TBD (Land use, climate change, pollinators, pollination risk)

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Contents

1 Science Instructions

- Reports are up to 2,500 words (including references, notes and captions)
- Up to 4 figures or tables
- Approximately 30 references

2 Key Papers

2.1 Already Read

☐ Outhwaite et al. (in press). *Nature*
☐ Millard et al. (2021). *Nature Communications*
☐ Biesmeijer et al. (2006). *Science*
☐ van Klink et al. (2020). *Science*
☐ Silva et al. (2021). *Science Advances*
☐ Soroye et al. (2020). *Science*
☐ Halsch et al. (2021). *PNAS*
☐ Basset & Lamarre (2019). *Science*
☐ Dainese et al. (2019). *Science Advances*
☐ Albrecht et al. (2012). *Proceedings B*
☐ Peters et al. (2019). *Nature*
☐ Piano et al. (2017). *Global Change Biology*
☐ Oliver et al. (2017). *Global Change Biology*
☐ Potts et al. (2010). *Trends in Ecology & Evolution*
☐ Rodger et al. (2021). *Science Advances*

- ☐ Woodcock et al. (2019). *Nature Communications*
- ☐ Lister & Garcia (2018). *PNAS*
- ☐ Wagner et al. (2020). *Annual Review of Entomology*
- ☐ Powney et al. (2019). *Nature Communications*
- ☐ Brittain et al. (2013). *Global Change Biology*
- ☐ Samways et al. (2020). *Biological Conservation*
- ☐ Genung et al. (2017). *Ecology*
- ☐ Uhler et al. (2021). *Nature Communications*
- ☐ Oliver et al. (2016). *Landscape Ecology*
- ☐ Mantyka-Pringle et al. (2012). *Global Change Biology*
- ☐ Warren et al. (2001). *Nature*
- ☐ Suggitt et al. (2018). *Nature Climate Change*
- ☐ Wilson & Fox (2021). *Ecological Entomology*
- ☐ Janzen & Hallwachs (2019). *Biological Conservation*
- ☐ Platts et al. (2019). *Scientific Reports*
- ☐ Aizen et al. (2008). *Current Biology*
- ☐ Holzschuh et al. (2011). *Proceedings B*
- ☐ Dornelas et al. (2019). *Ecology Letters*
- ☐ Martay et al. (2017). *Ecography*
- ☐ Oliver et al. (2015). *Nature Communications*
- ☐ Hickling et al. (2006). *Global Change Biology*
- ☐ Winfree et al. (2018). *Science*
- ☐ Ricketts et al. (2004). *PNAS*
- ☐ De Palma et al. (2016). *Scientific Reports*
- ☐ Klein et al. (2007). *Proceedings B*

2.2 To Read

- ☒ Potts et al. (2010). *Trends in Ecology & Evolution*
- ☒ Rodger et al. (2021). *Science Advances*
- ☒ Wagner et al. (2020). *Annual Review of Entomology*
- ☒ Powney et al. (2019). *Nature Communications*
- ☒ Samways et al. (2020). *Biological Conservation*
- ☒ Brittain et al. (2013). *Global Change Biology*
- ☒ Woodcock et al. (2019). *Nature Communications*
- ☒ Genung et al. (2017). *Ecology*
- ☒ Oliver et al. (2016). *Landscape Ecology*
- ☒ Uhler et al. (2021). *Nature Communications*
- ☒ Wilson & Fox (2021). *Ecological Entomology*
- ☒ Janzen & Hallwachs (2019). *Biological Conservation*
- ☒ Platts et al. (2019). *Scientific Reports*
- ☐ Lenoir et al. (2020). *Nature Ecology & Evolution*
- ☐ Deutsch et al. (2008). *PNAS*
- ☐ Lonsdorf et al. (2009). *Annals of Botany*

2.2.1 Pollen limitation

- ☒ Aizen et al. (2008). *Current Biology*
- ☒ Holzschuh et al. (2011). *Proceedings B*

3 Introduction

Recent studies have highlighted rapid ongoing changes in insect biodiversity (*1–3*). Some of these studies have reported net declines (*1*, *3*), at least for terrestrial insects (*1*), while others have shown mixtures of gains and losses (*2*). Pollinator biodiversity specifically has been shown to be undergoing rapid changes (*4–8*), with potential consequences for the provision of pollination to wild plants and crops. Importantly, evidence for insect biodiversity trends has been biased toward Western Europe and North America, with little coverage of tropical regions (*9*, *10*). Although a few studies have shown steep declines of insects in the tropics (*3*), evidence about insect biodiversity trends there often remains anecdotal (*11*), with global syntheses (*1*, *2*) having strong geographic biases towards non-tropical regions.

Among the drivers of insect and pollinator biodiversity changes, human land-use disturbance and climate change are prominent (*5*, *10*). A large number of studies have shown substantial effects of human land use and agricultural intensification on insects, including pollinators (*12–15*). Climate change is emerging as an increasingly important driver of changes in insect biodiversity (*8*, *12*, *16–19*). Tropical insects are expected to be more susceptible to climate change, owing to their narrower physiological tolerance compared to non-tropical species (*20*), but evidence about the response of tropical insects to climate change remains very scarce (*19*). Evidence is now accumulating for strong interactive effects of land-use change and climate change on insects (*21–25*). A key mechanism underpinning this interactive effect is the altered microclimatic conditions in areas where vegetation has been modified for human land use (*21*). The interaction between the effects of climate change and land use is often synergistic, leading to greater declines in biodiversity than if the pressures acted alone (*21*, *23–25*), and larger declines in tropical than non-tropical insect biodiversity (*25*).

Changes in the biodiversity and composition of pollinator communities will have large effects on the provision of pollination services. Pollen limitation from animal pollinator losses has already been shown to reduce the reproductive success of wild plants (*4*, *26*), and the productivity of certain crops (*27–30*), although there is no evidence yet that pollen limitation is causing wholesale reductions in yields of crops that rely on animal pollination (*31*). Evidence that insect biodiversity responds to human pressures more strongly in the tropics than elsewhere (*15*, *25*) is noteworthy, given that the majority of animal-pollination-dependent crops are grown there (*32*). However, it is not only tropical countries that will experience the effects of pollinator losses and subsequent pollen limitation, with highly developed countries benefiting from imports of animal-pollination-dependent foods from tropical areas (*33*). Abundance, species diversity and functional diversity of pollinators have all been implicated as determinants of the delivery of pollination service (*30*, *34–38*). Previous attempts to model the provision of crop pollination service have been based on predictions of pollinator abundance, which bears a direct relation to pollination of plants, and has been shown to give a reasonable approximation of pollen deposition in at least some study systems (*39*).

We present a global assessment of the interactive effects of climate change and land use on pollinator abundance, and predictions of the risk to crop pollination worldwide from the inferred changes in pollinator abundance. Our analyses are based on the PREDICTS database of biodiversity comparisons in different land uses (*40*), together with a list of species identified in the literature as likely pollinators (*15*). We use mixed-effects models to fit total pollinator community abundance as a function of land use (primary vegetation versus cropland) and a measure of historical climate change between a baseline period (XXXX-XXXX) and the X years prior to biodiversity sampling, standardized by monthly climate variability in the baseline period (*25*). Using estimated proportional reduction of pollinator total abundance as a proxy for relative risk to pollination services, together with estimates of where crops are grown(*41*), how dependent these crops are on animal pollination (*32*), and projections of historical and future climate change, we predict which locations and crops are likely to be at greatest risk from pollination shortfalls.

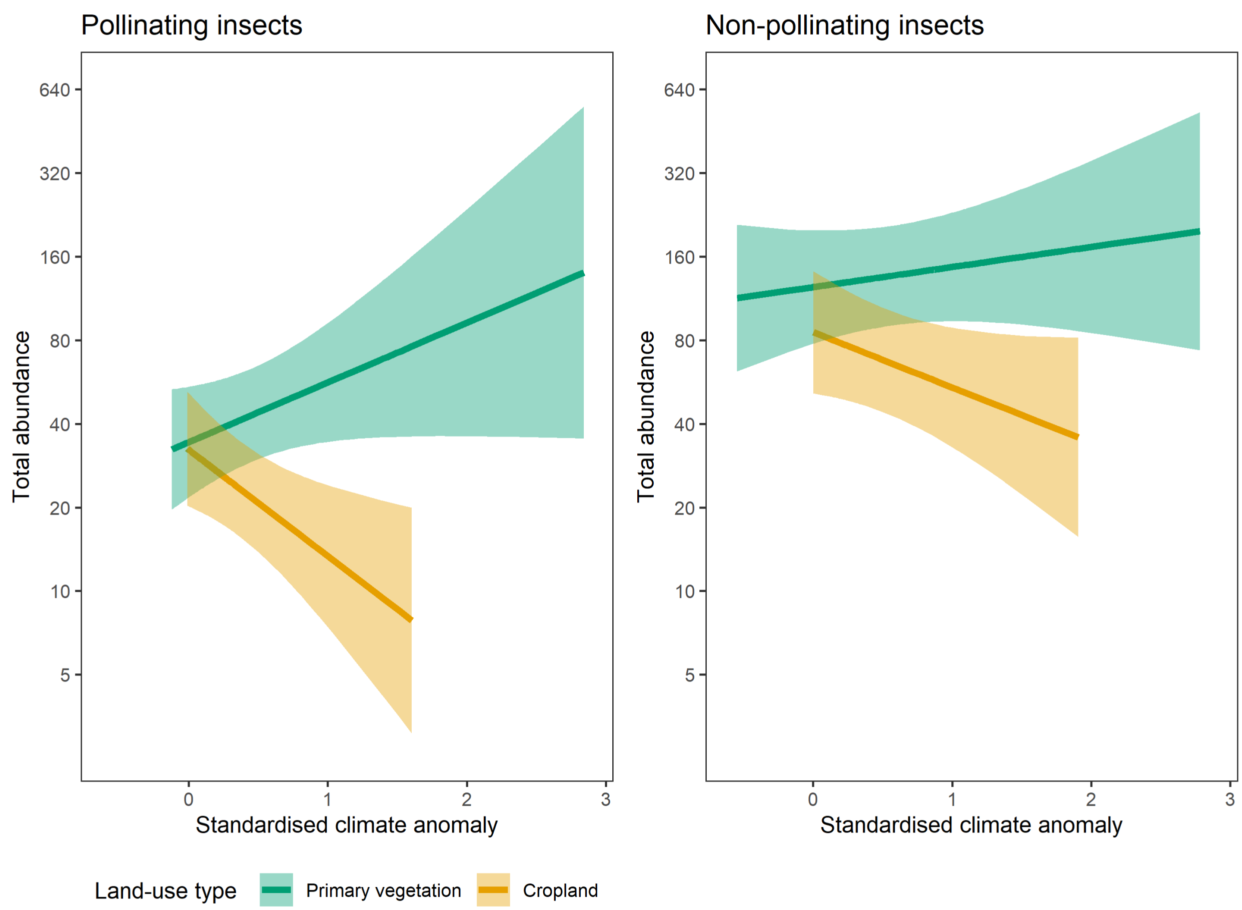

Figure 1: Response of pollinating and non-pollinating insect total abundance to standardised temperature anomaly on primary vegetation and cropland (note that abundance is plotted on a loge scale). Both panels represent a linear mixed-effects model for pollinating or non-pollinating insects. Coloured lines represent mean fitted estimates for each interaction, and shading 95% confidence intervals around that prediction: green, primary vegetation; orange, cropland.

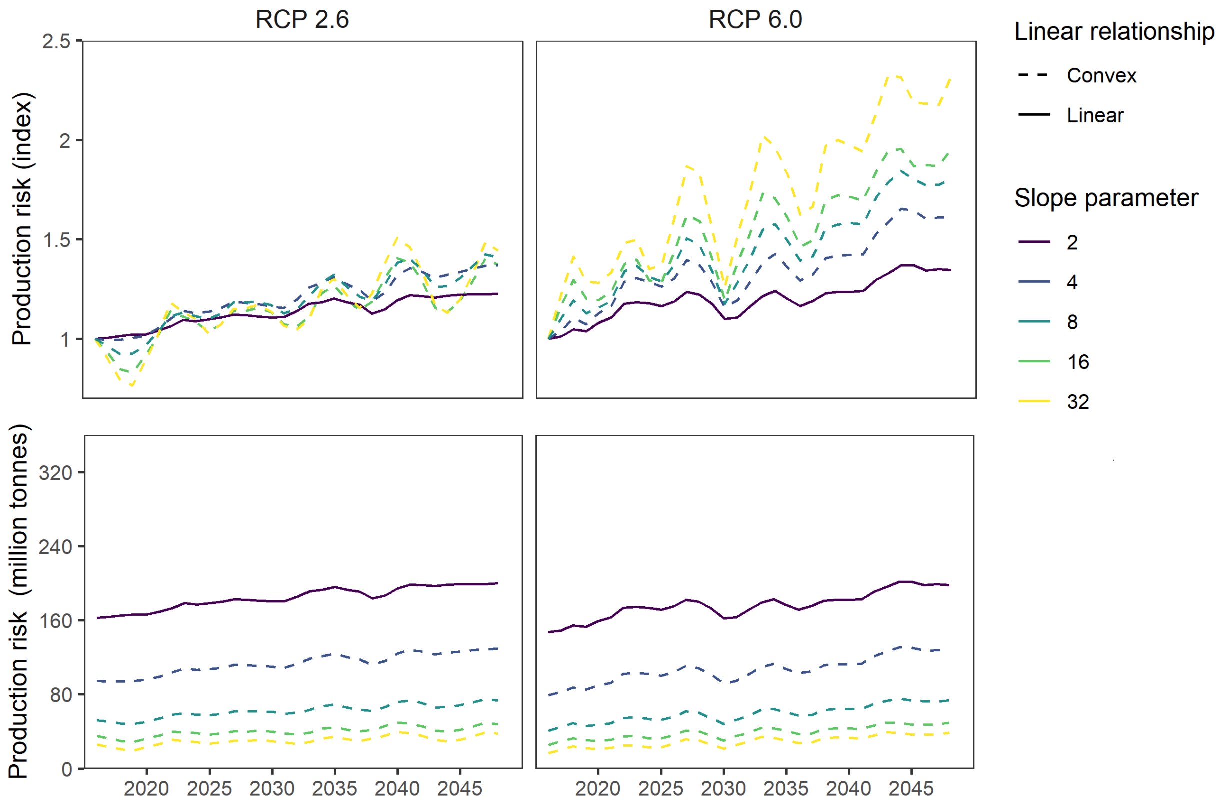

Figure 2: Projected change in total production risk under an ensemble mean of two RCP scenarios (6.0 and 2.6) and a set of different abundance-production relationships, for both an index of change in risk and total pollination production risk. For each year into the future, the standardised temperature anomaly was projected globally for all cells of pollination-dependent production, using a 3-year rolling average. We used data on crop production from the year 2000 (the latest year when such data are available for all crops), therefore assuming that the distribution of the production of these crops does not change. For each annual projection of standardised temperature anomaly, insect pollinator abundance on cropland was predicted according to the model in Figure 1 (left panel), and then expressed as proportional abundance loss compared to cropland that has experienced no warming (i.e. standardised temperature anomaly of 0). In each cell, animal pollination-dependent production was then adjusted for the percentage reduction in abundance at that cell, before summing animal-pollination-dependent production for all cells at each time step. Line type refers to the shape of the abundance-production relatiionship: dashed, convex; and solid, linear. Colour refers to the degree of convexity of the relationship between abundance and production, with the highest level of convexity in yellow.

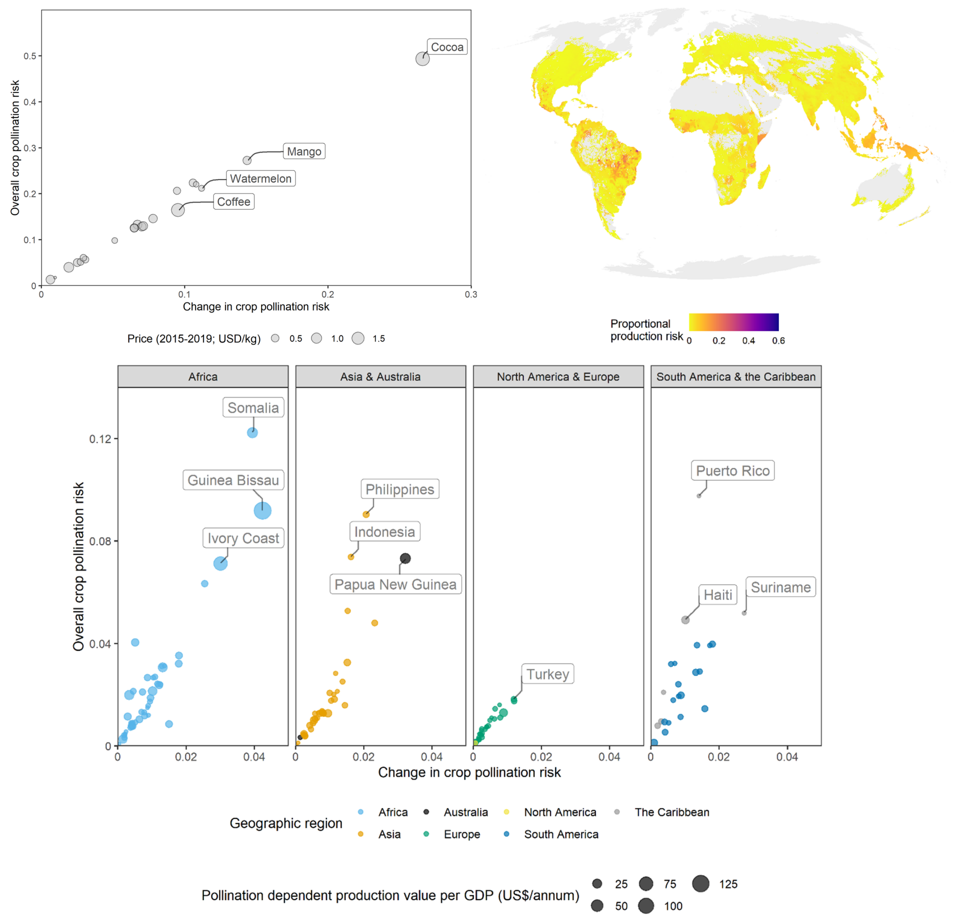

Figure 3: Projected change in proportional production risk for 2050 under an ensemble mean of RCP scenario 6.0 and a linear relationship between abundance and production loss. Top left: Proportional production risk for the top 20 crops by pollination dependent production (see Figure S01 for the top 20 crops). Overall risk is the median of proportional production risk for all cells of that crop, whilst change in risk is the difference in overall risk between the start and the end of the series. Point size represents an estimation of the per kg value of each crop for the years 2015-2019, calculated from FAO data. Top right: Proportional production risk at the level of each spatial cell (see Figure S08 to see how cell-level risk differs among abundance-production scenarios). Bottom: Proportional production risk at the level of each country. Here overall risk is the median of proportional production risk for all cells of that country, whilst change in risk is the difference in overall risk between the start and the end of the series. Point size here represents the total value of the pollination dependent production in that country (according to Monfreda et al 2008) adjusted for GDP. Colour represents the geographic region of each country, distinguishing between regions within a panel: Blue, Africa; orange, Asia; black, Australia; green, Europe; yellow, North America; dark blue, South America; grey, the Caribbean.

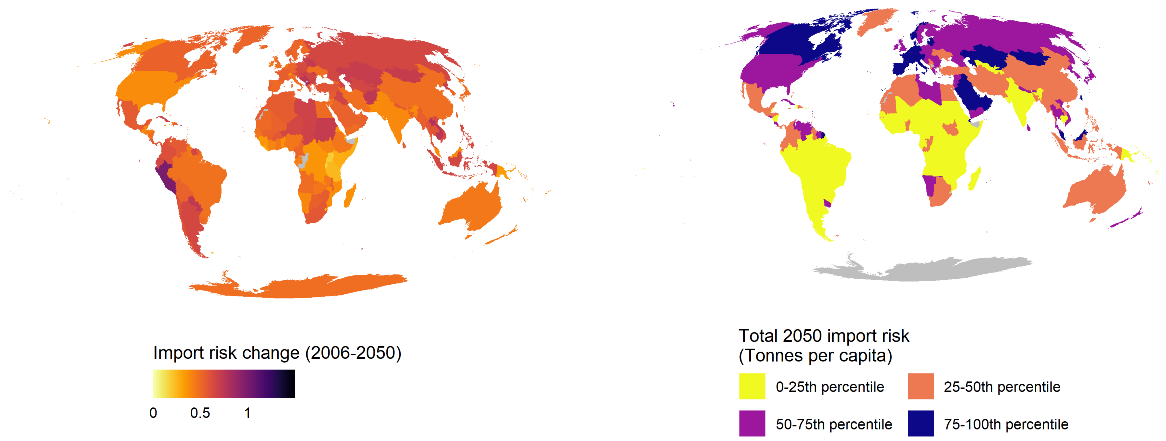

Figure 4: Projected change in import risk for 2050 under an ensemble mean of RCP scenario 6.0 and a linear relationship between abundance and production loss. Import risk is a measure of how the effects of localised production risk might be distributed among other countries, calculated using trade flow data from da Silva et al (2021). Left panel: Change in import risk betwen 2006 and 2050. Colours represent the degree of import risk change, from no change at 0 in yellow to a doubling at 1 in purple. Right panel: Total import risk in 2020 adjusted for population and then converted to a percentile. Colours represent each percentile grouping: yellow, 0-25th percentile; orange, 25-50th; purple, 50-75th; dark blue, 75-100th.

4 Results and Discussion

1. R. van Klink, D. E. Bowler, K. B. Gongalsky, A. B. Swengel, A. Gentile, J. M. Chase, Meta-analysis reveals declines in terrestrial but increases in freshwater insect abundances. *Science*. **368**, 417–420 (2020).

2. M. Dornelas, N. J. Gotelli, H. Shimadzu, F. Moyes, A. E. Magurran, B. J. McGill, A balance of winners and losers in the anthropocene. *Ecology Letters*. **22**, 847–854 (2019).

3. B. C. Lister, A. Garcia, Climate-driven declines in arthropod abundance restructure a rainforest food web. *Proceedings of the National Academy of Sciences*. **115**, E10397–E10406 (2018).

4. J. C. Biesmeijer, S. P. M. Roberts, M. Reemer, R. Ohlemüller, M. Edwards, T. Peeters, A. P. Schaffers, S. G. Potts, R. Kleukers, C. D. Thomas, J. Settele, W. E. Kunin, Parallel declines in pollinators and insect-pollinated plants in britain and the netherlands. *Science*. **313**, 351–354 (2006).

5. S. G. Potts, J. C. Biesmeijer, C. Kremen, P. Neumann, O. Schweiger, W. E. Kunin, Global pollinator declines: Trends, impacts and drivers. *Trends in Ecology & Evolution*. **25**, 345–353 (2010).

6. T. H. Oliver, N. J. B. Isaac, T. A. August, B. A. Woodcock, D. B. Roy, J. M. Bullock, Declining resilience of ecosystem functions under biodiversity loss. *Nature Communications*. **6**, 10122 (2015).

7. G. D. Powney, C. Carvell, M. Edwards, R. K. A. Morris, H. E. Roy, B. A. Woodcock, N. J. B. Isaac, Widespread losses of pollinating insects in britain. *Nature Communications*. **10**, 1018 (2019).

8. P. Soroye, T. Newbold, J. Kerr, Climate change contributes to widespread declines among bumble bees across continents. *Science*. **367**, 685–688 (2020).

9. Y. Basset, G. P. A. Lamarre, Toward a world that values insects. *Science*. **364**, 1230–1231 (2019).

10. D. L. Wagner, Insect declines in the anthropocene. *Annual Review of Entomology.* **65**, 457–480 (2020).

11. D. H. Janzen, W. Hallwachs, Perspective: Where might be many tropical insects? *Biological Conservation.* **233**, 102–108 (2019).

12. M. S. Warren, J. K. Hill, J. A. Thomas, J. Asher, R. Fox, B. Huntley, D. B. Roy, M. G. Telfer, S. Jeffcoate, P. Harding, G. Jeffcoate, S. G. Willis, J. N. Greatorex-Davies, D. Moss, C. D. Thomas, Rapid responses of british butterflies to opposing forces of climate and habitat change. *Nature.* **414**, 65–69 (2001).

13. A. De Palma, S. Abrahamczyk, M. A. Aizen, M. Albrecht, Y. Basset, A. Bates, R. J. Blake, C. Boutin, R. Bugter, S. Connop, L. Cruz-López, S. A. Cunningham, B. Darvill, T. Diekötter, S. Dorn, N. Downing, M. H. Entling, N. Farwig, A. Felicioli, S. J. Fonte, R. Fowler, M. Franzén, D. Goulson, I. Grass, M. E. Hanley, S. D. Hendrix, F. Herrmann, F. Herzog, A. Holzschuh, B. Jauker, M. Kessler, M. E. Knight, A. Kruess, P. Lavelle, V. Le Féon, P. Lentini, L. A. Malone, J. Marshall, E. M. Pachón, Q. S. McFrederick, C. L. Morales, S. Mudri-Stojnic, G. Nates-Parra, S. G. Nilsson, E. Öckinger, L. Osgathorpe, A. Parra-H, C. A. Peres, A. S. Persson, T. Petanidou, K. Poveda, E. F. Power, M. Quaranta, C. Quintero, R. Rader, M. H. Richards, T. Roulston, L. Rousseau, J. P. Sadler, U. Samnegård, N. A. Schellhorn, C. Schüepp, O. Schweiger, A. H. Smith-Pardo, I. Steffan-Dewenter, J. C. Stout, R. K. Tonietto, T. Tscharntke, J. M. Tylianakis, H. A. F. Verboven, C. H. Vergara, J. Verhulst, C. Westphal, H. J. Yoon, A. Purvis, Predicting bee community responses to land-use changes: Effects of geographic and taxonomic biases. *Scientific Reports.* **6**, 31153 (2016).

14. I. Oliver, J. Dorrough, H. Doherty, N. R. Andrew, Additive and synergistic effects of land cover, land use and climate on insect biodiversity. *Landscape Ecology.* **31**, 2415–2431 (2016).

15. J. Millard, C. L. Outhwaite, R. Kinnersley, R. Freeman, R. D. Gregory, O. Adedoja, S. Gavini, E. Kioko, M. Kuhlmann, J. Ollerton, Z.-X. Ren, T. Newbold, Global effects of land-use intensity on local pollinator biodiversity. *Nature Communications.* **12**, 2902 (2021).

16. R. Hickling, D. B. Roy, J. K. Hill, R. Fox, C. D. Thomas, The distributions of a wide range of taxonomic groups are expanding polewards. *Global Change Biology.* **12**, 450–455 (2006).

17. B. Martay, M. J. Brewer, D. A. Elston, J. R. Bell, R. Harrington, T. M. Brereton, K. E. Barlow, M. S. Botham, J. W. Pearce-Higgins, Impacts of climate change on national biodiversity population trends. *Ecography.* **40**, 1139–1151 (2017).

18. J. Lenoir, R. Bertrand, L. Comte, L. Bourgeaud, T. Hattab, J. Murienne, G. Grenouillet, Species better track climate warming in the oceans than on land. *Nature Ecology & Evolution.* **4**, 1044–1059 (2020).

19. C. A. Halsch, A. M. Shapiro, J. A. Fordyce, C. C. Nice, J. H. Thorne, D. P. Waetjen, M. L. Forister, Insects and recent climate change. *Proceedings of the National Academy of Sciences.* **118**, e2002543117 (2021).

20. C. A. Deutsch, J. J. Tewksbury, R. B. Huey, K. S. Sheldon, C. K. Ghalambor, D. C. Haak, P. R. Martin, Impacts of climate warming on terrestrial ectotherms across latitude. *Proceedings of the National Academy of Sciences.* **105**, 6668–6672 (2008).

21. A. J. Suggitt, R. J. Wilson, N. J. B. Isaac, C. M. Beale, A. G. Auffret, T. August, J. J. Bennie, H. Q. P. Crick, S. Duffield, R. Fox, J. J. Hopkins, N. A. Macgregor, M. D. Morecroft, K. J. Walker, I. M. D. Maclean, Extinction risk from climate change is reduced by microclimatic buffering. *Nature Climate Change.* **8**, 713–717 (2018).

22. P. J. Platts, S. C. Mason, G. Palmer, J. K. Hill, T. H. Oliver, G. D. Powney, R. Fox, C. D. Thomas, Habitat availability explains variation in climate-driven range shifts across multiple taxonomic groups. *Scientific Reports*. **9**, 15039 (2019).

23. T. H. Oliver, S. Gillings, J. W. Pearce-Higgins, T. Brereton, H. Q. P. Crick, S. J. Duffield, M. D. Morecroft, D. B. Roy, Large extents of intensive land use limit community reorganization during climate warming. *Global Change Biology*. **23**, 2272–2283 (2017).

24. M. K. Peters, A. Hemp, T. Appelhans, J. N. Becker, C. Behler, A. Classen, F. Detsch, A. Ensslin, S. W. Ferger, S. B. Frederiksen, F. Gebert, F. Gerschlauer, A. Gütlein, M. Helbig-Bonitz, C. Hemp, W. J. Kindeketa, A. Kühnel, A. V. Mayr, E. Mwangomo, C. Ngereza, H. K. Njovu, I. Otte, H. Pabst, M. Renner, J. Röder, G. Rutten, D. Schellenberger Costa, N. Sierra-Cornejo, M. G. R. Vollstädt, H. I. Dulle, C. D. Eardley, K. M. Howell, A. Keller, R. S. Peters, A. Ssymank, V. Kakengi, J. Zhang, C. Bogner, K. Böhning-Gaese, R. Brandl, D. Hertel, B. Huwe, R. Kiese, M. Kleyer, Y. Kuzyakov, T. Nauss, M. Schleuning, M. Tschapka, M. Fischer, I. Steffan-Dewenter, Climate–land-use interactions shape tropical mountain biodiversity and ecosystem functions. *Nature*. **568**, 88–92 (2019).

25. C. L. Outhwaite, P. McCann, T. Newbold, Agriculture and climate change reshape insect biodiversity worldwide. *Nature* (In press).

26. J. G. Rodger, J. M. Bennett, M. Razanajatovo, T. M. Knight, M. van Kleunen, T.-L. Ashman, J. A. Steets, C. Hui, G. Arceo-Gómez, M. Burd, L. A. Burkle, J. H. Burns, W. Durka, L. Freitas, J. E. Kemp, J. Li, A. Pauw, J. C. Vamosi, M. Wolowski, J. Xia, A. G. Ellis, Widespread vulnerability of flowering plant seed production to pollinator declines. *Science Advances*. **7**, eabd3524 (2021).

27. A. Klein, I. Steffan–Dewenter, T. Tscharntke, Fruit set of highland coffee increases with the diversity of pollinating bees. *Proceedings of the Royal Society of London. Series B: Biological Sciences*. **270**, 955–961 (2003).

28. T. H. Ricketts, G. C. Daily, P. R. Ehrlich, C. D. Michener, Economic value of tropical forest to coffee production. *Proceedings of the National Academy of Sciences*. **101**, 12579–12582 (2004).

29. A. Holzschuh, C. F. Dormann, T. Tscharntke, I. Steffan-Dewenter, Expansion of mass-flowering crops leads to transient pollinator dilution and reduced wild plant pollination. *Proceedings of the Royal Society B: Biological Sciences*. **278**, 3444–3451 (2011).

30. B. A. Woodcock, M. P. D. Garratt, G. D. Powney, R. F. Shaw, J. L. Osborne, J. Soroka, S. A. M. Lindström, D. Stanley, P. Ouvrard, M. E. Edwards, F. Jauker, M. E. McCracken, Y. Zou, S. G. Potts, M. Rundlöf, J. A. Noriega, A. Greenop, H. G. Smith, R. Bommarco, W. van der Werf, J. C. Stout, I. Steffan-Dewenter, L. Morandin, J. M. Bullock, R. F. Pywell, Meta-analysis reveals that pollinator functional diversity and abundance enhance crop pollination and yield. *Nature Communications*. **10**, 1481 (2019).

31. M. A. Aizen, L. A. Garibaldi, S. A. Cunningham, A. M. Klein, Long-term global trends in crop yield and production reveal no current pollination shortage but increasing pollinator dependency. *Current Biology*. **18**, 1572–1575 (2008).

32. A.-M. Klein, B. E. Vaissière, J. H. Cane, I. Steffan-Dewenter, S. A. Cunningham, C. Kremen, T. Tscharntke, Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society B: Biological Sciences*. **274**, 303–313 (2007).

33. F. D. S. Silva, L. G. Carvalheiro, J. Aguirre-Gutiérrez, M. Lucotte, K. Guidoni-Martins, F. Mertens, Virtual pollination trade uncovers global dependence on biodiversity of developing countries. *Science Advances*. **7**, eabe6636 (2021).

34. M. Albrecht, B. Schmid, Y. Hautier, C. B. Müller, Diverse pollinator communities enhance plant reproductive success. *Proceedings of the Royal Society B: Biological Sciences*. **279**, 4845–4852 (2012).

35. C. Brittain, C. Kremen, A.-M. Klein, Biodiversity buffers pollination from changes in environmental conditions. *Global Change Biology*. **19**, 540–547 (2013).

36. M. A. Genung, J. Fox, N. M. Williams, C. Kremen, J. Ascher, J. Gibbs, R. Winfree, The relative importance of pollinator abundance and species richness for the temporal variance of pollination services. *Ecology*. **98**, 1807–1816 (2017).

37. R. Winfree, J. R. Reilly, I. Bartomeus, D. P. Cariveau, N. M. Williams, J. Gibbs, Species turnover promotes the importance of bee diversity for crop pollination at regional scales. *Science*. **359**, 791–793 (2018).

38. M. Dainese, E. A. Martin, M. A. Aizen, M. Albrecht, I. Bartomeus, R. Bommarco, L. G. Carvalheiro, R. Chaplin-Kramer, V. Gagic, L. A. Garibaldi, J. Ghazoul, H. Grab, M. Jonsson, D. S. Karp, C. M. Kennedy, D. Kleijn, C. Kremen, D. A. Landis, D. K. Letourneau, L. Marini, K. Poveda, R. Rader, H. G. Smith, T. Tscharntke, G. K. S. Andersson, I. Badenhausser, S. Baensch, A. D. M. Bezerra, F. J. J. A. Bianchi, V. Boreux, V. Bretagnolle, B. Caballero-Lopez, P. Cavigliasso, A. Ćetković, N. P. Chacoff, A. Classen, S. Cusser, F. D. da Silva e Silva, G. A. de Groot, J. H. Dudenhöffer, J. Ekroos, T. Fijen, P. Franck, B. M. Freitas, M. P. D. Garratt, C. Gratton, J. Hipólito, A. Holzschuh, L. Hunt, A. L. Iverson, S. Jha, T. Keasar, T. N. Kim, M. Kishinevsky, B. K. Klatt, A.-M. Klein, K. M. Krewenka, S. Krishnan, A. E. Larsen, C. Lavigne, H. Liere, B. Maas, R. E. Mallinger, E. M. Pachon, A. Martínez-Salinas, T. D. Meehan, M. G. E. Mitchell, G. A. R. Molina, M. Nesper, L. Nilsson, M. E. O'Rourke, M. K. Peters, M. Plećaš, S. G. Potts, D. de L. Ramos, J. A. Rosenheim, M. Rundlöf, A. Rusch, A. Sáez, J. Scheper, M. Schleuning, J. M. Schmack, A. R. Sciligo, C. Seymour, D. A. Stanley, R. Stewart, J. C. Stout, L. Sutter, M. B. Takada, H. Taki, G. Tamburini, M. Tschumi, B. F. Viana, C. Westphal, B. K. Willcox, S. D. Wratten, A. Yoshioka, C. Zaragoza-Trello, W. Zhang, Y. Zou, I. Steffan-Dewenter, A global synthesis reveals biodiversity-mediated benefits for crop production. *Science Advances*. **5**, eaax0121 (2019).

39. E. Lonsdorf, C. Kremen, T. Ricketts, R. Winfree, N. Williams, S. Greenleaf, Modelling pollination services across agricultural landscapes. *Annals of Botany*. **103**, 1589–1600 (2009).

40. L. N. Hudson, T. Newbold, S. Contu, S. L. L. Hill, I. Lysenko, A. De Palma, H. R. P. Phillips, T. I. Alhusseini, F. E. Bedford, D. J. Bennett, H. Booth, V. J. Burton, C. W. T. Chng, A. Choimes, D. L. P. Correia, J. Day, S. Echeverría-Londoño, S. R. Emerson, D. Gao, M. Garon, M. L. K. Harrison, D. J. Ingram, M. Jung, V. Kemp, L. Kirkpatrick, C. D. Martin, Y. Pan, G. D. Pask-Hale, E. L. Pynegar, A. N. Robinson, K. Sanchez-Ortiz, R. A. Senior, B. I. Simmons, H. J. White, H. Zhang, J. Aben, S. Abrahamczyk, G. B. Adum, V. Aguilar-Barquero, M. A. Aizen, B. Albertos, E. L. Alcala, M. del Mar Alguacil, A. Alignier, M. Ancrenaz, A. N. Andersen, E. Arbeláez-Cortés, I. Armbrecht, V. Arroyo-Rodríguez, T. Aumann, J. C. Axmacher, B. Azhar, A. B. Azpiroz, L. Baeten, A. Bakayoko, A. Báldi, J. E. Banks, S. K. Baral, J. Barlow, B. I. P. Barratt, L. Barrico, P. Bartolommei, D. M. Barton, Y. Basset, P. Batáry, A. J. Bates, B. Baur, E. M. Bayne, P. Beja, S. Benedick, Å. Berg, H. Bernard, N. J. Berry, D. Bhatt, J. E. Bicknell, J. H. Bihn, R. J. Blake, K. S. Bobo, R. Bóçon, T. Boekhout, K. Böhning-Gaese, K. J. Bonham, P. A. V. Borges, S. H. Borges, C. Boutin, J. Bouyer, C. Bragagnolo, J. S. Brandt, F. Q. Brearley, I. Brito, V. Bros, J. Brunet, G. Buczkowski, C. M. Buddle, R. Bugter, E. Buscardo, J. Buse, J. Cabra-García, N. C. Cáceres, N. L. Cagle, M. Calviño-Cancela, S. A. Cameron, E. M. Cancello, R. Caparrós, P. Cardoso, D. Carpenter, T. F. Carrijo, A. L. Carvalho, C. R. Cassano, H. Castro, A. A. Castro-Luna, C. B. Rolando, A. Cerezo, K. A. Chapman, M. Chauvat, M. Christensen, F. M. Clarke, D. F. R. Cleary, G. Colombo, S. P. Connop, M. D. Craig, L. Cruz-López, S. A. Cunningham, B. D'Aniello, N. D'Cruze, P. G. da Silva, M. Dallimer, E. Danquah, B. Darvill, J. Dauber, A. L. V. Davis, J. Dawson, C. de Sassi, B. de Thoisy, O. Deheuvels, A. Dejean, J.-L. Devineau, T. Diekötter, J. V. Dolia, E. Domínguez, Y. Dominguez-Haydar, S. Dorn, I. Draper, N. Dreber, B. Dumont, S. G. Dures, M. Dynesius, L. Edenius, P. Eggleton, F. Eigenbrod, Z. Elek, M. H. Entling, K. J. Esler, R. F. de Lima, A. Faruk, N. Farwig, T. M. Fayle, A. Felicioli, A. M. Felton, R. J. Fensham, I. C. Fernandez, C. C. Ferreira, G. F. Ficetola, C. Fiera, B. K. C. Filgueiras, H. K. Fırıncıoğlu, D. Flaspohler, A. Floren, S. J. Fonte, A. Fournier, R. E. Fowler, M. Franzén, L. H. Fraser, G. M. Fredriksson, G. B. Freire, T. L. M. Frizzo, D. Fukuda, D. Furlani, R. Gaigher, J. U. Ganzhorn, K. P. García, J. C. Garcia-R, J. G. Garden, R. Garilleti, B.-M. Ge, B. Gendreau-Berthiaume, P. J. Gerard, C. Gheler-Costa, B. Gilbert, P. Giordani, S. Giordano, C. Golodets, L. G. L. Gomes, R. K. Gould, D. Goulson, A. D. Gove, L. Granjon, I. Grass, C. L. Gray, J. Grogan, W. Gu, M. Guardiola, N. R. Gunawardene, A. G. Gutierrez, D. L. Gutiérrez-Lamus, D. H. Haarmeyer, M. E. Hanley, T. Hanson, N. R. Hashim, S. N. Hassan, R. G. Hatfield, J. E. Hawes, M. W. Hayward, C. Hébert, A. J. Helden, J.-A. Henden, P. Henschel, L. Hernández, J. P. Herrera, F. Herrmann, F. Herzog, D. Higuera-Diaz, B. Hilje, H. Höfer, A. Hoffmann, F. G. Horgan, E. Hornung, R. Horváth, K. Hylander, P. Isaacs-Cubides, H. Ishida, M. Ishitani, C. T. Jacobs, V. J. Jaramillo, B. Jauker, F. J. Hernández, M. F. Johnson, V. Jolli, M. Jonsell, S. N. Juliani, T. S. Jung, V. Kapoor, H. Kappes, V. Kati, E. Katovai, K. Kellner, M. Kessler, K. R. Kirby, A. M. Kittle, M. E. Knight, E. Knop, F. Kohler, M. Koivula, A. Kolb, M. Kone, Á. Kőrösi, J. Krauss, A. Kumar, R. Kumar, D. J. Kurz, A. S. Kutt, T. Lachat, V. Lantschner, F. Lara, J. R. Lasky, S. C. Latta, W. F. Laurance, P. Lavelle, V. Le Féon, G. LeBuhn, J.-P. Légaré, V. Lehouck, M. V. Lencinas, P. E. Lentini, S. G. Letcher, Q. Li, S. A. Litchwark, N. A. Littlewood, Y. Liu, N. Lo-Man-Hung, C. A. López-Quintero, M. Louhaichi, G. L. Lövei, M. E. Lucas-Borja, V. H. Luja, M. S. Luskin, M. C. MacSwiney G, K. Maeto, T. Magura, N. A. Mallari, L. A. Malone, P. K. Malonza, J. Malumbres-Olarte, S. Mandujano, I. E. Måren, E. Marin-Spiotta, C. J. Marsh, E. J. P. Marshall, E. Martínez, G. Martínez Pastur, D. Moreno Mateos, M. M. Mayfield, V. Mazimpaka, J. L. McCarthy, K. P. McCarthy, Q. S. McFrederick, S. McNamara, N. G. Medina, R. Medina, J. L. Mena, E. Mico, G. Mikusinski, J. C. Milder, J. R. Miller, D. R. Miranda-Esquivel, M. L. Moir, C. L. Morales, M. N. Muchane, M. Muchane, S. Mudri-Stojnic, A. N. Munira, A. Muoñz-Alonso, B. F. Munyekenye, R. Naidoo, A. Naithani, M. Nakagawa, A. Nakamura, Y. Nakashima, S. Naoe, G. Nates-Parra, D. A. Navarrete Gutierrez, L. Navarro-Iriarte, P. K. Ndang'ang'a, E. L. Neuschulz, J. T. Ngai, V. Nicolas, S. G. Nilsson, N. Noreika, O. Norfolk, J. A. Noriega, D. A. Norton, N. M. Nöske, A. J. Nowakowski, C. Numa, N. O'Dea, P. J. O'Farrell, W. Oduro, S. Oertli, C. Ofori-Boateng, C. O. Oke, V. Oostra, L. M. Osgathorpe, S. E. Otavo, N. V. Page, J. Paritsis, A. Parra-H, L. Parry, G. Pe'er, P. B. Pearman, N. Pelegrin, R. Pélissier, C. A. Peres, P. L. Peri, A. S. Persson, T. Petanidou, M. K. Peters, R. S. Pethiyagoda, B. Phalan, T. K. Philips, F. C. Pillsbury, J. Pincheira-Ulbrich, E. