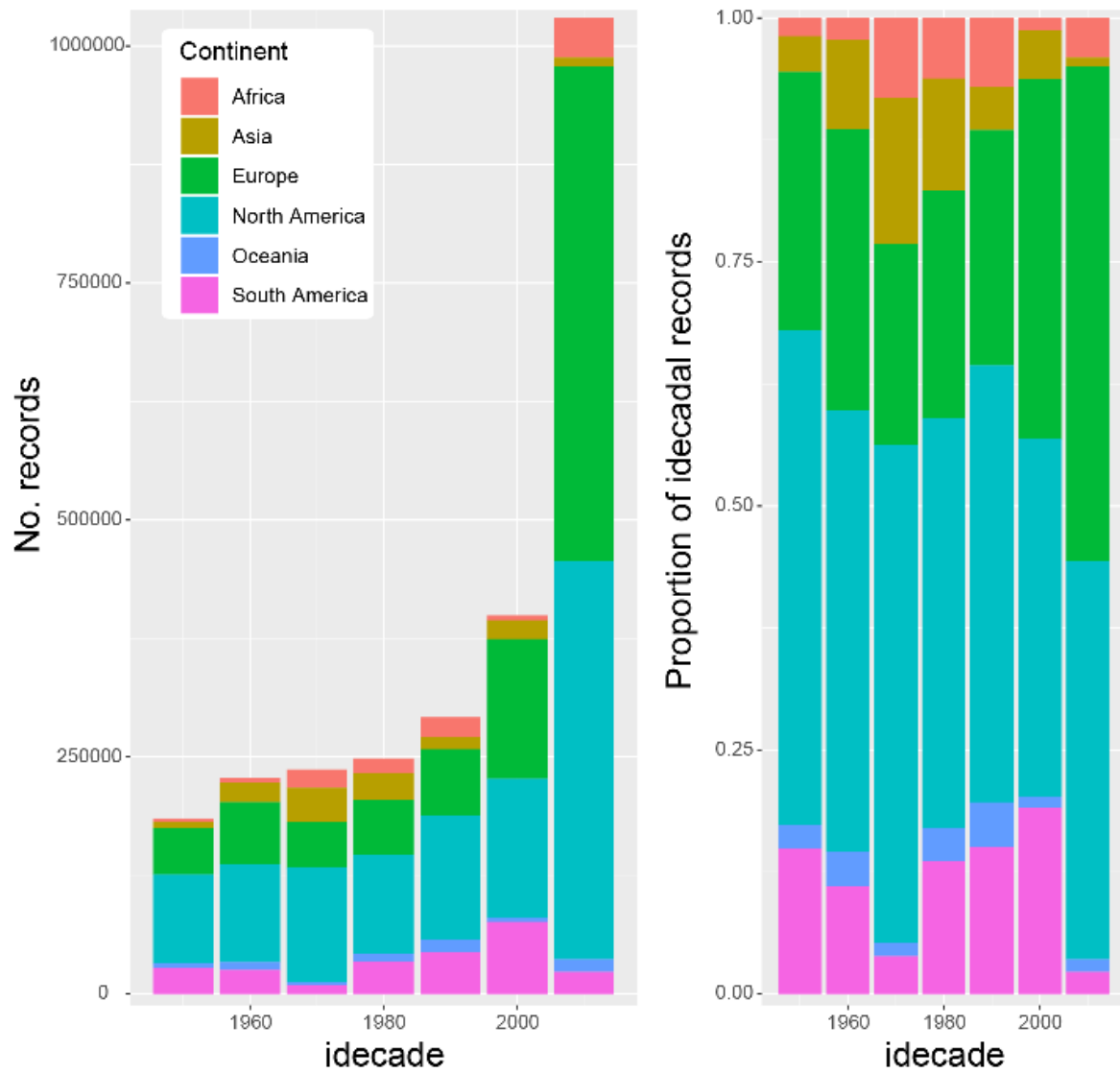
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561

