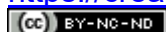


Article (refereed) - postprint

Woodcock, Ben A.; Ridding, Lucy; Pereira, M. Gloria; Sleep, Darren; Newbold, Lindsay; Oliver, Anna; Shore, Richard F.; Bullock, James M.; Heard, Matthew S.; Gweon, Hyun S.; Pywell, Richard F..2021.
Neonicotinoid use on cereals and sugar beet is linked to continued low exposure risk in honeybees.

© 2020 Elsevier B.V.

This manuscript version is made available under the CC BY-NC-ND 4.0 license
<https://creativecommons.org/licenses/by-nc-nd/4.0/>



This version is available at <http://nora.nerc.ac.uk/id/eprint/529307>

Copyright and other rights for material on this site are retained by the rights owners. Users should read the terms and conditions of use of this material at <https://nora.nerc.ac.uk/policies.html#access>.

This is an unedited manuscript accepted for publication, incorporating any revisions agreed during the peer review process. There may be differences between this and the publisher's version. You are advised to consult the publisher's version if you wish to cite from this article.

The definitive version was published in *Agriculture, Ecosystems and Environment*, 308, 107205. <https://doi.org/10.1016/j.agee.2020.107205>

The definitive version is available at <https://www.elsevier.com/>

Contact UKCEH NORA team at
noraceh@ceh.ac.uk

Long-term trends in the occupancy of ants revealed through use of multi-sourced data sets

Running title: Occupancy trends in ants

Julie K. Sheard^{*1} ORCID: 0000-0002-1073-0221, Carsten Rahbek^{1,2,3,4,5} ORCID: 0000-0003-4585-0300, Robert R. Dunn⁶ ORCID: 0000-0002-6030-4837, Nathan J. Sanders⁷ ORCID: 0000-0001-6220-6731, Nick J.B. Isaac⁸ ORCID: 0000-0002-4869-8052

¹Center for Macroecology, Evolution and Climate, GLOBE Institute, University of Copenhagen, Universitetsparken 15, 2100 Copenhagen, Denmark

²Center for Global Mountain Biodiversity, GLOBE Institute, University of Copenhagen, Universitetsparken 15, 2100 Copenhagen, Denmark

³Institute of Ecology, Peking University, Beijing 100871, China

⁴Department of Life Sciences, Imperial College London, Ascot SL5 7PY, UK.

⁵Danish Institute for Advanced Study, University of Southern Denmark, Campusvej 55, 5230 Odense M, Denmark

⁶Department of Applied Ecology, North Carolina State University, Raleigh, North Carolina, USA

⁷Department of Ecology and Evolutionary Biology, University of Michigan, Ann Arbor, Michigan, USA

⁸UK Centre for Ecology & Hydrology, Crowmarsh Gifford, Maclean Building, Wallingford, OX10 8BB, UK

*Corresponding author:

Julie Koch Sheard

Center for Macroecology, Evolution and Climate,

23 GLOBE Institute,
24 University of Copenhagen,
25 Universitetsparken 15, 2. sal, 2100 København Ø, Denmark
26 Julie.sheard@sund.ku.dk

27 ABSTRACT

28 We combined participatory science data and museum records to understand long-term changes in
29 occupancy for 29 ant species in Denmark over 119 years. Bayesian occupancy modelling indicated
30 change in occupancy for fifteen species: five increased, four declined, and six showed fluctuating
31 trends. We consider how trends may have been influenced by life-history and habitat changes. Our
32 results build on an emerging picture that biodiversity change in insects is more complex than
33 implied by the simple insect decline narrative.

34 **Key words:** Bayesian occupancy modelling, citizen science, Denmark, Formicidae, museum data.

35 INTRODUCTION

36 There is a pressing need to understand which insect taxa are declining, which are stable, which are
37 increasing and why. Most evidence is from bees, butterflies and dragonflies [1–6]; ants, despite
38 their ubiquity, importance, and abundance [7,8], have largely been ignored. The dearth of long-term
39 studies of ants is likely attributable to the cost of acquiring data over large temporal and spatial
40 scales [9]. One solution is to combine data from multiple sources [10–12], including museum
41 collections and participatory science (citizen science) projects [4,12–14].

42 There are several challenges in dealing with long-term data from multiple sources: differential
43 sampling effort [15], species bias [16,17] and identification errors [18]. Bayesian occupancy models
44 [19] have proven useful in addressing these challenges, e.g. by using contextual information on
45 sampling effort [20–22]. Thus, measuring occupancy trends has become a common way to assess
46 biodiversity changes [23].

47 Here, we use Bayesian occupancy modelling [19,24] to estimate long-term changes in
48 occupancy of 29 Danish ant species from 1900-2019 and consider possible drivers.

49 MATERIAL AND METHODS

50 (a) Data

51 The combined data set consisted of seven data sets (table 1) binned into decades (figure 1a) and 10
52 × 10 km grid cells. We excluded detections of unidentified and non-native species and those
53 without collection date or geographic coordinates. The combined data set spanned 119 years (108
54 sampled years), from 1900-2019, and included 4,597 unique detections (combinations of site, date
55 and species) for 51 species (table 1; electronic supplementary material, S1), covering 75 % of
56 Denmark (472 of 633 grid cells; figure 1b; electronic supplementary material S2). However, 188
57 grid cells were only visited in a single decade. These were excluded from our model, reducing

spatial coverage to 45 %. Of the remaining 284 grid cells, 88 % were included in two or more of the individual data sets.

Table 1. Overview of data sets used in this study after filtering. The combined data set covered the years 1900-2019; although 12 years were unsampled, all decades were. There were 4,597 unique detections for 51 species and 472 10 x 10 km grid cells, covering 75 % of Denmark. ¹Museum collection, ²Personal collection, ³Participatory science, ⁴Field Course.

data source	datatype	decades	unique detections	native species	modelled species	Total grid cells (included in model)	visits
NHM Denmark ¹ [25]	1	11 (1903-2003)	2379	45	29	294 (218)	1552
NHM Aarhus ¹ [26]	1	7 (1900-1972)	408	30	24	146 (114)	274
C. Skøtt ² [27]	1	2 (1960-1979)	940	32	26	216 (166)	885
Ant Hunt ³ [28]	3	1 (2017-2018)	666	28	23	184 (136)	501
S. Schär ² [29]	1	1 (2011-2015)	88	29	24	17 (15)	57
EuroAnts ⁴ [30]	2	1 (2012-2019)	98	27	19	4 (4)	11
H. Holgersen ¹ [31]	1	1 (1981-1987)	18	13	13	9 (8)	11
combined		12 (1900-2019)	4,597	51	29	472 (284)	3,291

We classified the data into three data types [12,32], based on information about the sampling protocols and the number of species recorded during a visit (electronic supplementary material S3). Most data sets are based on collections, which are likely presence-only data sets and were categorised as datatype1. However, EuroAnts is a field course where students record all species found at sites, so was categorised as datatype2. The Ant Hunt used two-hour baiting experiments rather than active searching and was categorised as datatype3. These last two data sets are more likely to contain true absence data. Further information about the data sets is provided in electronic supplementary material, S1-S4.

Species detections were converted to detection histories [33] by organising data into visits (unique grid cell–date combinations). Species were assigned a 1 if detected during a visit and a 0 if not, generating non-detections [32,34–37]. Species were selected for occupancy modelling based on total number of detections, proportion of non-detections and the 90th percentile of detections within decades, resulting in 30 species [38,39]. We excluded *Lasius platythorax*, a species only recently separated from *Lasius niger* [40], leaving 29 species (electronic supplementary material, S5).

78 (b) Bayesian occupancy modelling

79 We fitted a Bayesian occupancy model for each species following [12,32,39,41,42] to estimate
80 occupancy (proportion of occupied 10 x 10 km grid cells) per decade from 1900-2019.

81 The occupancy model consists of two sub models. The state model describes the true
82 occupancy state of a species (1 or 0) based on the probability of occupancy ψ at a grid cell i during
83 a decade t : $z_{it} \sim \text{Bernoulli}(\psi_{it})$; $\text{logit}(\psi_{it}) = \log(\psi_{it}/1-\psi_{it}) = b_t + u_i$, where b_t and u_i are the effects of
84 grid cell and decade. Observations (y) are conditional on the species being present ($z = 1$): $y_{itv}|z_{it} \sim$
85 $\text{Bernoulli}(p_{itv} * z_{it})$, where p is the detection probability (p). Detection is modelled in the observation
86 sub-model. For each visit (v), grid cell (i) and decade (t), for a given datatype the probability of
87 detection is given by $\text{logit}(p_{itv}) = \log(p_{itv}/1-p_{itv}) = a_t + \beta_1 * \text{datatype2}_{itv} + \beta_2 * \text{datatype3}_{itv}$, where a_t is
88 the decade effect. Parameters β_1 and β_2 estimate differences in $\log(p_{itv})$ for datatype2 and datatype3,
89 relatively to datatype1.

90 Model priors were set following others, with vague, uninformative priors for all parameters
91 except the decade effect of the state model, where we use a random walk, allowing the model to
92 share information between time periods, which is especially advantageous for data sets with low
93 recording intensity [39,41,42]:

$$94 \quad b_t \sim \begin{cases} \text{Normal}(\mu_b, 10^4) & \text{for } t = 1 \\ \text{Normal}(b_{t-1}, \sigma_b^2) & \text{for } t > 1 \end{cases}, \text{ where, } \mu_b \sim \text{Normal}(0, 100) \text{ and } \sigma_b \sim |\text{Student-t on 1 df}|$$

95 Data formatting and Bayesian occupancy modelling were carried out in the package sparta version
96 0.2.7 in R version 3.6.3 [43,44] using JAGS version 4.3.0 [45] through the package R2jags version
97 0.6.1 [46], with half-Cauchy hyperpriors using 3 chains, 50,000 iterations, a burn in of 25,000
98 iterations and a thinning rate of 3 [36]. If convergence ($\text{Rhat} < 1.1$) [24,47] was not reached, models
99 were rerun doubling the number of iterations and always discarding half as burn in.

100 We evaluated model performance by calculating the median uncertainty (the width of the 68%
101 credible interval (1 standard deviation either side of the mean)) for each species across decades and

for each decade across species. We then calculated Spearman's rank correlation between uncertainty and 1) number of detections for a species, 2) median occupancy and 3) decade.

Occupancy change

We calculated mean occupancy for each decade and identified the peaks and troughs for each species. We calculated the difference between the peaks and troughs and report a "confidence" score for change as the percentage of the posterior distribution that has the same sign as the mean. Species with confidence scores <80 % were classified as stable. If confidence scores were ≥ 80 %, species with only positive changes were categorised as increasing, species with only negative changes as declining, and species that showed both positive and negative changes as fluctuating. We interpret a confidence score ≥ 95 % as strong evidence of change, ≥ 90 % as moderate evidence, and ≥ 80 % as weak evidence.

RESULTS

Five species increased in occupancy, four declined, six fluctuated, and fourteen were stable (figure 2), including some that show change, but with too high uncertainty to draw firm conclusions (electronic supplementary material, S4 and S6). Spearman's rank correlation showed no correlation between uncertainty and the number of detections ($\rho = 0.26$, $p = 0.17$) or decade ($\rho = -0.35$, $p = 0.27$), but there was a significant correlation with species occupancy ($\rho = 0.48$, $p = 0.008$, electronic supplementary material, S7).

Increasing species

Camponotus herculeanus increased from 0.04 in 1900-1909 to 0.09 in 1940-1949 (125 % change, 82 % confidence). It remained stable until 1950-1959, then increased from 0.065 to 0.24 in 2010-2019 (269 % change, 97 % confidence,). *Formica picea* increased from 0.25 in 1900-1909 to 0.41 in 1970-1979 (64 % change, 83 % confidence), then stabilised. *Formica rufa* increased from 0.67 in

125 1900-1909 to 0.84 in 1970-1979 (25 % change, 83 % confidence), where it stabilised. *Formica*
126 *uralensis* increased from 0.05 in 1900-1909 to 0.27 in 1970-1979 (440 % change, 97 %
127 confidence), then stabilised until 1980-1989 (79 % confidence) before increasing again from 0.19 to
128 0.35 in 2010-2019 (84 % change, 87 % confidence). *Myrmica ruginodis* was stable until 1950-
129 1959, then increased from 0.80 to 0.88 in 1970-1979 (10 % change, 83 % confidence), where it
130 stabilized.

131 *Declining species*

132 *Lasius fuliginosus* was stable until 1920-1929, then declined from 0.71 to 0.43 in 1970-1979 (39 %
133 change, 94 % confidence), where it stabilised. *Myrmica rubra* was stable until 1940-1949, then
134 declined from 0.87 to 0.62 in 1990-1999 (29 % change, 88 % confidence). *Myrmica sabuleti* was
135 stable until 1940-1949 before declining from 0.70 to 0.05 in 2010-2019 (93 % change, 100 %
136 confidence). *Myrmica schencki* was stable until 1940-1949, then declined from 0.37 to 0.24 in
137 2010-2019 (35 % change, 82 % confidence).

138 *Fluctuating species*

139 *Formica polyclena* increased from 0.29 in 1900-1909 to 0.75 in 1940-1949 (159 % change, 88 %
140 confidence), then declined to 0.17 in 1960-1969 (77 % change, 99 % confidence) and increased to
141 0.71 in 1990-1999 (318 % change, 99 % confidence) before declining to 0.54 in 2010-2019 (24 %
142 change, 80 % confidence). *Formica rufibarbis* was stable until 1930-1939, then declined from 0.58
143 to 0.35 in 1970-1979 (40 % change, 95 % confidence). It then increased to 0.52 in 2010-2019 (49 %
144 change, 85 % confidence). *Formica sanguinea* increased from 0.20 in 1900-1909 to 0.43 in 1960-
145 1969 (115 % change, 89 % confidence), then declined to 0.22 in 2010-2019 (49 % change, 93 %
146 confidence). *Lasius umbratus* declined from 0.49 in 1900-1909 to 0.21 in 1970-1979 (57 % change,
147 92 % confidence) then increased to 0.48 in 2010-2019 (129 % change, 94 % confidence). *Myrmica*

148 *rugulosa* was stable until 1940-1949, then declined from 0.39 to 0.28 in 1970-1979 (28 % change,
149 86 % confidence) then increased to 0.44 in 2010-2019 (57 % change, 83 % confidence).
150 *Tetramorium caespitum* was stable until 1940-1949, then increased from 0.66 in 1940-1949 to 0.80
151 in 1980-1989 (21 % change, 83 % confidence), then declined back to 0.66 in 2010-2019 (18 %
152 change, 86 % confidence).

