

Is the insect apocalypse upon us? How to find out

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1 **KEYWORDS: Insect declines, biodiversity crisis, biomass, monitoring, entomology**

2 **ABSTRACT**

3 In recent decades, entomologists have documented alarming declines in occurrence, taxonomic
4 richness, and geographic range of insects around the world. Additionally, some recent studies
5 have reported that insect abundance and biomass, often of common species, are rapidly
6 declining, which has led some to dub the phenomenon an “Insect Apocalypse”. Recent reports
7 are sufficiently robust to justify immediate actions to protect insect biodiversity worldwide. We
8 caution, however, that we do not yet have the data to assess large-scale spatial patterns in the
9 severity of insect trends. Most documented collapses are from geographically restricted studies
10 and, alone, do not allow us to draw conclusions about insect declines on continental or global
11 scales, especially with regards to future projections of total insect biomass, abundance, and
12 extinction. There are many challenges to understanding insect declines: only a small fraction of
13 insect species have had any substantial population monitoring, millions of species remain
14 unstudied, and most of the long-term population data for insects come from human-dominated
15 landscapes in western and northern Europe. But there are still concrete steps we can take to
16 improve our understanding of potential declines. Here, we review the challenges scientists face
17 in documenting insect population and diversity trends, including communicating their findings,
18 and recommend research approaches needed to address these challenges.

19

20

21 **INTRODUCTION**

22 Declines of insect abundance, biomass, and range are being reported worldwide, from the arctic
23 to the tropics, across insect orders, and from a spectrum of ecological guilds (e.g., Fox 2013,
24 Hallmann et al. 2017, Loboda et al. 2018, Lister & Garcia 2018, and reviews by Sanchez-Bayo
25 & Wyckhuys 2019, Wagner 2017, 2019b). Though fewer than 100 insect species are documented
26 as extinct (IUCN 2019), more recent extinctions have assuredly occurred on islands and
27 deforested tropical regions. One important aspect of many recent studies is the decline of
28 formerly common species, not just rare taxa (Conrad et al. 2006, Van Dyck et al. 2009, Fox et al.
29 2015), with the realization that such losses likely come with changes to ecosystem connectivity
30 and function (Gaston & Fuller 2007, Dirzo et al. 2014). Some studies have reported dramatic
31 declines: Hallmann et al. (2017) found a 75% decrease in flying-insect biomass over a three-
32 decade period from 63 preserves in northwestern Germany. Declines are also reported from
33 many western and northern European countries, representing a suite of different insect orders
34 (e.g., Conrad et al. 2006, Shortall et al. 2009, Schuch et al. 2012, Van Strien et al. 2019,
35 Hallmann et al. 2019; see also reviews by Sanchez-Bayo & Wyckhuys 2019, Wagner 2017,
36 2019b). Two of the studies that drew worldwide media attention (Lister & Garcia 2018, Sanchez-
37 Bayo & Wyckhuys 2019) not only ignited discussion of insect declines among scientists and lay
38 people alike, but also received substantial criticism—their methods, results, and extrapolations
39 are much contested (Komonen et al. 2019, Mupepele et al. 2019, Simmons et al. 2019, Thomas

40 et al. 2019, Wagner 2019a, Willig et al. 2019; see Saunders 2019 for a review of the datasets
41 informing this discussion).

42 Many insect taxa are unequivocally in decline across many regions of the planet, and we know
43 enough to take conservation action (Basset & Lamarre 2019, Janzen & Hallwachs 2019, Forister
44 et al. 2019). However, important aspects of the insect decline phenomenon remain largely
45 unknown. Most importantly, we need to understand how quickly populations are trending
46 upward or downward. Annual declines of 1-2% for species in densely human-populated areas are
47 unfortunate but relatively unsurprising, while >3% annual declines in areas far removed from
48 most human activities would be stunning. Failure to make such distinctions can lead to untenable
49 extrapolations, e.g., that 40% of the world's insects will be extinct in a few decades, as posited in
50 Sanchez-Bayo & Wyckhuys (2019). Next, are the rates of population change of insects roughly
51 on par with those of plants, birds, and mammals, as found generally by Dirzo et al. (2014)? If so,
52 then the apocalypse is one suffered by all species. An answer to this question could also point to
53 the drivers. If insects are declining at rates appreciably faster than vertebrates and plants in the
54 same regions, it may be prudent to focus research on stressors like that especially impact insects
55 (e.g., insecticide use), or it may be an indication of what is to come for other taxa. Finally, with
56 so few data from outside Europe, it is difficult to gauge how widespread the phenomenon is,
57 especially in the tropics (Basset & Lamarre 2019, Janzen & Hallwachs 2019), where more 85%
58 of all insect species occur (Stork 2018), and in temperate regions of the southern hemisphere.
59 Many studies show that there are winners as well as losers in recent insect biodiversity change
60 (Brooks et al. 2012; Boyes et al 2019) and that net loss of insect abundance/biomass has not been
61 reported from all study locations (Shortall et al. 2009; Valtonen et al. 2017; Herrera 2019).
62 Overall, although progress is being made, attempts to answer questions regarding the magnitude,
63 and in many cases even the existence, of insect declines face many challenges. Here, we outline
64 these challenges, but focus on research recommendations, from increased monitoring, to
65 community science and pleas for more rigorous methodologies and meta-analyses. We also
66 touch on matters of unexplored data streams, reporting bias, and funding needs.

67

68 **CHALLENGES**

69 *The Insect Side*

70 The greatest challenge to studying insect population trends, be it declines in diversity,
71 abundance, range, occurrence or other metrics, is the paucity of baseline data (Cardoso et al.
72 2011, Eisenhauer et al. 2019, Wagner 2017, 2019b, Cardoso & Leather 2019): we lack robust
73 records of past insect populations and diversity. Traditionally, entomological collections have
74 been focused on documenting species diversity rather than abundance, often for a narrow range
75 of taxa, and as such, yield little information about population numbers and survey effort,
76 rendering many historical collection events essentially non-replicable. The geographic
77 distribution of haphazardly distributed baseline data is also a problem – those data that do exist
78 come mostly from “anthroposcapes,” or human-altered ecosystems. While these data are useful
79 for evaluating direct human effects on insects, they are not useful for drawing conclusions about

80 insect populations in areas with modest human activity and wildlands (Wagner 2019b). The
81 temporal distribution of available baseline datasets is also an issue. Many of the baseline data
82 that do exist post-date the onset of purported drivers of insect declines, for example, the UK
83 Butterfly Monitoring Scheme, a flagship long-term insect monitoring effort, began in 1976, after
84 agricultural intensification was well underway (Pollard & Yates 1994).

85 Additionally, large natural fluctuations in invertebrate populations from year to year, and
86 sometimes even within a single year, make drawing conclusions from demographic studies of
87 insects challenging (Fox et al. 2019). This large interannual population variation is dependent on
88 many intrinsic and extrinsic factors (Hanski 1990), including myriad natural enemies (Turchin et
89 al. 1999) and the vagaries of weather (Wolda 1983, Nelson et al. 2013). This is especially
90 problematic for the interpretation of “snapshot” surveys where population data from one period
91 are compared with population data from another period, without data from intervening years
92 (Habel et al. 2019).

93 Entomologists and those reliant on sound insect identifications also face an enormous taxonomic
94 impediment (Samways 1993, Habel et al. 2019), especially in tropical regions. It is difficult to
95 know what we are losing when 80% of insect species (representing, conservatively, four million
96 species) remain undescribed and their natural histories unknown (Stork 2018). High insect
97 species diversity compounds this problem; identification of every insect even in a small sample
98 in an area with low alpha diversity can be time- or cost-prohibitive. Declines in insect
99 identification expertise further degrade the ability to determine biodiversity and population
100 trends for most insect lineages (Hopkins & Freckleton 2002); growing sources of identification
101 knowledge through community science, machine learning, and genetic barcoding are helpful, but
102 cannot compensate the continuing loss of professional taxonomist expertise. Using indicator taxa
103 can be an effective approach to sidestep aspects of the taxonomic impediment problem but doing
104 so often results in inadequate knowledge and compromised measures of interest (McGeoch 1998,
105 Thomas 2005).

106 There are many consequences of this shortfall of insect biodiversity knowledge, when combined
107 with a general lack of baseline population data. One illustration can be seen in the number of
108 insects with global conservation statuses evaluated by the International Union for Conservation
109 of Nature: only 8,355 insect species have been evaluated, and 2,104 of those are “data deficient”
110 (IUCN 2019), out of an estimated 5.5 million insect species worldwide (Stork 2018).

111 *The Human Side*

112 Scientific, public and political interest in insect population declines and conservation is
113 encouraging and has led to new research programs, redoubled interest in sampling
114 methodologies, catalyzed interest in analyses of historical data sets, led to biodiversity-friendly
115 government initiatives, and increased funding for the study of insects. Several high-profile
116 studies finding large declines in insect populations or biomass have spurred massive media
117 attention and generated unprecedented public interest in insects and their ecosystem services.
118 Unfortunately, some media reports of insect declines have made extrapolations that have leapt
119 beyond credible evidence, though there are examples of more balanced coverage (e.g., Yong

120 2019). Exaggerated claims can sometimes trigger complex feedback loops between scientists,
121 institutions, media and the public (Ransohoff & Ransohoff 2001, Bubela 2006, Caulfield &
122 Condit 2012). To avoid such claims from being made, it is incumbent upon scientists to continue
123 presenting thoughtful, critical assessments; the risks of false positives are high. Because global
124 insect populations have such importance, and also because of the enormous data gaps and
125 potential biases, it is especially important to commit to elevated standards of study design,
126 evidence, and communication.

127 Human psychology also poses challenges for understanding the insect decline phenomenon, and
128 we should be aware of human tendencies that affect this field. For example, humans tend to view
129 insects as one homogeneous group, which masks the complex and variable effects occurring
130 across taxa and guilds (Habel et al. 2019). Older people recall seeing more moths in headlights
131 (“the moth snowstorm”), summer nights filled with fireflies, and splatted insects on their
132 windshields. Such anecdotes are valuable, but only rarely can be substantiated. On the other
133 hand, younger people may not notice what has been lost as a result of shifting baseline syndrome
134 (Pauly 1995, Soga & Gaston 2018). However, it is also true that a generational shift in where
135 people live has also occurred, with broad shifts toward cities and hence the experience of the
136 subset of species that thrive in cities. Confirmation bias, the tendency to interpret data to support
137 existing hypotheses (Nickerson 1988), could creep into experimental design and analyses,
138 especially in ecological studies where many effects interact weakly. Publication bias is also no
139 doubt at play, where statistically significant results are selected for publication more often than
140 studies with non-significant results (Rosenthal 1979). How large a problem might it be that
141 studies documenting losses are more likely to be written, reviewed, and accepted for publication
142 than studies showing little change? Indeed, studies of insects in general are less likely to be
143 published than studies of other taxonomic groups (Leather 2009), another form of publication
144 bias. There is also a tendency for the most extreme results to be published and cited (Ioannidis
145 2005) - this may be especially relevant for a topical issue like insect declines. While most
146 scientists are already aware of these issues, it is important to regularly remind ourselves of them.

147

148 **RESEARCH RECOMMENDATIONS**

149 Determining the scale and severity of declines in insect diversity, abundance, and range must be
150 among the most urgent global research, conservation, and legislative priorities going forward.
151 But what research will be most effective? Entomologists have unique opportunities in this
152 moment of heightened public awareness.

153 *Monitoring*

154 First, we need to establish insect monitoring networks on a global scale. By using repeatable
155 sampling methods, new monitoring programs can augment pre-existing ones, and help determine
156 population trends, identify drivers of trends, and serve to engage the public through community
157 science (Lewandowski & Oberhauser 2017). We advocate for large-scale programs to monitor
158 abundances, biomass, and species diversity using standardized, effort-based methods such as
159 Malaise trapping, pitfall trapping, suction trapping, light trapping, count surveying, and new

160 methods such as the modified window traps of Knuff et al. (2019) or smart insect cameras
161 (Hogeweg et al. 2019). Although biomass is an imperfect estimator of diversity because it can be
162 sensitive to changes in abundances of large species (e.g., Shortall et al. 2009), it is a valuable
163 metric from the ecosystem perspective. Determining biomass trends also does not require fine-
164 scale taxonomic knowledge, which is often limited to individuals with specialized training. We
165 advocate this approach with necessary caveats; it is often impractical to attempt monitoring all
166 insect species from any community with appreciable diversity (though meta-barcoding and other
167 genetic approaches can help).

168 Long-term monitoring should consider the relative economic and ecological costs and benefits;
169 although regular lethal trapping may not have major impacts on insect communities (Gezon et al.
170 2015), the economic costs of sampling and identification of large volumes of many taxa may be
171 prohibitive (Tepedino et al. 2015; Drinkwater et al. 2019). Better-known taxa like butterflies,
172 macromoths, orthopterans, and some bees and beetles can serve as indicator or substitute species
173 for other insect groups, but only when carefully validated (Henry et al. 2019).

174 Effective long-term monitoring takes many forms, including complex spatial designs with many
175 observers and single-observer designs with temporally intensive data from fewer sites (Pocock et
176 al. 2015). Continuous, or at least multi-year, time-series are especially valuable for insects,
177 where year-to-year population variation can be high. Although longitudinal time-series (e.g.,
178 Wepprich et al. 2019) provide better inferential power, “snapshot” surveys are useful for taxa or
179 regions limited by a lack of continuous historical data, if scientists control for variation in effort
180 and changes in methods – whether through strong data filtering or direct statistical modeling
181 (Tingley 2017) – and can replicate previously conducted surveys on a broad geographic scale.

182 Though existing long-term monitoring programs are relatively rare, programs that do exist
183 provide invaluable data and can be used as models for new monitoring efforts. A non-exhaustive
184 list of such programs include the Wijster Biological Station pitfall program (NL; Den Boer &
185 van Dijk 1994), the Rothamsted Insect Survey (UK; Storkey et al. 2016), the Krefeld
186 Entomological Society surveys (DE; Hallmann et al. 2017), the United Kingdom, Dutch &
187 Catalan Butterfly Monitoring Schemes (UK; Pollard & Yates 1994, NL; Van Swaay et al. 1997,
188 ES; Melero et al. 2016), midwestern butterfly surveys (US; Swengel et al. 2011, Wepprich et al.
189 2019), and the Shapiro butterfly surveys (US; Forister et al. 2011). Collectively, these programs
190 form the basis for a large part of what we know about long-term diversity and population trends
191 in insects – the next step is expanding and complementing these schemes on a global scale, while
192 continuing to support existing programs.

193 *Surveying across space*

194 Surveys across light pollution, agricultural intensification, pesticide use, plant invasion, urban
195 heat island, human density, or other gradients could provide insight into what factors are
196 contributing to insect declines and their relative importance. There is an urgent need to gather
197 demographic data from tropical sites—while not wholly surprising, it is ironic that we know the
198 least about the Earth’s most species rich and ecologically diverse entomofaunas (Stork 2018). In
199 addition, surveys that substitute space for time can serve as an imperfect substitute for baseline
200 data. This survey strategy is commonly used in ecology when time-series data are lacking (Blois

201 et al. 2013) and can prove particularly powerful when tested against experimental data and, for
202 the subset of sites for which they are available, time-series data (Lahr et al. 2018).

203 *Making time-series data available*

204 We also need to make baseline data more open and accessible. Continuous or nearly continuous
205 time-series of insect abundance and diversity have been collected by observers outside of insect
206 conservation and ecology circles. For example, changes in lady beetle populations have been
207 monitored using control plots at experimental farms (Alyokhin & Sewell 2004). Vertebrate
208 ecologists studying insectivores that also collect insect (prey) abundance data have the potential
209 to contribute much to our knowledge of insect population trends (e.g., Harris et al. 2019).

210 Data collected by agricultural and silvicultural monitoring, land-management agencies, insect
211 collectors, and nature enthusiasts can all be useful. These datasets, like datasets from traditional
212 ecological sources, should be made available and posted to online repositories like Dryad
213 (datadryad.org), BioTIME (biotime.st-andrews.ac.uk; Dornelas et al. 2018), or the Global
214 Biodiversity Information Facility (gbif.org) when possible. We recognize that there are social
215 and financial barriers to contributing data sets to online repositories that still need to be
216 addressed, and care needs to be taken to protect the intellectual property rights of ongoing long-
217 term surveys to ensure their continuity (Pearce-Higgins et al. 2018).

218 *Community science*

219 Some of the best long-term monitoring data comes from community or citizen scientists. The
220 biomass declines reported by Hallmann et. al. (2017) in Germany are based on the work of the
221 Krefield Entomological Society, an organization of knowledgeable entomologists, most of which
222 commit their free time to insect research. Beyond already existing community science efforts, the
223 current moment is also an opportunity to reach new audiences with a message of insect
224 conservation on a global scale (see Pocock et al. 2018). Concerned community scientists can be
225 recruited to re-sample “snapshot” surveys on a large geographic scale. Similarly, enlisting school
226 classrooms to participate in insect monitoring can provide useful data (e.g., the School Malaise
227 Trap Program in Canada: Steinke et al. 2017, and Saunders et al. 2018). Live pitfall and LED
228 UV-light traps are inexpensive to set up and monitor and can mitigate ethical concerns
229 sometimes associated with specimen collecting, especially by the public. Taxa such as
230 caterpillars, larger beetles, and wasps can be imaged (and identified) with cell phones, offering
231 myriad possibilities. School monitoring programs also have the potential to be expanded to larger
232 geographic scales.

233 Such community science efforts simultaneously serve to educate, raise awareness about the
234 importance of insects, and provide opportunities for invertebrate conservation (Lewandowski &
235 Oberhauser 2017). Error and bias due to variation in the expertise of the participants is a
236 recognized issue (Gardiner et al. 2012) and designing protocols that account for or minimize this
237 is important (see Dennis et al. 2017); training projects such as BioLinks
238 (<https://www.fscbiodiversity.uk/projects/biolinks>) can play invaluable roles. There are many
239 successful insect-related community science projects that collect useful data on insect
240 abundance, diversity, or distribution that can serve as models. Examples include The Monarch

241 Larva Monitoring Project, National Moth Recording Scheme, Caterpillars Count, Bumble Bee
242 Watch, Lost Lady Bug Project, Firefly Watch, Wild Bee Garden Count, Western Monarch
243 Thanksgiving Count, Australia’s Wild Pollinator Count, UK Pollinator Monitoring Scheme,
244 iNaturalist.org, and BugGuide.net.

245 *Reporting and synthesizing results*

246 Once insect trend data have been collected, they need to be shared, and well-designed insect
247 demography studies should be published or otherwise made available. To combat publication
248 bias, researchers, reviewers, and journal editors alike need to publish reports of increasing and
249 stable trends, in addition to documenting declines. Reports of where insects are not declining are
250 as important as reports of where they are declining, since this heterogeneity can help elucidate
251 key threats. Unbiased reporting will also reduce systematic biases in the literature, which is
252 helpful for researchers performing systematic reviews and meta-analyses. These forms of
253 evidence synthesis can effectively provide a means of evaluating the scale and severity of insect
254 declines and their potential drivers when they follow question formulation tools like PICO
255 (Richardson et al. 1995) and reporting guidelines like ROSES (Haddaway et al. 2018). We
256 recommend projects such as the EntoGEM systematic mapping project (Grames et al. 2019;
257 <https://entogem.github.io>), a community-driven effort to assimilate global literature and data sets
258 relevant to insect population and diversity trends.