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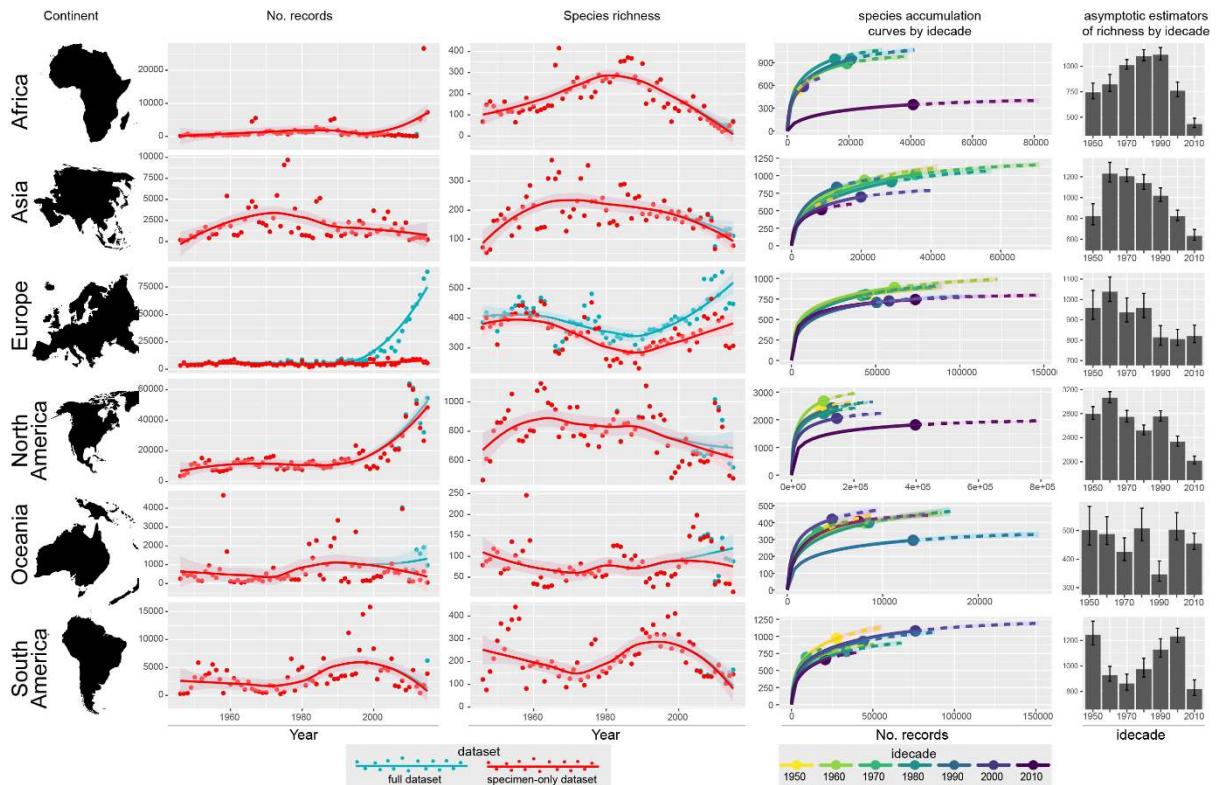
568 **Figure S3:** Contribution by idecade of each continent (Antarctica excluded) to the full bee

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

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

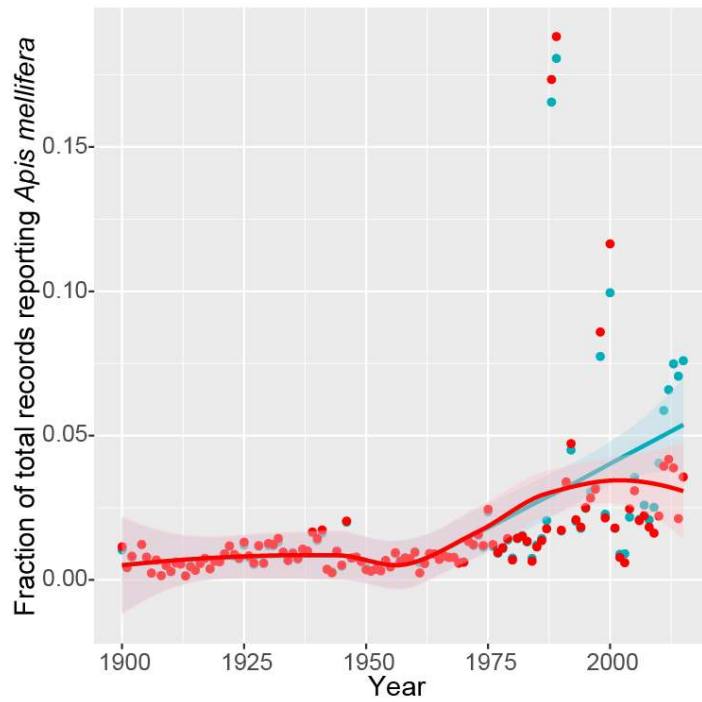
571 worldwide idecadal GBIF records with a species ID.