153 DISCUSSION

154 Although 14 of 29 species showed stable occupancies from 1900-2019, estimates remained
155 imprecise for many species, and 22 species could not be assessed owing to data deficiency
156 (electronic supplementary material S1 and S5). However, the analysed species exhibit typical
157 behaviours, life histories, foraging strategies, etc. of many native Danish ants.

158 Four declining species and three fluctuating species exhibit declines in recent years. Two of
159 these (*F. polychaeta* and *F. sanguinea*) are mound-building species typically found in forests with
160 open, sun-exposed areas [48,49]. Danish forests have been increasing since the 1900s and today
161 cover 14.7 % of the country [50]. This decline is mainly driven by an increase in monocultures of
162 coniferous plantations [51], which are generally dense and with low light levels in the understorey.
163 Closure of the tree canopy, habitat change, and disturbance have caused declines in *Formica* spp.
164 elsewhere [52]. Two forest species (*C. herculeanus* and *F. rufa*) increased in occupancy (though the
165 trend for *F. rufa* may be changing with a 14 % decline from 1970-1979 to 2010-2019, 73 %
166 confidence). *Camponotus herculeanus* typically occurs in coniferous or mixed conifer–broadleaf
167 forests with a high percentage of *Picea abies* [48,52], which is one of the most common Danish
168 trees [50].

169 Four of the species that have shown some decline (*L. fuliginosus*, *M. sabuleti*, *M. schencki*, *T.*
170 *caespitum*) occur in dry open habitats [48,49]. Their decline may be linked to decreases in available
171 habitat and increases in precipitation. The extent of dry, open habitats in Denmark has declined

172 from ~ 25 % in 1888 to < 10 % in 2004, owing to conversion to agriculture and forest [51]. Average
173 precipitation (mm) and days with ≥ 10 mm precipitation have increased from 712 mm and 17 days
174 in 1961-1990 to 791.9 mm and 20.3 days in 2006-2015 [53]. Conversely, three of the recently
175 increasing species (*M. ruginodis*, *F. picea* and *F. uralensis*) occur in wetter habitats, such as bogs
176 and water-drenched soils [49].

177 Dietary specialists may be more sensitive to disturbance, such as urbanisation [54]. Most
178 Danish ants are generalist omnivores, but the diets of four recently declining species (*L. fuliginosus*,
179 *M. schencki*, *F. polychaeta* and *F. sanguinea*) tend to be especially protein-rich [49].

180 Finally, changes in the occupancy of some ant species may be due to changes in conditions
181 for other species on which they depend. In areas where they co-occur, *F. uralensis* is outcompeted
182 by *F. sanguinea* and *M. rubra* [49], so its increase could be linked to decreasing competition.
183 *Lasius umbratus* (currently increasing) depends on species such as *L. niger* and *L. platythorax* for
184 nest construction [49] and may benefit from *L. niger* being the most common ant species in
185 Denmark.

186 CONCLUSION AND FUTURE DIRECTIONS

187 We provide the first insights to our knowledge into long-term occupancy trends for ants. We find
188 declining species are associated with dry, undisturbed habitats and open forests and have protein-
189 rich diets, whereas increasing species are wet- and disturbance-tolerant and tend to be omnivores.
190 These trends appear to be directly linked to changes in habitat and climate.

191 Ants can host many dependent species [55,56]. As a result, species that depend on declining
192 ant species may also decline. For example, 70 taxa were found in nests of *F. polychaeta* [56] and the
193 decline in the distribution of *M. sabuleti* may be a contributing factor to the decline in its butterfly
194 parasite, *Maculinea arion*, which is currently found in only one area of Denmark [57].

195 A key caveat of studying ants compared to other insect taxa is that colonies are the units of
196 selection, and colonies can persist for decades, while workers might live for less than a year.
197 However, most of the data come from collections of workers.

198 The lack of standardised long-term data is problematic for many taxa besides ants, and this
199 challenge is unlikely to change in the near future. While combining multi-sourced data is helpful,
200 and may shed some light on the occupancy of overlooked taxa, it is not a panacea. Many species
201 lacked sufficient data for modelling. Participatory science has proven efficient for compiling data,
202 yet participants may overlook rare and cryptic species and are likely to be spatially biased.
203 Combining participatory science with expert searches and focusing on resampling of sites could
204 prove beneficial. For example, in this study, 188 grids were visited in just one decade. Through
205 resampling, spatial coverage could be increased to 75 %, thereby improving our ability to
206 understand both historic and future trends in occupancy.

207 FUNDING

208 This work was supported by the June 15th Foundation, Knud Højgaards Foundation, the Augustinus
209 Foundation, the Beckett Foundation and the Danish National Research Foundation (DNRF96).

210 ACKNOWLEDGEMENTS

211 We would like to thank Anders Tøttrup, Pernille Hjort and Mia Pedersen, who were instrumental in
212 the success of the Ant Hunt. We received support from the Natural History Museum of Denmark,
213 the Danish Nature Agency, Mogens Gissel, the Natural History Museum Aarhus, David Nash,
214 Bjørn Hermansen, and the families and schools who participated in the Ant Hunt.

215 REFERENCES

- 216 1. van Swaay CAM. 1990 An assessment of the changes in butterfly abundance in The
217 Netherlands during the 20th Century. *Biol. Conserv.* **52**, 287–302. (doi:10.1016/0006-

- 218 3207(90)90073-X)
- 219 2. Thomas JA, Telfer MG, Roy DB, Preston CD, Greenwood JJD, Asher J, Fox R, Clarke RT,
 220 Lawton JH. 2004 Comparative Losses of British Butterflies, Birds, and Plants and the Global
 221 Extinction Crisis. *Science* (80-.). **303**, 1879–1881. (doi:10.1126/science.1095046)
- 222 3. Kuussaari M, Heliölä J, Pöyry J, Saarinen K. 2007 Contrasting trends of butterfly species
 223 preferring semi-natural grasslands, field margins and forest edges in northern Europe. *J.*
 224 *Insect Conserv.* **11**, 351–366. (doi:10.1007/s10841-006-9052-7)
- 225 4. Cameron SA, Lozier JD, Strange JP, Koch JB, Cordes N, Solter LF, Griswold TL. 2011
 226 Patterns of widespread decline in North American bumble bees. *Proc. Natl. Acad. Sci.* **108**,
 227 662–667. (doi:10.1073/pnas.1014743108)
- 228 5. Powney GD, Carvell C, Edwards M, Morris RKA, Roy HE, Woodcock BA, Isaac NJB. 2019
 229 Widespread losses of pollinating insects in Britain. *Nat. Commun.* **10**. (doi:10.1038/s41467-
 230 019-08974-9)
- 231 6. Termaat T *et al.* 2019 Distribution trends of European dragonflies under climate change.
 232 *Divers. Distrib.* **25**, 936–950. (doi:10.1111/ddi.12913)
- 233 7. Del Toro I, Ribbons RR, Pelini SL. 2012 The little things that run the world revisited: A
 234 review of ant-mediated ecosystem services and disservices (Hymenoptera: Formicidae).
 235 *Myrmecological News* **17**, 133–146.
- 236 8. Wilson EO. 1987 The Little Things That Run the World (The Importance and Conservation
 237 of Invertebrates). *Conserv. Biol.* **1**, 344–346.
- 238 9. Grant EHC. 2015 Please don't misuse the museum: 'declines' may be statistical. *Glob.*
 239 *Chang. Biol.* **21**, 1018–1024. (doi:10.1111/gcb.12702)

- 240 10. Fletcher RJ, Hefley TJ, Robertson EP, Zuckerberg B, McCleery RA, Dorazio RM. 2019 A
241 practical guide for combining data to model species distributions. *Ecology* **100**.
242 (doi:10.1002/ecy.2710)
- 243 11. Miller DAW, Pacifici K, Sanderlin JS, Reich BJ. 2019 The recent past and promising future
244 for data integration methods to estimate species' distributions. *Methods Ecol. Evol.* **10**, 22–
245 37. (doi:10.1111/2041-210X.13110)
- 246 12. Jönsson GM, Broad GR, Umner SS, Isaac NJB. 2021 A century of social wasp occupancy
247 trends from natural history collections : spatiotemporal resolutions have little effect on model
248 performance. *Insect Conserv. Divers.* (doi:10.1111/icad.12494)
- 249 13. Tingley MW, Beissinger SR. 2009 Detecting range shifts from historical species
250 occurrences: new perspectives on old data. *Trends Ecol. Evol.* **24**, 625–633.
251 (doi:10.1016/j.tree.2009.05.009)
- 252 14. Pocock MJO, Tweddle JC, Savage J, Robinson LD, Roy HE, Crowston K. 2017 The
253 diversity and evolution of ecological and environmental citizen science. *PLoS One* **12**,
254 e0172579. (doi:10.1371/journal.pone.0172579)
- 255 15. Dennis RLH, Sparks TH, Hardy PB. 1999 Bias in butterfly distribution maps: the effects of
256 sampling effort. *J. Insect Conserv.* **3**, 33–42.
- 257 16. Hassall C. 2012 Predicting the distributions of under-recorded Odonata using species
258 distribution models. *Insect Conserv. Divers.* **5**, 192–201. (doi:10.1111/j.1752-
259 4598.2011.00150.x)
- 260 17. Snäll T, Kindvall O, Nilsson J, Pärt T. 2011 Evaluating citizen-based presence data for bird
261 monitoring. *Biol. Conserv.* **144**, 804–810. (doi:10.1016/j.biocon.2010.11.010)

- 262 18. Maldonado C, Molina CI, Zizka A, Persson C, Taylor CM, Albán J, Chilquillo E, Rønsted N,
263 Antonelli A. 2015 Estimating species diversity and distribution in the era of Big Data: to
264 what extent can we trust public databases? *Gobal Ecol. Biogeogr.* **24**, 973–984.
265 (doi:10.1111/geb.12326)
- 266 19. MacKenzie DI, Nichols JD, Royle JA, Pollock KH, Hines JE, Bailey LL. 2006 *Occupancy*
267 *Estimation and Modeling: Inferring Patterns and Dynamics of Species Occurrence*. San
268 Diego, CA, USA: Elsevier.
- 269 20. van Strien AJ, Termaat T, Groenendijk D, Mensing V, Kéry M. 2010 Site-occupancy models
270 may offer new opportunities for dragonfly monitoring based on daily species lists. *Basic*
271 *Appl. Ecol.* **11**, 495–503. (doi:10.1016/j.baae.2010.05.003)
- 272 21. van Strien AJ, van Swaay CAM, Kéry M. 2011 Metapopulation dynamics in the butterfly
273 *Hipparchia semele* changed decades before occupancy declined in The Netherlands. *Ecol.*
274 *Appl.* **21**, 2510–2520.
- 275 22. Isaac NJB, van Strien AJ, August TA, de Zeeuw MP, Roy DB. 2014 Statistics for citizen
276 science: Extracting signals of change from noisy ecological data. *Methods Ecol. Evol.* **5**,
277 1052–1060. (doi:10.1111/2041-210X.12254)
- 278 23. Noon BR, Bailey LL, Sisk TD, McKelvey KS. 2012 Efficient Species-Level Monitoring at
279 the Landscape Scale. *Conserv. Biol.* **26**, 432–441. (doi:10.1111/j.1523-1739.2012.01855.x)
- 280 24. Kéry M, Schaub M. 2012 *Bayesian Population Analysis Using WinBUGS: A Hierarchical*
281 *Perspective*. Elsevier.
- 282 25. Calabuig I. 2014 Danish ants (Formicidae). Copenhagen, Denmark: Zoological Museum,
283 Natural History Museum of Denmark. (doi:10.15468/xcwkbfb)

- 284 26. Simonsen T, Sheard JK. 2020 *Natural History Museum Aarhus Ant Collection*. Version 1.2.
285 Aarhus, Denmark: Natural History Museum Aarhus. (doi:0.15468/wp3kzr)
- 286 27. Sheard JK, Nielsen MG, Pedersen JS. 2020 *Skoett Ant Collection*. Version 1.4. Copenhagen,
287 Denmark: Center for Macroecology, Evolution and Climate, University of Copenhagen.
288 Occurrence dataset. (doi:10.15468/2xh5fd)
- 289 28. Sheard JK, Sanders NJ, Dunn RR, Rahbek C. 2020 *The Danish Ant Hunt*. Version 1.8.
290 Copenhagen, Denmark: Center for Macroecology, Evolution and Climate, University of
291 Copenhagen. Sampling event dataset. (doi:10.15468/dcijn)
- 292 29. Fisher B, Fong J (2020). *AntWeb*. San Francisco, CA: California Academy of Sciences.
293 Occurrence dataset (doi:10.15468/wqmjjt)
- 294 30. Sheard JK, Nash DR (2020). *Euroants*. Copenhagen, Denmark: Department of Biology,
295 University of Copenhagen. Occurrence dataset. (doi:10.15468/jpacce)
- 296 31. Fiskå A. 2018 *MUST, Insecta. Version 9.266*. Stavanger, Norway: Museum Stavanger.
297 (doi:10.15468/zkm8mj)
- 298 32. van Strien AJ, van Swaay CAM, Termaat T. 2013 Opportunistic citizen science data of
299 animal species produce reliable estimates of distribution trends if analysed with occupancy
300 models. *J. Appl. Ecol.* **50**, 1450–1458. (doi:10.1111/1365-2664.12158)
- 301 33. Kéry M, Royle JA, Schmid H, Schaub M, Volet B, Häfliger G, Zbinden N. 2010 Site-
302 occupancy distribution modeling to correct population-trend estimates derived from
303 opportunistic observations. *Conserv. Biol.* **24**, 1388–1397. (doi:10.1111/j.1523-
304 1739.2010.01479.x)
- 305 34. Woodcock BA, Isaac NJB, Bullock JM, Roy DB, Garthwaite DG, Crowe A, Pywell RF.

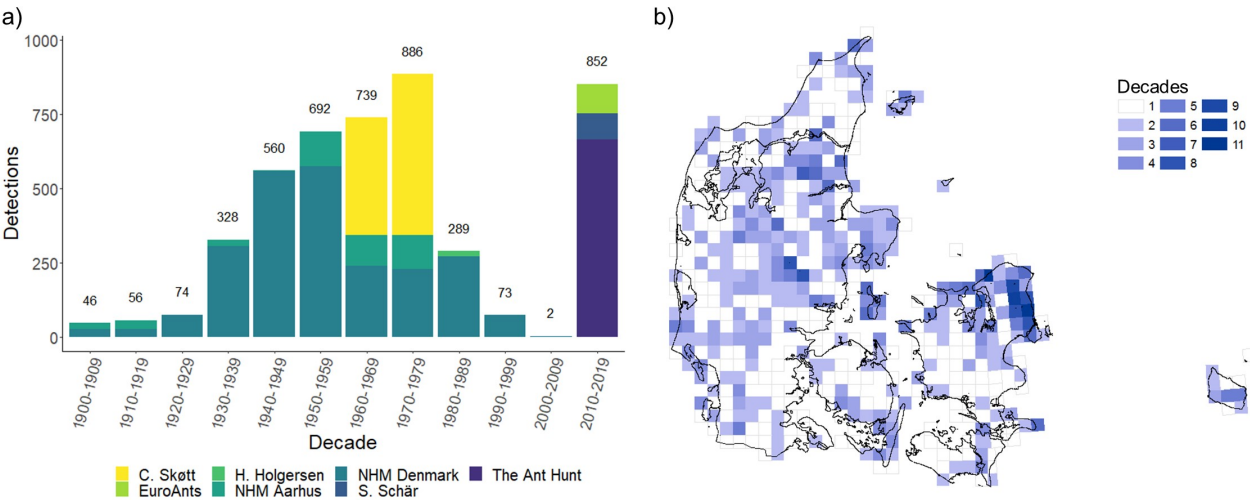
- 306 2016 Impacts of neonicotinoid use on long-term population changes in wild bees in England.
307 *Nat. Commun.* **7**. (doi:10.1038/ncomms12459)
- 308 35. Powney GD, Carvell C, Edwards M, Morris RKA, Roy HE, Woodcock BA, Isaac NJB. 2019
309 Widespread losses of pollinating insects in Britain. *Nat. Commun.* **10**. (doi:10.1038/s41467-
310 019-08974-9)
- 311 36. Outhwaite CL, Gregory RD, Chandler RE, Collen B, Isaac NJB. 2020 Complex long-term
312 biodiversity change among invertebrates, bryophytes and lichens. *Nat. Ecol. Evol.* **4**, 384–
313 392. (doi:10.1038/s41559-020-1111-z)
- 314 37. Dennis EB, Brereton TM, Morgan BJT, Fox R, Shortall CR, Prescott T, Foster S. 2019
315 Trends and indicators for quantifying moth abundance and occupancy in Scotland. *J. Insect*
316 *Conserv.* **23**, 369–380. (doi:10.1007/s10841-019-00135-z)
- 317 38. Pocock MJO, Logie MW, Isaac NJB, Outhwaite CL, August T. 2019. Rapid assessment of
318 the suitability of multi-species citizen science datasets for occupancy trend analysis. *bioRxiv*,
319 813626. (doi:10.1101/813626)
- 320 39. Outhwaite CL *et al.* 2019 Annual estimates of occupancy for bryophytes, lichens and
321 invertebrates in the UK, 1970-2015. *Scient. data* **6**, 259. (doi:10.1038/s41597-019-0269-1)
- 322 40. Seifert B. 1991 *Lasius platythorax* n.sp., a Widespread Sibling Species of *Lasius niger*
323 (Hymenoptera: Formicidae). *Entomol. Gen.* **16**, 69–81.
- 324 41. Outhwaite CL, Chandler RE, Powney GD, Collen B, Gregory RD, Isaac NJB. 2018 Prior
325 specification in Bayesian occupancy modelling improves analysis of species occurrence data.
326 *Ecol. Indic.* **93**, 333–343. (doi:10.1016/j.ecolind.2018.05.010)
- 327 42. Chandler RE, Scott EM. 2011 *Statistical Methods for Trend Detection and Analysis in the*

- 328 *Environmental Sciences*. Chichester, UK.: John Wiley & Sons.
- 329 43. R Core Team. 2018 *R: a language and environment for statistical computing*. Vienna,
330 Austria: R Foundation for Statistical Computing. See <http://www.R-project.org/>.
- 331 44. August T, Powney GD, Outhwaite CL, Harrower CA, Hill M, Hatfield J, Mancini FI, Isaac
332 NJB. 2018 *sparta: Trend analysis for unstructured data. R package version 0.2.07*. See
333 <https://github.com/BiologicalRecordsCentre/sparta>.
- 334 45. Plummer M. 2017 2009 *JAGS. Version 4.3.0*. See [http://sourceforge.net/projects/mcmc-](http://sourceforge.net/projects/mcmc-jags/files/)
335 [jags/files/](http://sourceforge.net/projects/mcmc-jags/files/).
- 336 46. Su Y, Yajima M. 2015 *Package 'R2jags'*. See [https://cran.r-project.org/web/](https://cran.r-project.org/web/packages/R2jags/)
337 [packages/R2jags/](https://cran.r-project.org/web/packages/R2jags/).
- 338 47. Gelman A, Rubin DB. 1992 Inference from Iterative Simulation Using Multiple Sequences.
339 *Stat. Sci.* **7**, 457–511. (doi:10.2307/2246134)
- 340 48. Douwes P, Abenius J, Cederberg B, Wahlstedt U, Hall K, Starkenberg M, Reisborg C,
341 Östman T. 2012 *Nationalnyckeln till Sveriges flora och fauna. Steklar: Myror - getingar.*
342 *Hymenoptera: Formicidae-Vespidae*. [The national key to the flora and fauna of Sweden.
343 Hymenoptera: Formicidae-Vespidae] Uppsala: ArtDatabanken, SLU [In Swedish, with parts
344 in English.].
- 345 49. Seifert B. 2018 *The Ants of Central and North Europe*. Tauer: Lutra Verlags- und
346 Vertriebsgesellschaft.
- 347 50. Nord-Larsen, T., Johannsen, V. K., Riis-Nielsen, T., Thomsen, I. M., & Jørgensen BB. 2020
348 *Skovstatistik 2019: Forest statistics 2019*. Frederiksberg: Institut for Geovidenskab og
349 Naturforvaltning, Københavns Universitet.

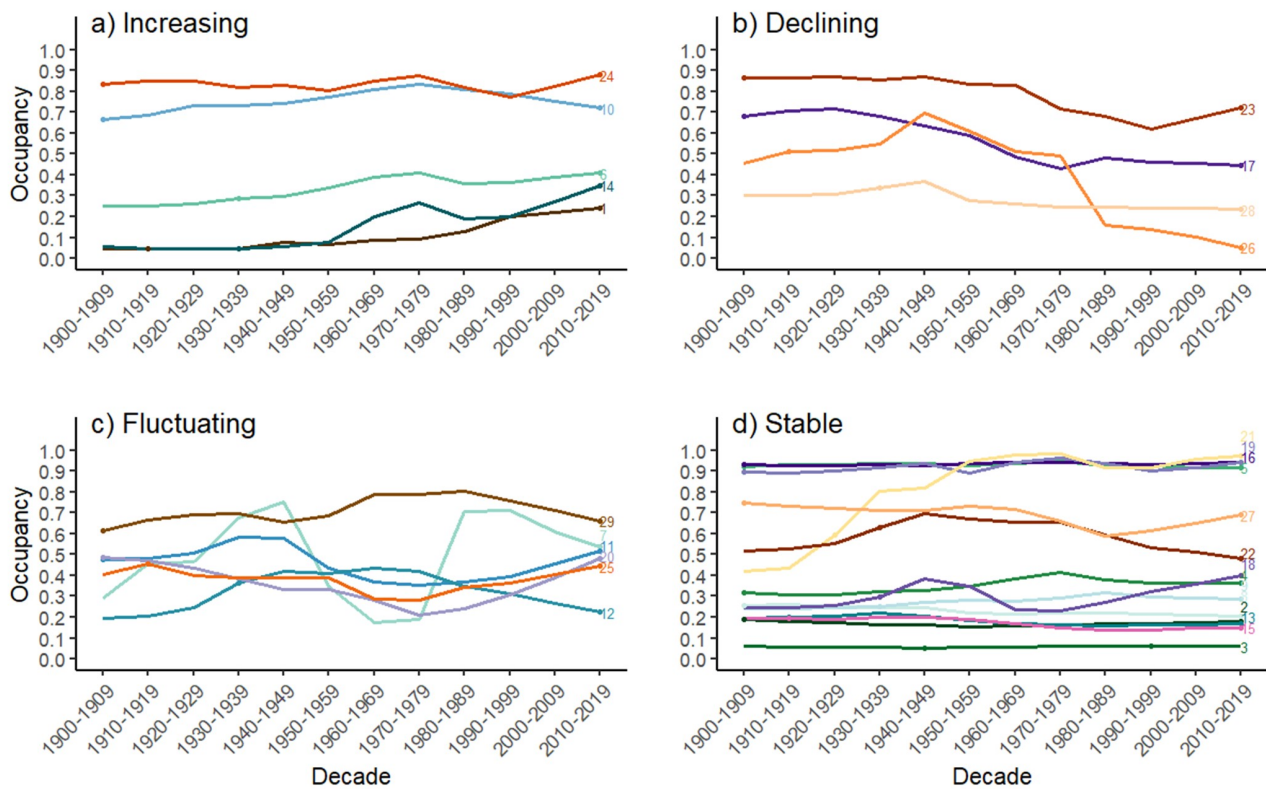
- 350 51. Levin G, Normander B. 2008 Arealanvendelse i Danmark siden slutningen af 1800-tallet.
351 [Land-use in Denmark since the end of the 19th century] *Fagl. Rapp. DMU*, no. 682. Aarhus,
352 Denmark: Danmarks Miljøundersøgelser, Aarhus Universitet. See
353 <http://www.dmu.dk/Pub/FR682.pdf>. [In Danish, with English abstract.]
- 354 52. Dekoninck, W, Hendrickx, F, Grootaert, P, Maelfait, J-P. 2010. Present conservation status
355 of red wood ants in north-western Belgium: Worse than previously, but not a lost cause. *Eur.*
356 *J. Entomol.*, **107**, 209–218.
- 357 53. DMI. 2021 *Klimanormaler for Danmark* [Climate normals for Denmark]. See
358 <https://www.dmi.dk/vejrkiriv/normaler-danmark/> (accessed on 4 February 2021). [In
359 Danish.]
- 360 54. Callaghan CT, Bowler DE, Pereira HM. 2021. Thermal flexibility and a generalist life
361 history promote urban affinity in butterflies. *Glob. Change Biol.*, **27**, 3532–3546.
362 (doi.org/10.1111/gcb.15670)
- 363 55. Witek, M, Barbero, F, Markó, B. 2014. *Myrmica* ants host highly diverse parasitic
364 communities: from social parasites to microbes. *Insect. Soc.*, **61**, 307–323
- 365 56. Härkönen SK, Sorvari J. 2014 Species richness of associates of ants in the nests of red wood
366 ant *Formica polyctena* (Hymenoptera, Formicidae). *Insect Conserv. Divers.* **7**, 485–495.
367 (doi:10.1111/icad.12072)
- 368 57. Ugelvig LV, Nielsen PS, Boomsma JJ, Nash DR. 2011 Reconstructing eight decades of
369 genetic variation in an isolated Danish population of the large blue butterfly *Maculinea arion*.
370 *BMC Evol. Biol.* **11**, 201. (doi:10.1186/1471-2148-11-201)
- 371 58. Sheard, JK, Rahbek, C, Dunn, RR, Sanders, NJ, Isaac, NJB. 2021 Data from: Long-term

372 trends in the occupancy of ants revealed through use of multi-sourced datasets. Dryad
373 Digital Repository. (doi:10.5061/dryad.bnzs7h4bj)

374 **FIGURE AND TABLE LEGENDS**



375
376 **Figure 1.** Temporal and spatial distribution of the combined data set. a) Number of detections for each decade within
377 each data set. b) Number of decades with data for each 10 × 10 km grid cell of Denmark.



ID	Species	Trend	ID	Species	Trend	ID	Species	Trend
1	<i>Camponotus herculeanus</i>	Increasing	11	<i>Formica rufibarbis</i>	Fluctuating	21	<i>Leptothorax acervorum</i>	Stable
2	<i>Formica cinerea</i>	Stable	12	<i>Formica sanguinea</i>	Fluctuating	22	<i>Myrmica lobicornis</i>	Stable
3	<i>Formica cunicularia</i>	Stable	13	<i>Formica truncorum</i>	Stable	23	<i>Myrmica rubra</i>	Declining
4	<i>Formica exsecta</i>	Stable	14	<i>Formica uralensis</i>	Increasing	24	<i>Myrmica ruginodis</i>	Increasing
5	<i>Formica fusca</i>	Stable	15	<i>Formicoxenus nitidulus</i>	Stable	25	<i>Myrmica rugulosa</i>	Fluctuating
6	<i>Formica picea</i>	Increasing	16	<i>Lasius flavus</i>	Stable	26	<i>Myrmica sabuleti</i>	Declining
7	<i>Formica polyctena</i>	Fluctuating	17	<i>Lasius fuliginosus</i>	Declining	27	<i>Myrmica scabrinodis</i>	Stable
8	<i>Formica pratensis</i>	Stable	18	<i>Lasius meridionalis</i>	Stable	28	<i>Myrmica schencki</i>	Declining
9	<i>Formica pressilabris</i>	Stable	19	<i>Lasius niger</i>	Stable	29	<i>Tetramorium caespitum</i>	Fluctuating
10	<i>Formica rufa</i>	Increasing	20	<i>Lasius umbratus</i>	Fluctuating			

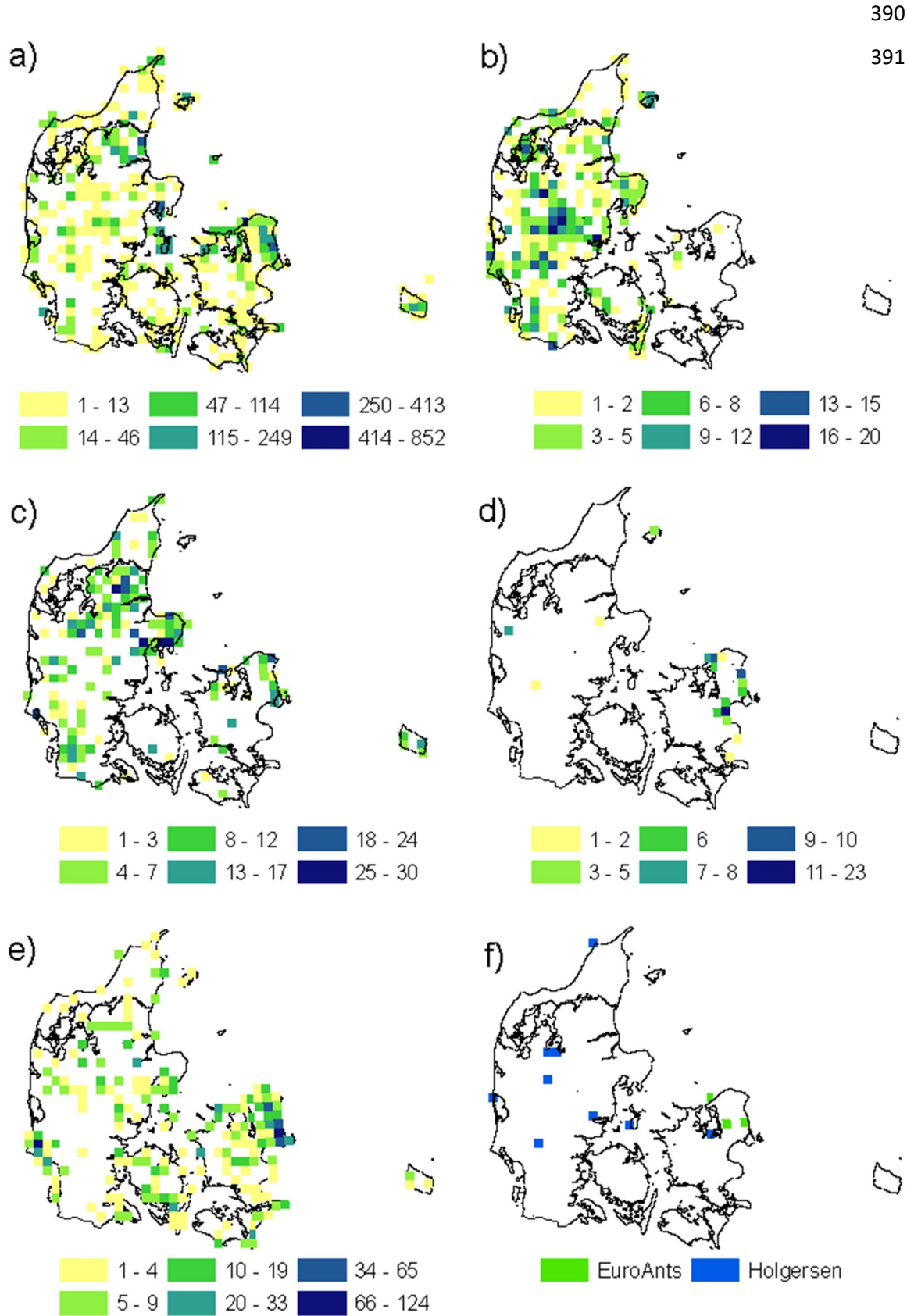
Figure 2. Occupancy trends for 29 ant species in Denmark based on decades from 1900-2019. Each line represents a species labelled by a number as indicated in the key. Lines depict the mean of the posterior distribution of occupancy estimates for each decade: the same data are plotted with credible intervals in ESM S4. Points represent the first and last decade where a species has been detected.

383 **Table S1:** Overview of all native species found in Denmark, including first and last detection year, number of detections in each dataset and the total number of
384 detections.

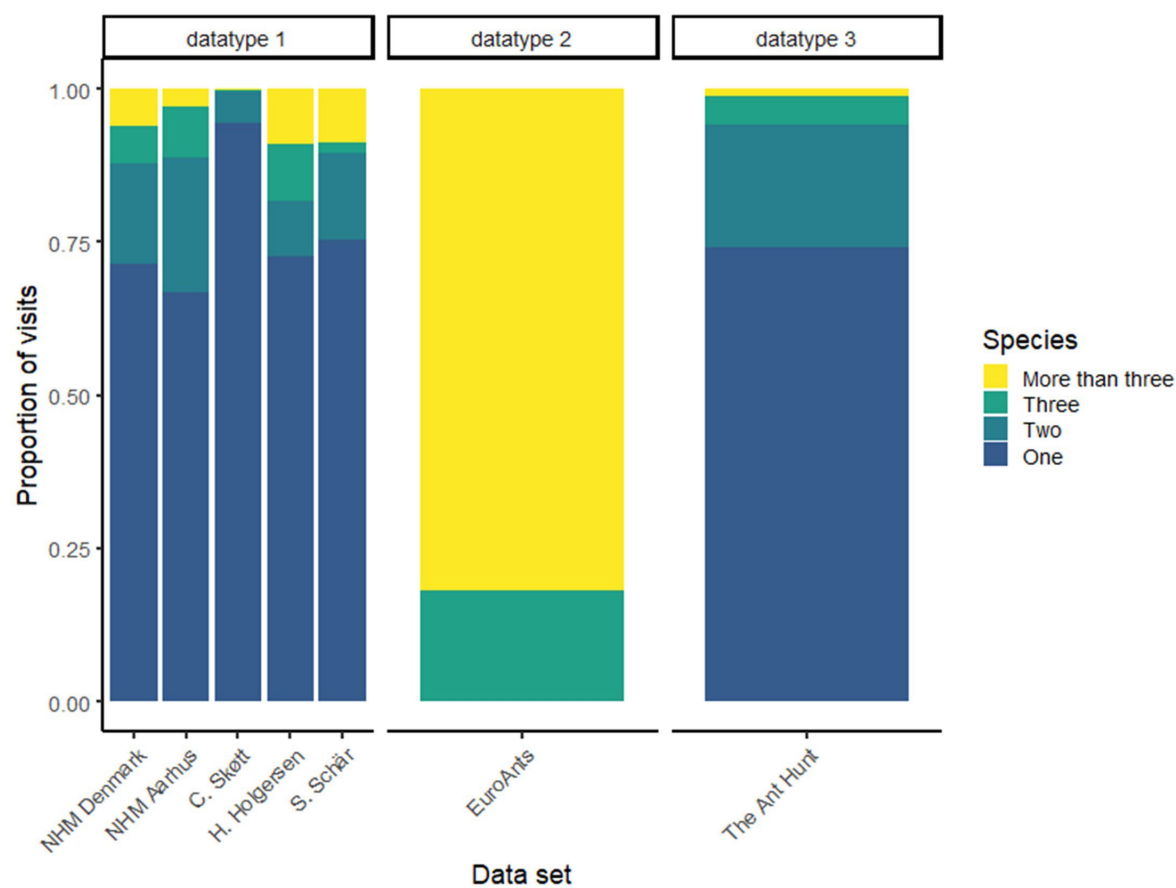
species	decades	years			detections							
		first	last	total (n)	Ant Hunt	EuroAnts	Holgersen	NHM Aarhus	NHM Denmark	Schär	Skøtt	total
<i>Camponotus herculeanus</i>	9	1913	2015	30			2	2	36	1	4	45
<i>Camponotus ligniperda</i>	6	1929	2015	9				1	7	1	1	10
<i>Formica cinerea</i>	9	1909	2018	30	6		2		55		9	72
<i>Formica clara</i>	1	2012	2018	2	4	1						5
<i>Formica cunicularia</i>	5	1942	1994	16					22			22
<i>Formica exsecta</i>	8	1908	2017	36	1		1	3	43	2	33	83
<i>Formica foreli</i>	1	2012	2019	3		3				1		4
<i>Formica forsslundi</i>	2	1974	1989	2					2			2
<i>Formica fusca</i>	12	1901	2019	77	85	5	1	37	196	3	84	411
<i>Formica gagatoides</i>	2	1964	1972	3				2	2			4
<i>Formica lugubris</i>	2	1941	2018	2	1				1			2
<i>Formica picea</i>	8	1935	2019	32	1	2	1		28	2	43	77
<i>Formica polystena</i>	10	1914	2019	52	34	6			109	3		152
<i>Formica pratensis</i>	10	1908	2017	36	1			3	47		16	67
<i>Formica pressilabris</i>	7	1939	2017	32	1	2	1	1	40		13	58
<i>Formica rufa</i>	11	1908	2018	68	7	3		50	154	3	87	304
<i>Formica rufibarbis</i>	10	1909	2019	55	4	5		2	128	4	12	155
<i>Formica sanguinea</i>	8	1935	2018	48	2	2		3	101	1	41	150
<i>Formica trunctorum</i>	8	1918	2017	27	2			2	37	1	4	46
<i>Formica uralensis</i>	7	1938	2019	20		3	1	1	48	1	29	83
<i>Formicoxenus nitidulus</i>	7	1912	2012	19				1	21	1	3	26
<i>Harpagoxenus sublaevis</i>	2	1964	1974	6					9		7	16
<i>Hypoconera punctatissima</i>	6	1944	2017	9	1				18		9	28
<i>Lasius brunneus</i>	6	1907	2019	8		1		1	8			10
<i>Lasius flavus</i>	9	1903	2019	48	22	6	1	16	71	4	52	172
<i>Lasius fuliginosus</i>	11	1908	2019	54	11	5	2	14	79	1	21	133
<i>Lasius meridionalis</i>	8	1935	2015	25					36	6		42
<i>Lasius mixtus</i>	7	1913	1971	10					12		2	14

<i>Lasius niger</i>	11	1903	2019	77	323	5	3	37	196	6	90	660
<i>Lasius platythorax</i>	1	2012	2018	5	41	7				4		52
<i>Lasius psammophilus</i>	1	2012	2019	6	2	4				4		10
<i>Lasius umbratus</i>	11	1900	2019	51	1	4		13	60	4	8	90
<i>Leptothorax acervorum</i>	10	1924	2019	42		5		6	84	6	88	189
<i>Leptothorax muscorum</i>	2	1971	1993	4					2		2	4
<i>Myrmecina graminicola</i>	1	1970	1970	1				1				1
<i>Myrmica lobicornis</i>	7	1933	2017	32	2			1	35	1	14	53
<i>Myrmica rubra</i>	11	1902	2019	70	37	4	1	49	158	7	46	302
<i>Myrmica ruginodis</i>	10	1904	2019	66	35	7	1	106	126	4	81	360
<i>Myrmica rugulosa</i>	10	1913	2018	48	6			18	62	4	18	108
<i>Myrmica sabuleti</i>	10	1911	2019	47	4	4		2	93	4	15	122
<i>Myrmica scabrinodis</i>	11	1901	2017	63	4	5	1	26	108	6	39	189
<i>Myrmica schencki</i>	7	1936	2018	28	3			1	39		6	49
<i>Myrmica specioidea</i>	3	1941	2012	3		1			2	1		4
<i>Myrmica sulcinodis</i>	5	1936	1973	10				1	12		12	25
<i>Stenamma debile</i> or <i>S. westwoodii</i>	2	1958	1995	2				1	1			2
<i>Temnothorax interruptus</i>	3	1969	1980	3					5			5
<i>Temnothorax nylanderi</i>	2	1988	2012	2		1			1			2
<i>Temnothorax parvulus</i>	1	2012	2012	1		1						1
<i>Temnothorax tuberum</i>	3	1942	1985	4					5			5
<i>Tetramorium atratulum</i>	1	1942	1942	1					1			1
<i>Tetramorium caespitum</i>	11	1903	2019	50	25	4	2	7	79	2	51	170

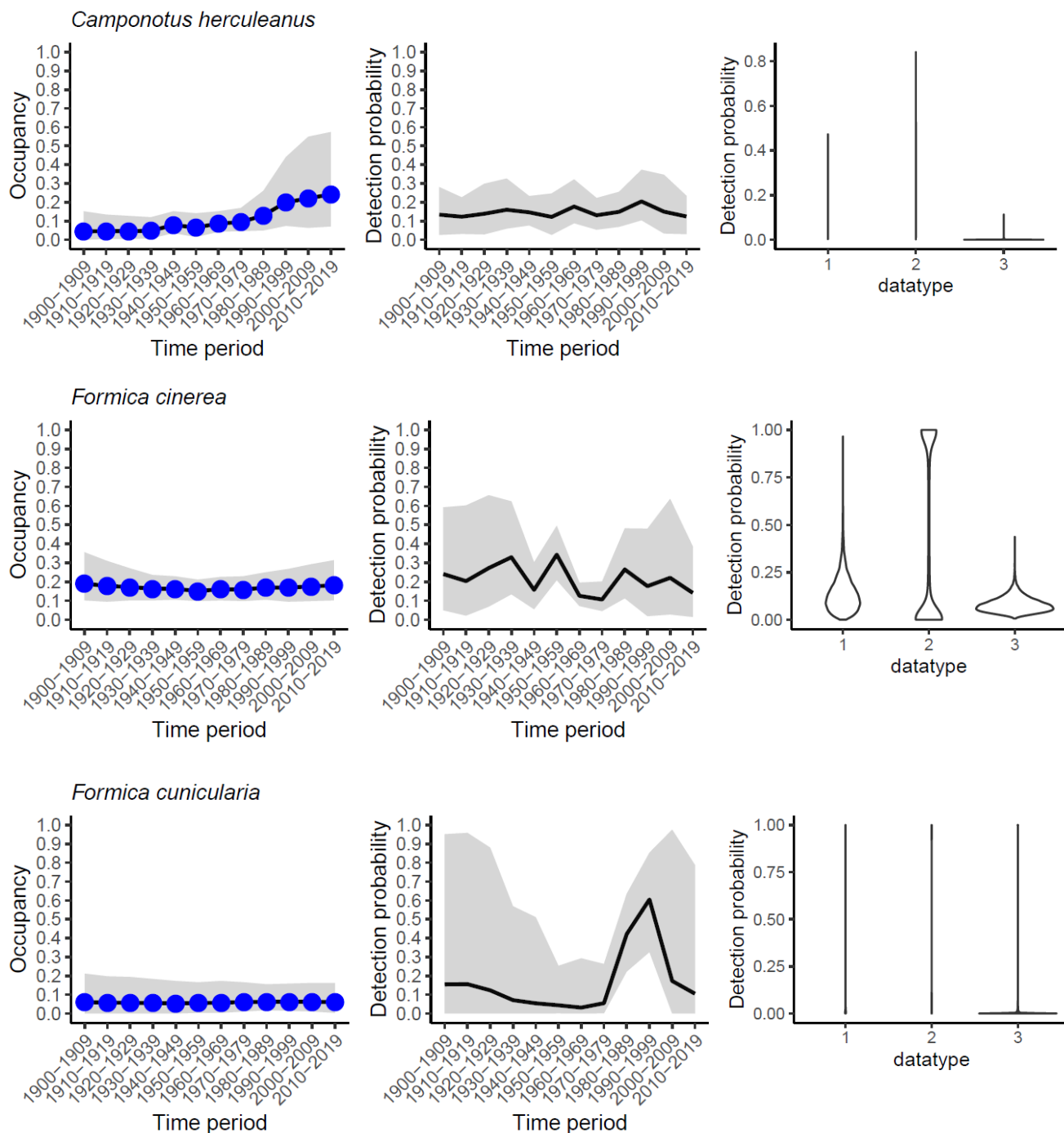
386 **Figure S2:** 10x10 km grid cell map of each of the data sets used in the study: a) the Natural History Museum of
 387 Denmark, scaled by number of occurrences, b) Christian Skøtt, scaled by number of occurrences, c) Natural History
 388 Museum of Aarhus, scaled by number of occurrences, d) Sāmi Schär, scaled by number of occurrences, e) the Ant
 389 Hunt, scaled by number of occurrences and f) EuroAnts and Holger Holgersen, no scaling.

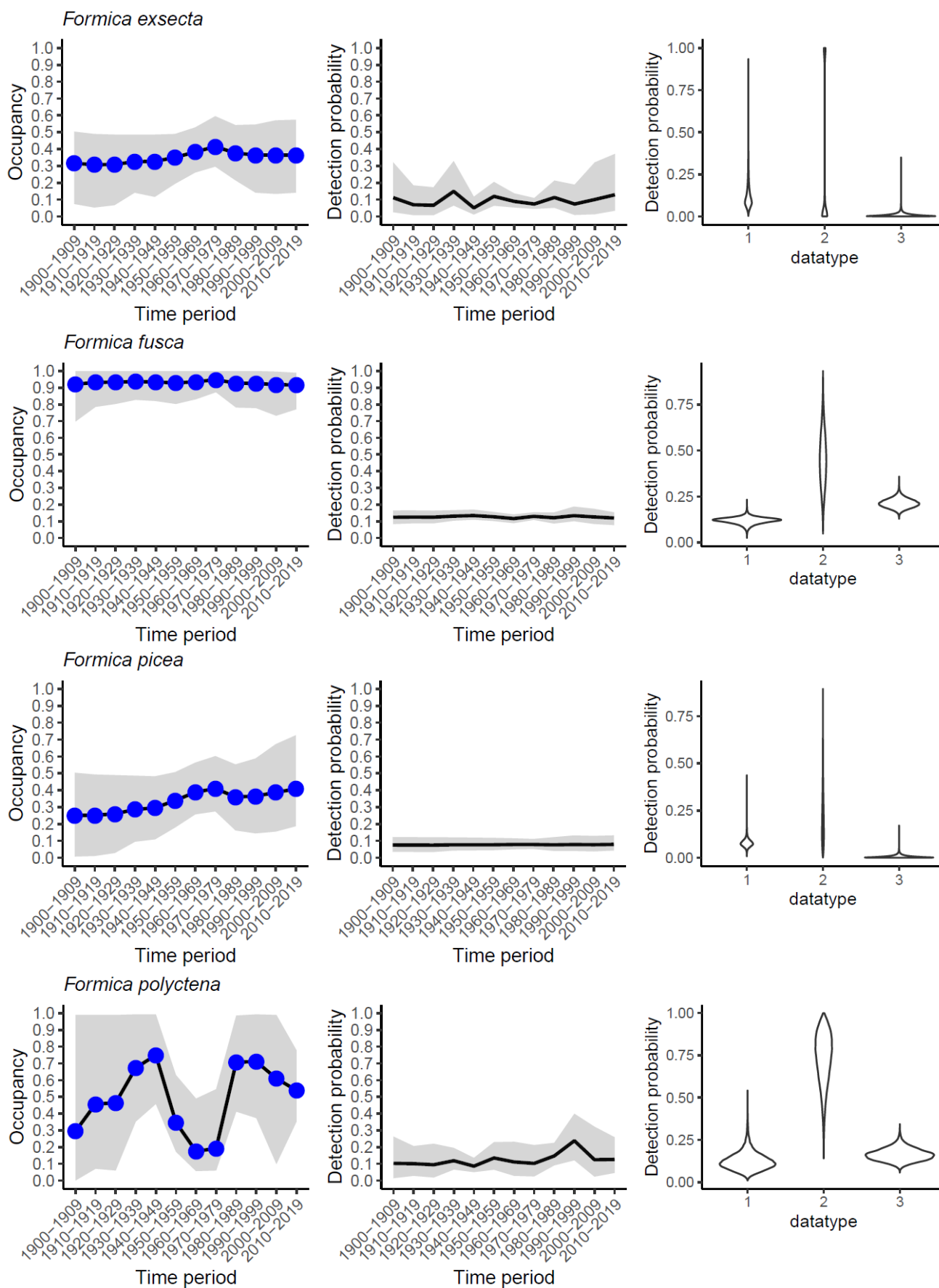


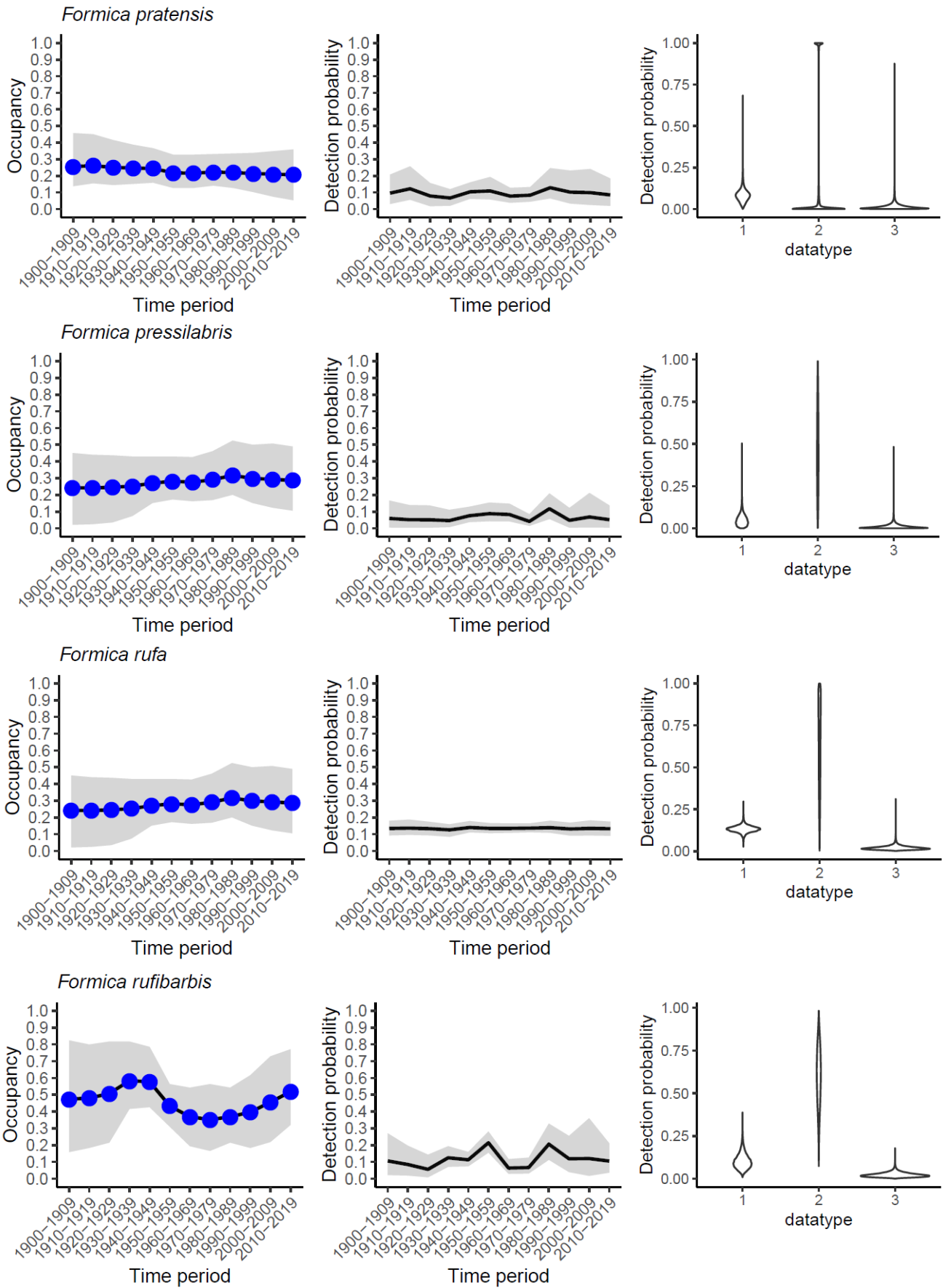
392 **Figure S3:** The proportion of visits that consist of a detection of a single species, two species, three species, or more
 393 than three species for the seven individual data sets grouped by datatype. A visit is a unique combination of site, here a
 394 10x10 km grid cell, and a date, here between 1900 and 2019. Data sets from the Natural History Museum of Aarhus, the
 395 Natural History Museum of Denmark, Christian Skøtt, Holger Holgersen, Sämi Schär and the Ant Hunt all had a
 396 median list length of 1 (mean = 1.49, 1.53, 1.06, 1.64, 1.54 and 1.33, respectively). The EuroAnts course had a median
 397 list length of 8 (mean = 9.09).



400 **Figure S4:** Decadal occupancy and detection probability for 29 ant species in Denmark from 1900-2019. The first
 401 column shows estimated occupancy for each decade. Blue dots indicate that models have converged ($R_{\text{hat}} < 1.1$). Solid
 402 lines represent the average values and the shaded area is the associated 95 % credible interval. The second column
 403 shows detection probability generated by the plot_DetectionOverTime function in the package Sparta for ListLength
 404 category 1 (The Natural History Museum of Denmark, the Natural History Museum of Aarhus, Holger Holgersen, Sæmi
 405 Schär and Christian Skøtt), defined by the at parameter. Solid lines represent the average values and the shaded area is
 406 the associated 95 % credible interval. The third column shows detection probability for the last decade (2010-2019)
 407 for each of the three datatypes (1 =the Natural History Museum of Denmark, the Natural History Museum of Aarhus,
 408 Holger Holgersen, Sæmi Schär, Christian Skøtt. 2 = the EuroAnts course and 3 = the Ant Hunt citizen science project).
 409 The difference between categories 2 and 3 are defined by parameters β_1 and β_2 .







419

Formica sanguinea

420

421

422

423

424

425

426

427

428

429

430

431

432

433

434

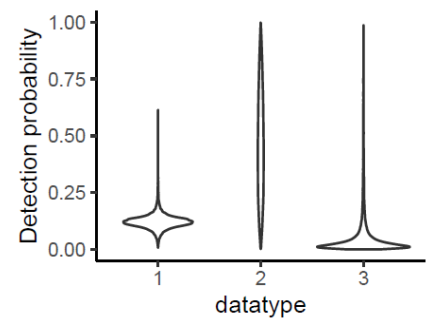
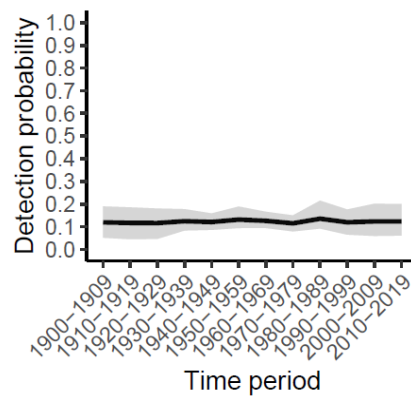
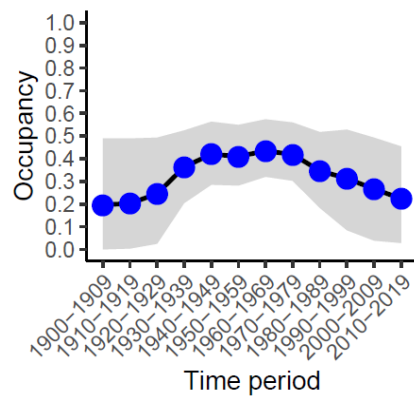
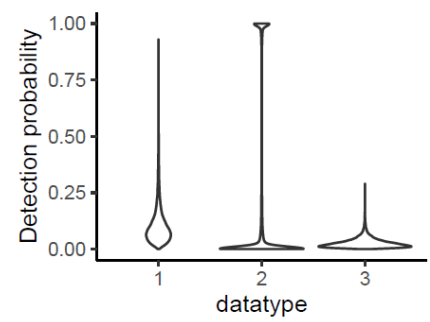
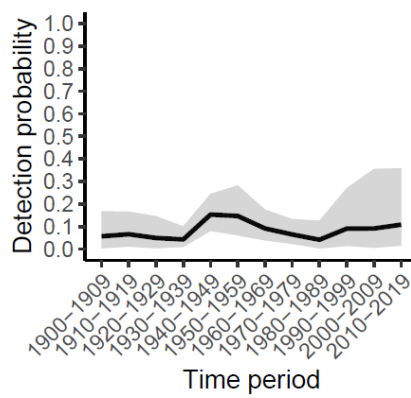
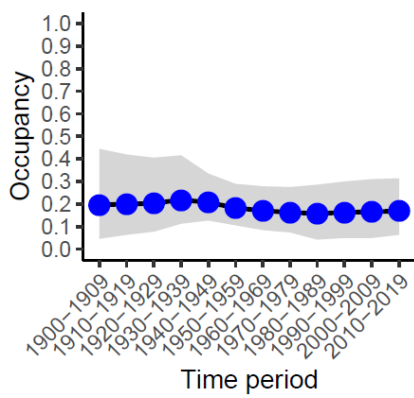
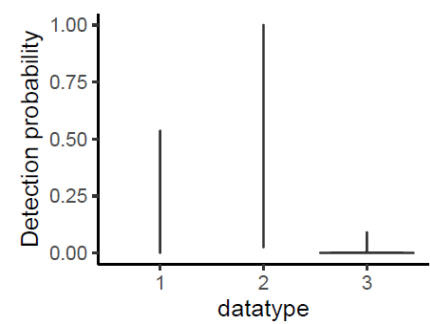
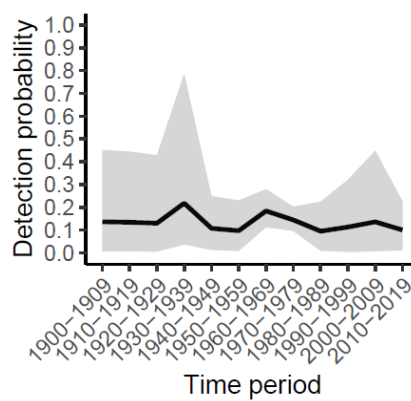
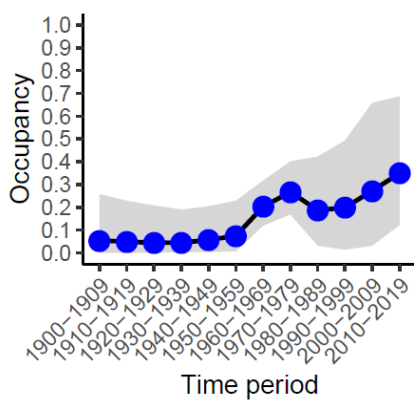
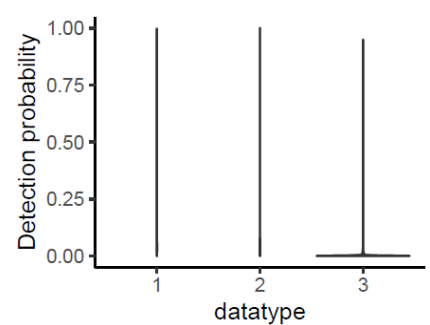
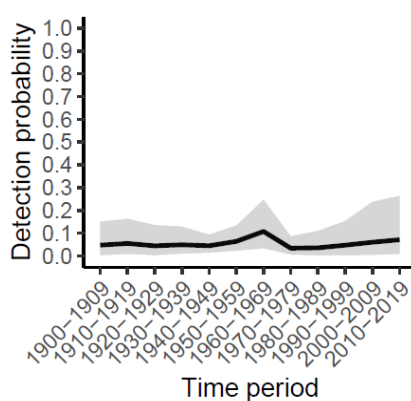
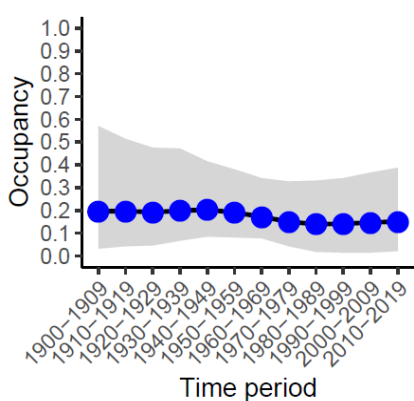
435

436

437

438

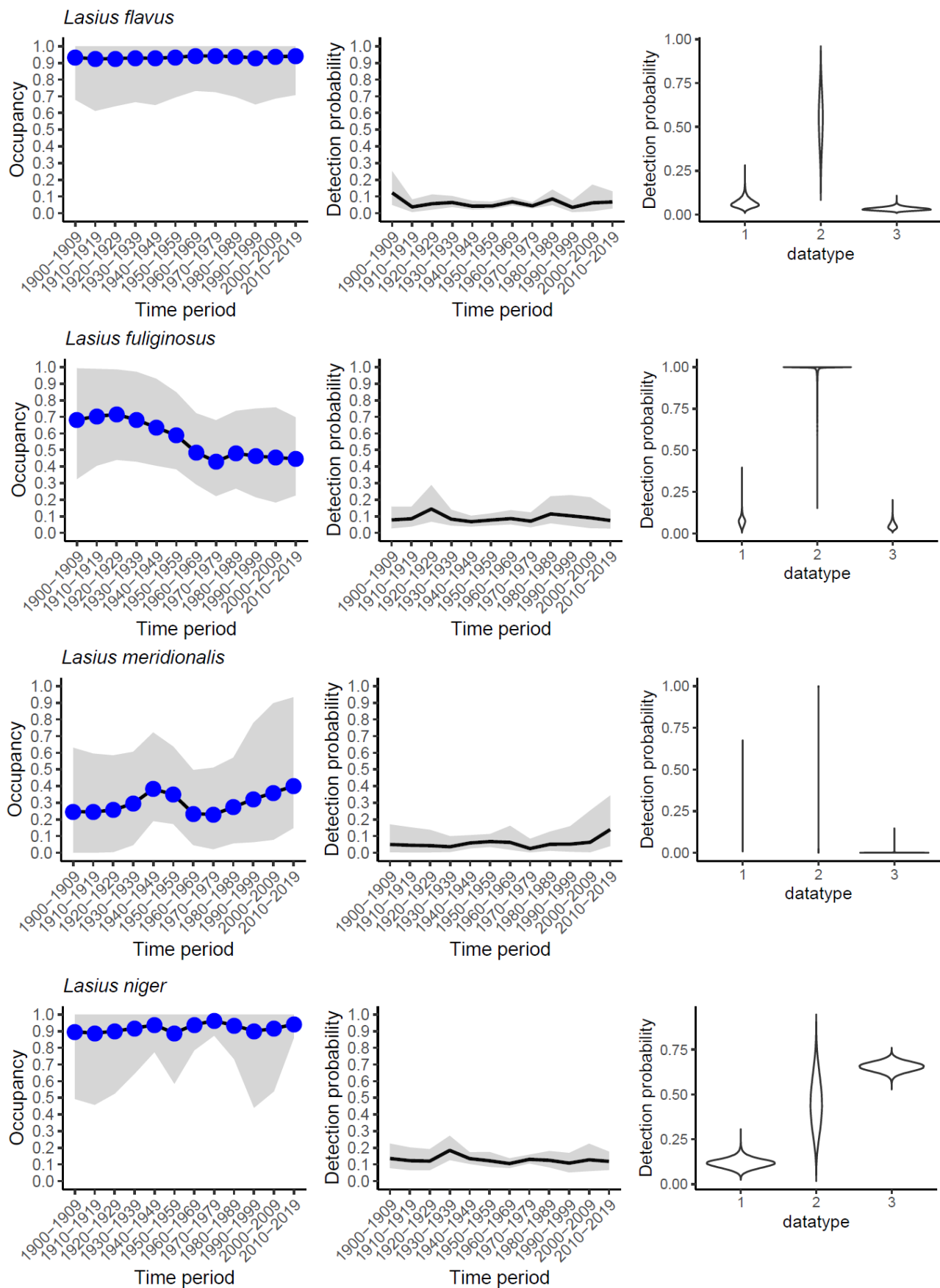
439

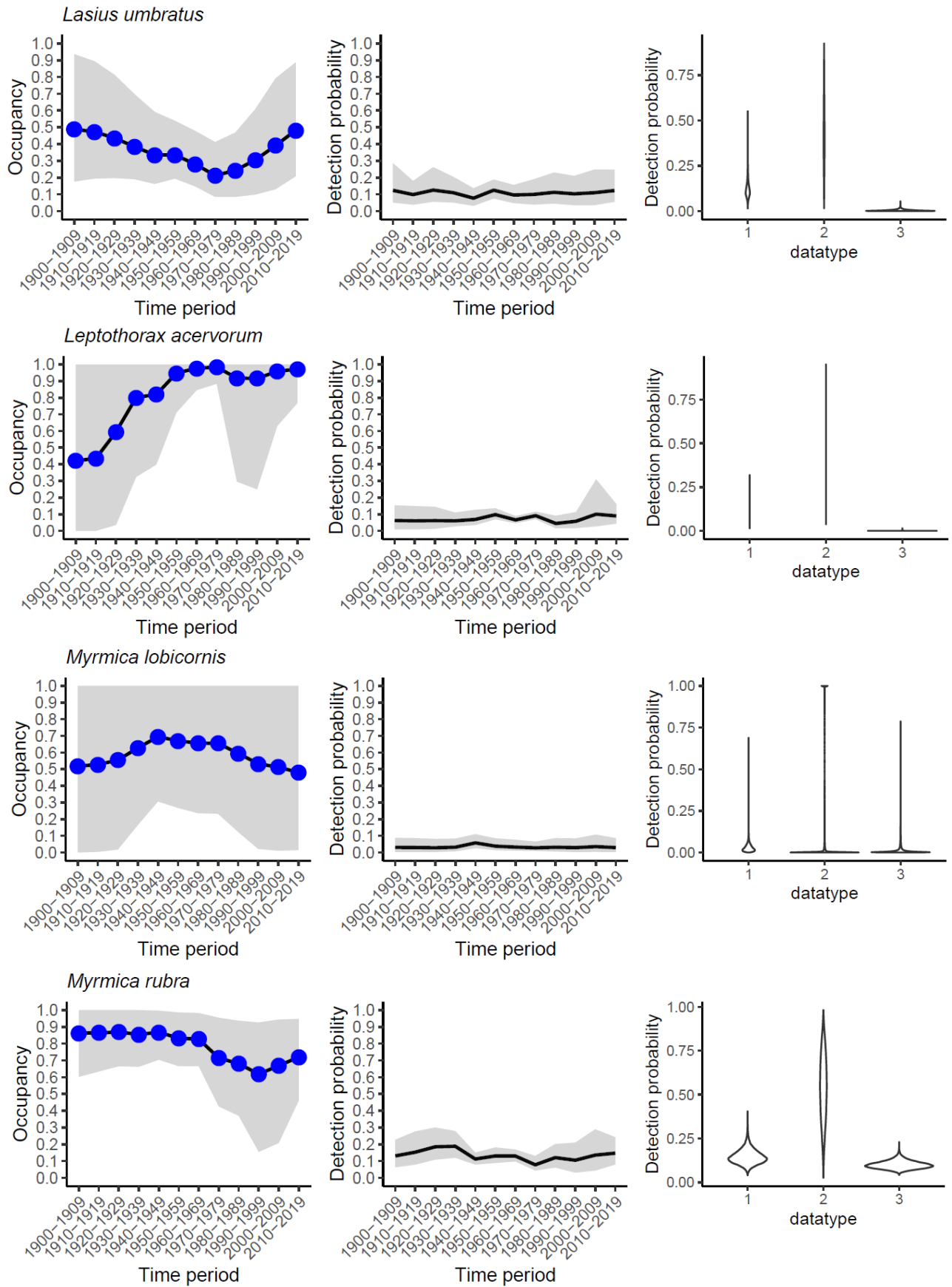
*Formica truncorum**Formica uralensis**Formicoxenus nitidulus*

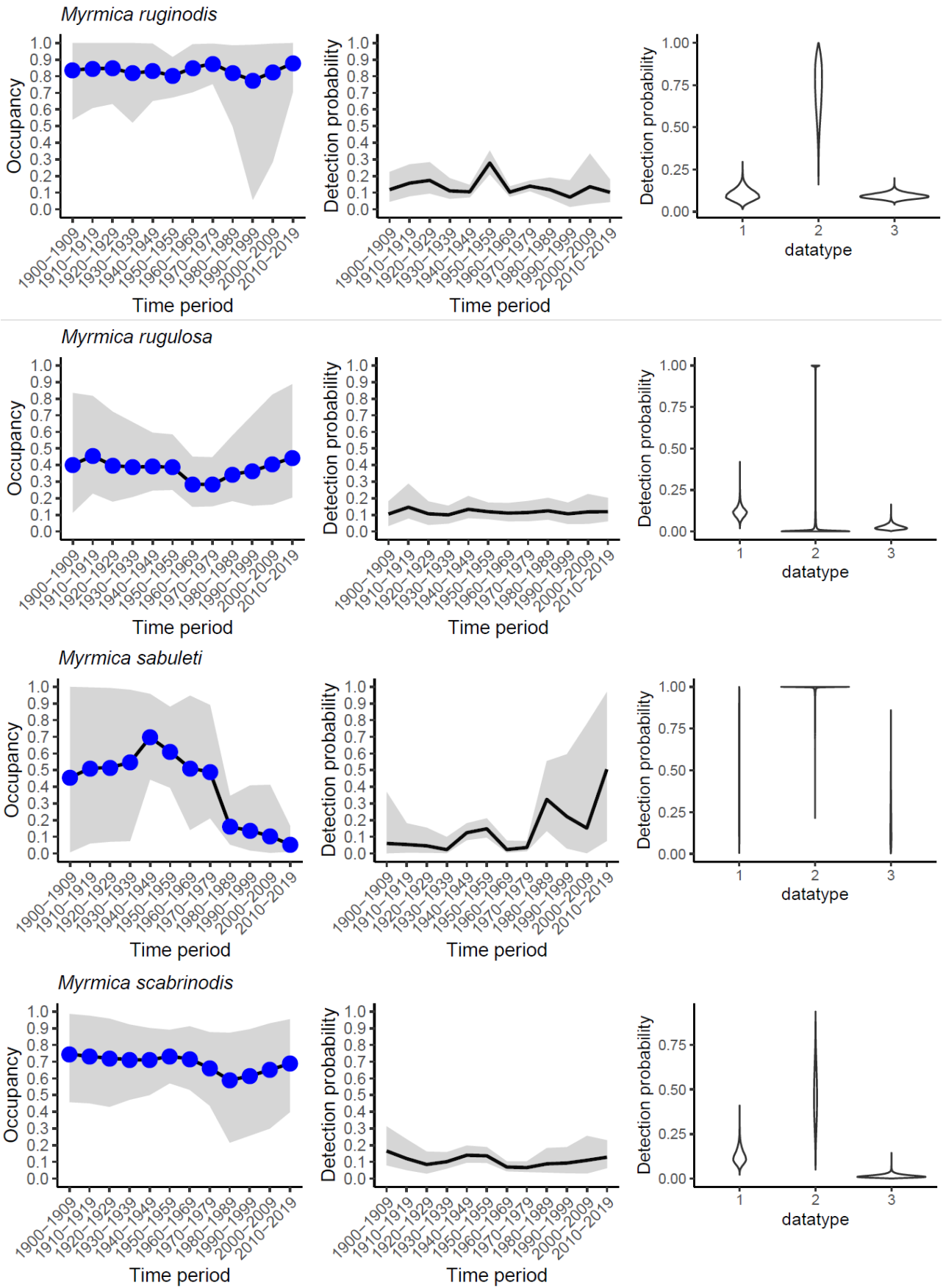
440

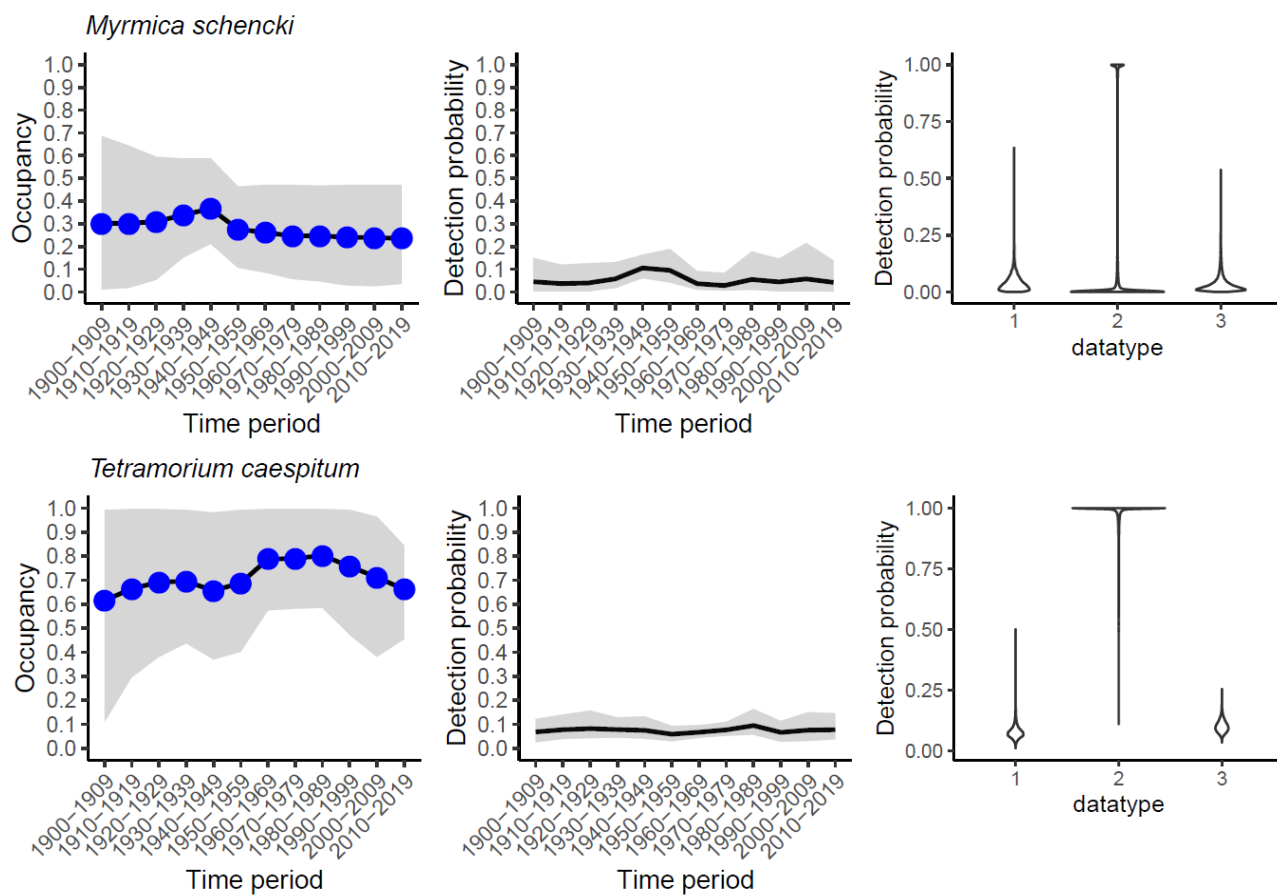
441

442









445

446 **Table S5: Species suitability for modelling**

447 Calculations of two metrics used to determine whether there is sufficient data to warrant occupancy modelling for each species in the two largest datasets individually
 448 and the combined dataset. The two metrics were the number of records of the focal species in the 10 % best recorded decades (90th percentile) and the proportion of
 449 total recording visits within the dataset that resulted in non-detections for the focal species, determined to be the best at describing suitability according to Pocock et al.
 450 2019. Species were determined to be suitable for occupancy modelling if either 1) the proportion of visits with non-detection of the focal species was < 0.958 and the
 451 90th percentile number of detections within a decade was ≥ 29 or 2) if the proportion of visits with non-detection of the focal species was ≥ 0.958 and the 90th
 452 percentile number of detections within a decade was ≥ 9.5 .

Species	NHM Denmark			NHM Aarhus			all data sets combined		
	90% detections	prop. non- detection	suitable?	90% detections	prop. non- detection	suitable?	90% detections	prop. non- detection	suitable?
<i>Camponotus herculeanus</i>	6.4	0.976	no	1	0.991	no	8.3	0.984	no
<i>Camponotus ligniperda</i>	2	0.995	no			no	2.6	0.997	no
<i>Formica cinerea</i>	12.4	0.961	yes			no	17.2	0.974	yes
<i>Formica clara</i>			no			no	4	0.998	no
<i>Formica cunicularia</i>	8.6	0.984	no			no	8.6	0.992	no
<i>Formica exsecta</i>	11.2	0.969	yes	1	0.987	no	19.5	0.970	yes
<i>Formica foreli</i>			no			no	3	0.999	no
<i>Formica forsslundi</i>	1	0.998	no			no	1	0.999	no
<i>Formica fusca</i>	43	0.859	yes	13	0.847	no	77.3	0.856	yes
<i>Formica gagatoides</i>			no	1	0.991	no	1	0.999	no
<i>Formica lugubris</i>	1	0.999	no			no	1	0.999	no
<i>Formica picea</i>	7.4	0.979	no			no	20.9	0.972	yes
<i>Formica polycтена</i>	20.4	0.921	no			no	23.3	0.947	no
<i>Formica pratensis</i>	10.6	0.966	yes	1.9	0.987	no	13.2	0.975	yes
<i>Formica pressilabris</i>	11	0.969	yes	1	0.996	no	12	0.978	yes
<i>Formica rufa</i>	36.3	0.888	yes	21	0.790	no	63	0.892	yes
<i>Formica rufibarbis</i>	30.6	0.907	yes	1	0.991	no	28.9	0.944	no
<i>Formica sanguinea</i>	19.8	0.928	no	1	0.991	no	32.6	0.947	yes
<i>Formica truncorum</i>	12	0.973	yes	1	0.991	no	11.5	0.983	yes
<i>Formica uralensis</i>	10.8	0.980	no	1	0.996	no	18.6	0.982	yes
<i>Formicoxenus nitidulus</i>	6.6	0.985	no	1	0.996	no	6.8	0.991	no
<i>Harpagoxenus sublaevis</i>	3.9	0.995	no			no	5.9	0.996	no
<i>Hypoponera punctatissima</i>	3.8	0.992	no			no	5.5	0.994	no
<i>Lasius alienus</i>			no			no	2	0.999	no
<i>Lasius brunneus</i>	3.6	0.995	no	1	0.996	no	3.2	0.997	no

<i>Lasius flavus</i>	16	0.948	no	5.4	0.934	no	32.2	0.937	yes
<i>Lasius fuliginosus</i>	14.4	0.946	no	4	0.952	no	18	0.957	no
<i>Lasius meridionalis</i>	10.6	0.973	yes			no	10.2	0.984	yes
<i>Lasius mixtus</i>	2.5	0.992	no			no	2.5	0.995	no
<i>Lasius niger</i>	40	0.863	yes	11.5	0.856	no	81	0.798	yes
<i>Lasius platythorax</i>			no			no	42	0.984	yes
<i>Lasius psammophilus</i>			no			no	10	0.996	no
<i>Lasius umbratus</i>	10.6	0.957	no	3	0.948	no	13	0.968	yes
<i>Leptothorax acervorum</i>	21.2	0.937	no	2.6	0.978	no	40.8	0.932	yes
<i>Leptothorax muscorum</i>	1	0.999	no			no	2	0.999	no
<i>Myrmecina graminicola</i>			no	1	0.996	no	1	1.000	no
<i>Myrmica lobicornis</i>	13	0.973	no			no	12.6	0.981	yes
<i>Myrmica rubra</i>	30.7	0.892	yes	15.5	0.795	no	42.8	0.896	yes
<i>Myrmica ruginodis</i>	27.2	0.908	no	38.8	0.594	yes	76.4	0.877	yes
<i>Myrmica rugulosa</i>	16.6	0.953	no	4.6	0.930	no	18.1	0.962	yes
<i>Myrmica sabuleti</i>	33.9	0.932	yes	1	0.996	no	33.3	0.957	yes
<i>Myrmica scabrinodis</i>	33.2	0.920	yes	5.5	0.891	no	37	0.930	yes
<i>Myrmica schencki</i>	15	0.971	yes	1	0.996	no	14.4	0.982	yes
<i>Myrmica specioides</i>	1	0.998	no			no	1	0.999	no
<i>Myrmica sulcinodis</i>	3.2	0.993	no	1	0.996	no	8	0.993	no
<i>Stenammina debile</i> or <i>S. westwoodii</i>			no	1	0.996	no	1	1.000	no
<i>Temnothorax interruptus</i>	2.6	0.996	no			no	2.6	0.998	no
<i>Temnothorax nylanderi</i>	1	0.999	no			no	1	0.999	no
<i>Temnothorax parvulus</i>			no			no	1	1.000	no
<i>Temnothorax tuberum</i>	1.8	0.997	no			no	1.8	0.998	no
<i>Tetramorium atratulum</i>	1	0.999	no			no	1	1.000	no
<i>Tetramorium caespitum</i>	14	0.943	no	3.6	0.969	no	30	0.940	yes
Suitable species			14			1			24

453

454

455 **Table S6:** Overview of all analysed species, including number of iterations needed to reach convergence, Rhat values,
 456 Precision, mean occupancy in each time period, directional occupancy change, 95 % equal-tailed credible intervals and
 457 confidence of change. Confidence above 80 %, indicating occupancy change, has been highlighted in bold.

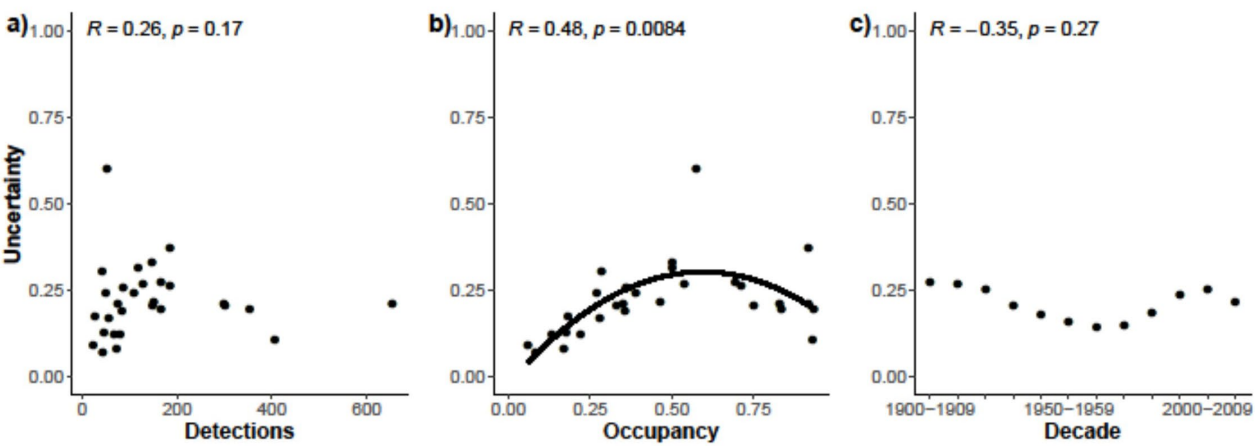
Species	Iterations	Rhat _{mean}	Rhat _{min}	Rhat _{max}	Precision	Time Period	Change	95% ETI	Confidence	Mean occupancy											
										1900-1909	1910-1919	1920-1929	1930-1939	1940-1949	1950-1959	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009	2010-2019
Stable species																					
<i>F. cinerea</i>	50000	1.016	1.003	1.029	0.034	1900-1909 to 1950-1959	-0.04	-0.22, 0.04	73	0.190	0.178	0.172	0.164	0.162	0.151						
						1950-1959 to 2010-2019	0.03	-0.05, 0.18	68							0.160	0.160	0.169	0.169	0.175	0.181
<i>F. cunicularia</i>	50000	1.066	1.038	1.100	0.009	1900-1909 to 1940-1949	-0.006	-0.08, 0.03	45	0.060	0.058	0.057	0.055	0.054							
						1940-1949 to 1990-1999	0.008	-0.05, 0.08	59						0.055	0.058	0.061	0.062	0.063		
						1990-1999 to 2010-2019	-0.002	-0.06, 0.05	48											0.062	0.061
<i>F. exsecta</i>	200000	1.015	1.008	1.020	0.026	1900-1909 to 1910-1919	-0.009	-0.15, 0.09	51	0.316	0.307										
						1910-1919 to 1970-1979	0.11	-0.04, 0.47	77			0.309	0.325	0.327	0.350	0.383	0.414				
						1970-1979 to 1990-1999	-0.05	-0.36, 0.07	65									0.377	0.364		
						1990-1999 to 2000-2009	0.0004	-0.13, 0.14	47											0.365	
						2000-2009 to 2010-2019	-0.0009	-0.14, 0.14	47												0.364
<i>F. fusca</i>	100000	1.006	1.002	1.010	8.634	1900-1909 to 1930-1939	0.02	-0.07, 0.22	49	0.921	0.932	0.934	0.937								
						1930-1939 to 1950-1959	-0.008	-0.12, 0.07	51					0.934	0.929						
						1950-1959 to 1970-1979	0.02	-0.04, 0.15	62							0.936	0.948				
						1970-1979 to 2010-2019	-0.03	-0.20, 0.05	66									0.927	0.926	0.918	0.917
<i>F. pratensis</i>	100000	1.020	1.007	1.032	0.009	1900-1909 to 1910-1919	0.005	-0.08, 0.11	52	0.256	0.261										
						1910-1919 to 1960-1969	-0.04	-0.25, 0.04	73			0.251	0.247	0.244	0.218	0.215					
						1960-1969 to 1970-1979	0.007	-0.04, 0.08	54								0.222				
<i>F. pressilabris</i>	50000	1.013	1.001	1.035	0.013	1900-1909 to 1910-1919	-0.001	-0.09, 0.08	46	0.243	0.242										
						1910-1919 to 1950-1959	0.04	-0.10, 0.27	63			0.245	0.252	0.270	0.281						
						1950-1959 to 1960-1969	-0.005	-0.12, 0.08	50							0.276					
						1960-1969 to 1980-1989	0.04	-0.05, 0.26	69								0.291	0.317			
						1980-1989 to 2010-2019	-0.03	-0.28, 0.11	59											0.298	0.293
<i>F. truncorum</i>	50000	1.008	1.001	1.017	0.039	1900-1909 to 1930-1939	0.02	-0.14, 0.23	61	0.197	0.199	0.203	0.219						0.162	0.165	0.169
						1930-1939 to 1980-1989	-0.06	-0.29, 0.05	77					0.207	0.182	0.170	0.162	0.158			
						1980-1989 to 2010-2019	0.01	-0.09, 0.16	53										0.162	0.165	0.169
<i>F. nitidulus</i>	50000	1.009	1.002	1.015	0.139	1900-1909 to 1910-1919	0.001	-0.15, 0.13	51	0.196	0.197										
						1910-1919 to 1920-1929	-0.005	-0.16, 0.11	49			0.192									
						1920-1929 to 1940-1949	0.011	-0.18, 0.19	57				0.199	0.202							
						1940-1949 to 1980-1989	-0.063	-0.31, 0.07	75						0.191	0.172	0.150	0.139			
						1980-1989 to 2010-2019	0.012	-0.11, 0.18	52											0.141	0.147

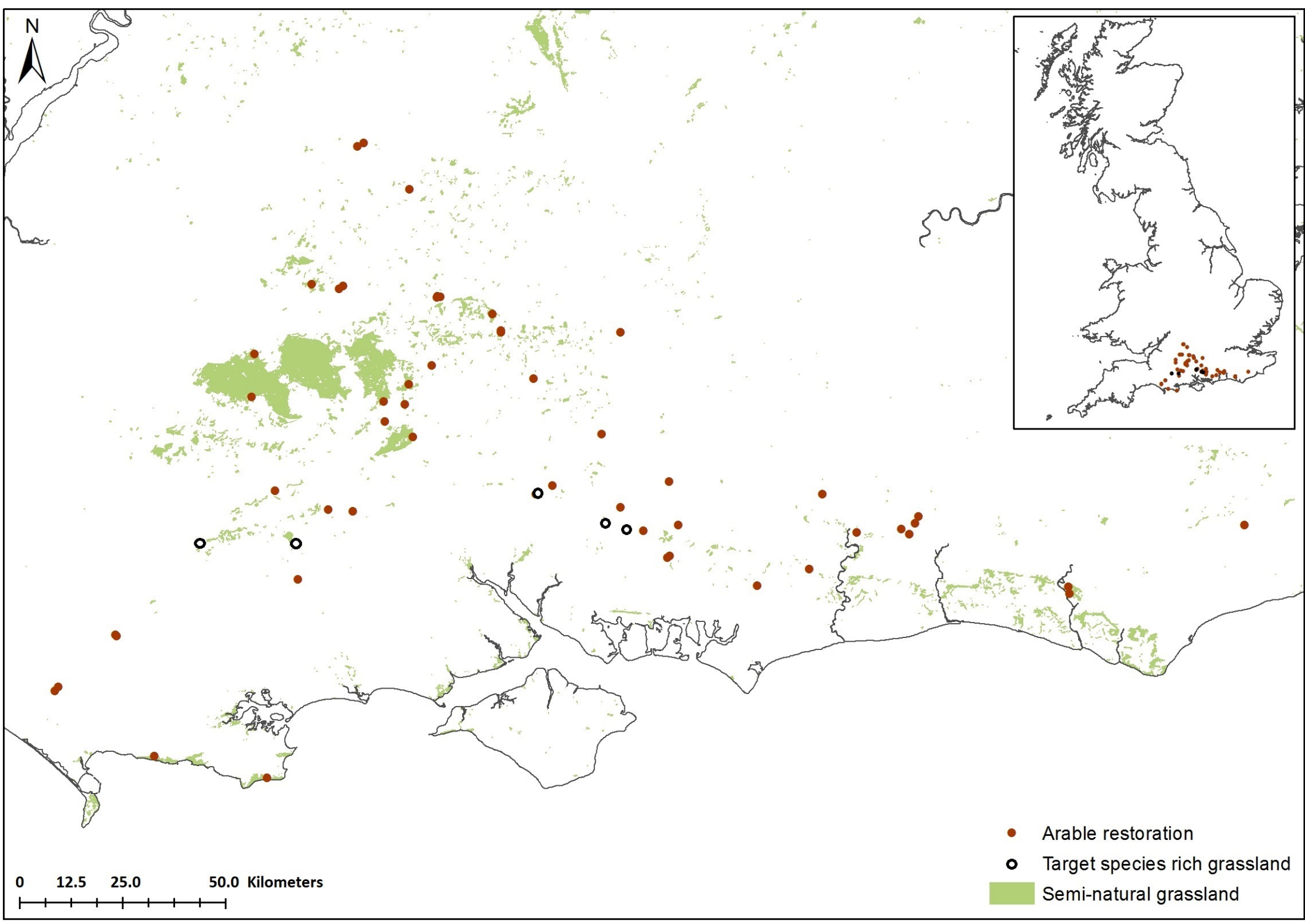
Species	Iterations	Rhat _{mean}	Rhat _{min}	Rhat _{max}	Precision	Time Period	Change	95% ETI	Confidence	Mean occupancy										
										1900-1909	1910-1919	1920-1929	1930-1939	1940-1949	1950-1959	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009
L. meridionalis	600000	1.023	1.004	1.047	24.455	1930-1939 to 1940-1949	-0.002	-0.10, 0.07	26	0.927										
						1940-1949 to 1970-1979	0.01	-0.05, 0.22	32	0.934 0.942 0.942										
						1970-1979 to 1990-1999	-0.01	-0.14, 0.06	28	0.937 0.931										
						1990-1999 to 2010-2019	0.01	-0.06, 0.13	28	0.937 0.941										
						1900-1909 to 1910-1919	-0.003	-0.21, 0.16	45	0.248	0.244									
						1910-1919 to 1940-1949	0.14	-0.14, 0.63	72			0.257	0.295	0.382						
L. niger	400000	1.006	1.003	1.011	519.021	1940-1949 to 1970-1979	-0.15	-0.61, 0.06	78	0.350 0.235 0.229										
						1970-1979 to 2010-2019	0.17	-0.08, 0.83	75	0.273 0.321 0.361 0.400										
						1900-1909 to 1910-1919	-0.009	-0.26, 0.19	43	0.897	0.888									
						1910-1919 to 1940-1949	0.05	-0.10, 0.44	51			0.900	0.918	0.938						
L. acervorum	100000	1.030	1.004	1.087	11.325	1940-1949 to 1950-1959	-0.05	-0.35, 0.06	59	0.889										
						1950-1959 to 1970-1979	0.07	-0.03, 0.39	68	0.939 0.962										
						1970-1979 to 1990-1999	-0.06	-0.54, 0.05	62	0.935 0.901										
						1900-1909 to 1970-1979	0.56	0.00, 1.00	72	0.421	0.435	0.594	0.801	0.819	0.947	0.977	0.983			
						1970-1979 to 1990-1999	-0.07	-0.72, 0.04	33	0.918 0.915										
M. lobicornis	200000	1.046	1.024	1.053	997.235	1990-1999 to 2010-2019	0.06	-0.10, 0.69	31	0.958 0.971										
						1900-1909 to 1940-1949	0.18	-0.20, 0.91	64	0.519	0.527	0.555	0.627	0.695						
M. scabrinodis	50000	1.008	1.002	1.020	1.781	1940-1949 to 2010-2019	-0.21	-0.93, 0.24	70	0.670 0.656 0.655 0.595 0.533 0.512 0.481										
						1900-1909 to 1940-1949	-0.04	-0.34, 0.23	60	0.746	0.731	0.721	0.712	0.710						
						1940-1949 to 1950-1959	0.02	-0.13, 0.24	56	0.732										
						1950-1959 to 1980-1989	-0.14	-0.56, 0.11	79	0.717 0.661 0.589										
						1980-1989 to 2010-2019	0.01	-0.14, 0.57	71	0.614 0.651 0.689										

464

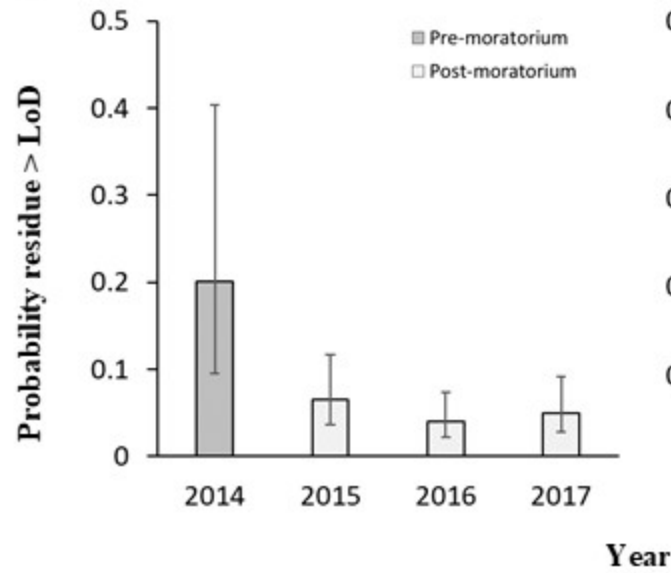
465

466 **Figure S7:** a) Effect of the number of detections in a decade for each individual species on uncertainty in occupancy,
 467 measured as the width of the 68% credible interval (1 standard deviation either side of the mean). b) Effect of
 468 occupancy estimate on uncertainty. The model performs with highest uncertainty at medium commonness. c) Effect of
 469 the modelled decade on uncertainty. Uncertainty is lowest for the last decades and the middle of the 20th century (but
 470 the effect is weak).

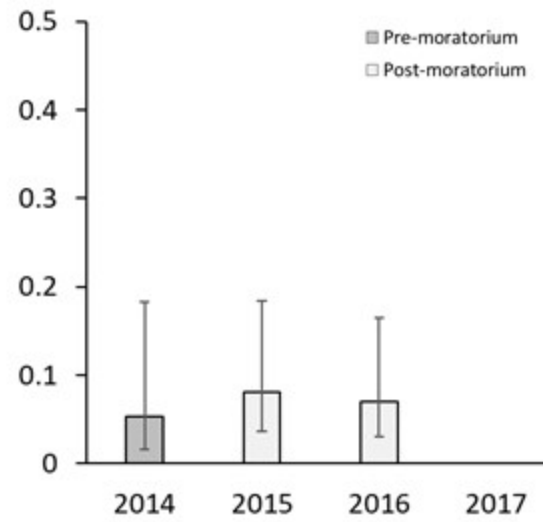




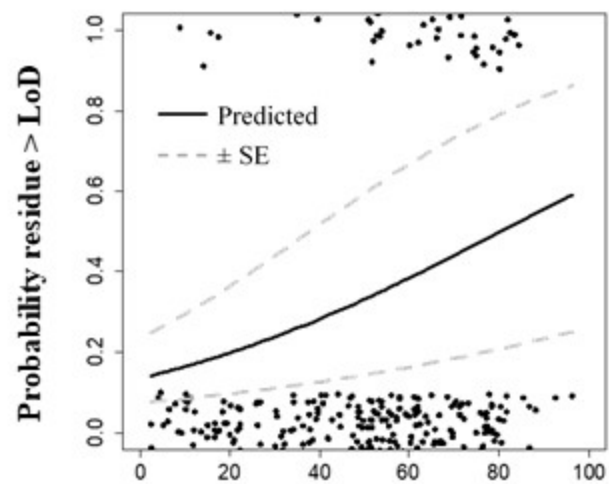
a) Clothianidin



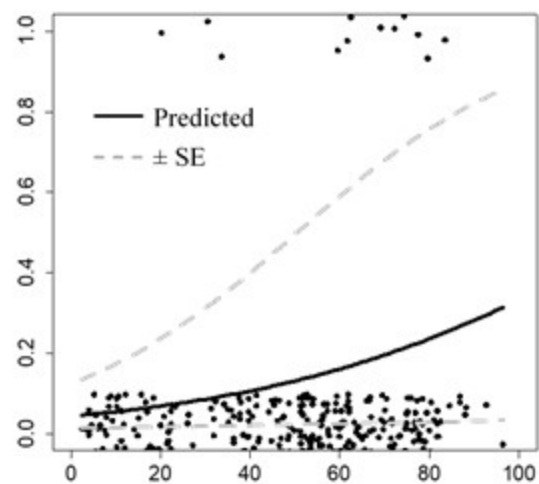
b) Thiamethoxam



a) Clothianidin



b) Thiamethoxam



Arable land percentage cover surrounding hives (2 km radius)