259 *Under-exploited datasets*

260 Beyond these steps, however, complementary approaches are needed to fully evaluate the
261 mechanisms, pattern, and consequences of insect declines, especially to provide alternative
262 baseline data. For example, NEXRAD is a network of weather radars in the United States that
263 are used to monitor birds (Dokter et al. 2018); data from these radars could also provide
264 estimates of aerial insect biomass flows over the last 25 years (Hu et al. 2016). The use of
265 museum collections to estimate insect trends (e.g., Cameron et al. 2011, Bartomeus et al. 2013,
266 Boyle et al. 2019) is becoming more powerful with new statistical methods. Caution is required
267 when using data that were not collected for this purpose (e.g., see Wepprich 2019), including
268 spatiotemporal bias (Ries et al. 2019), and abundance trends do not always correlate positively
269 with occurrence (range) data (Dennis et al. 2019). However, museum collections can be used to
270 infer trends and drivers of trends (e.g., Scheper et al. 2014, Meineke et al. 2019), and effort data
271 can sometimes be extracted from species-list length in a time or place (Van Strien et al. 2013).
272 Continued digitization efforts (e.g., iDigBio, LepNet, SCAN) are necessary to bring collection
273 data to bear on the issue of insect declines, since current numbers of digitized specimens are not
274 enough to draw conclusions about trends in many cases (Ries et al. 2019). Stored samples from
275 monitoring projects are also available and have been utilized to some extent (Shortall et al. 2009,
276 Hallmann et al. 2017) — most are available for further work. In some cases, data for
277 insectivorous taxa may exist where baseline data for insects do not, perhaps allowing inferences
278 about insect diversity and population levels (English et al. 2018, Wagner 2019b). Such
279 insectivorous taxa can also provide insect data directly, through DNA sequencing diet samples or
280 feces (e.g., Krauel et al. 2018). Entomologists should also think broadly and creatively about
281 new technologies and “Big Data” streams that could be used to study insects, from passive

282 acoustic monitoring (Zilli et al. 2014), smart insect cameras, and eDNA (Mächler et al. 2014) to
283 LIDAR (Simonson et al. 2014), and social media (Alvaro et al. 2015).

284

285 **FUNDING**

286 Few of these research priorities will be feasible without funding. There needs to be a recognition
287 by research funding agencies, foundations, and individuals that entomological survey and
288 monitoring work should receive a step-change in funding. Funding should more closely reflect
289 abundance, diversity, and ecological importance of taxa, not their perceived charisma (Clark &
290 May 2002). Crowdsourcing may draw in some funds, but what is required is stable, substantial
291 funding that will allow existing and future international collaborations to flourish. For this to
292 happen, we need to convince funders, and society, to support insect conservation as much as
293 insect control. Long-term monitoring studies can be unappealing to funders and yet are the main
294 lens through which we understand the rapid changes in biological systems; in this way they are
295 akin to public health surveillance, essential and yet radically underfunded compared to studies of
296 medical interventions.

297

298 **CONCLUSION**

299 Insects are in trouble, and we must take conservation actions now, rather than wait for biologists
300 to provide exhaustive demographic data, measure all drivers, and attempt to quantify population
301 trends across thousands of individual lineages. But the many data gaps presently in the insect
302 decline literature do matter, and it remains to be seen if some recent alarming results are
303 indicative of global-scale insect declines that would trigger losses of ecosystem function. The
304 drivers of declines are many, from habitat loss, agricultural intensification, and climate change,
305 to invasive species, pesticides, and light pollution, but much remains unknown, including the
306 scope and severity of insect declines. Despite the challenges faced by researchers studying trends
307 in insect diversity and demography, it is urgent that we fill these crucial data gaps and use
308 rigorous science to do so. It is time to get to work.

309

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311

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