572



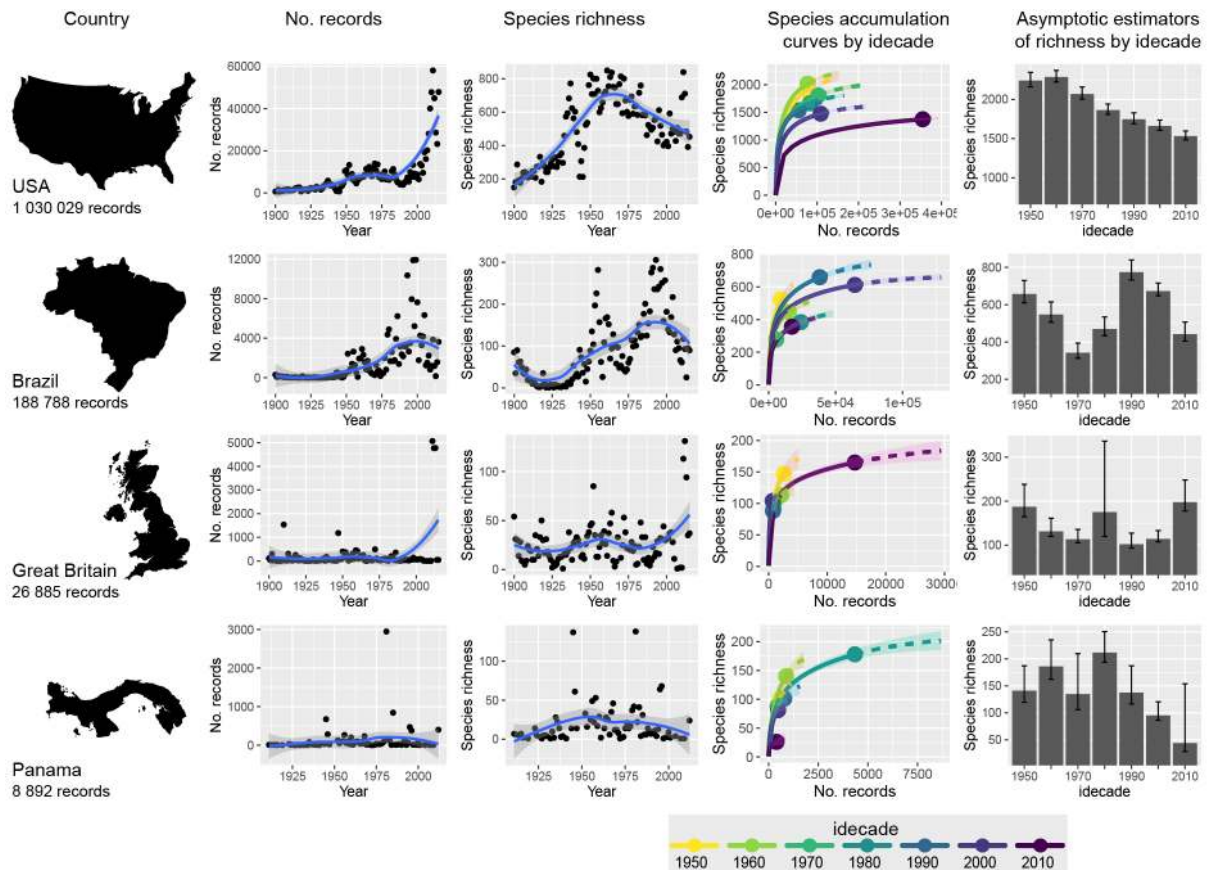
573

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 specims-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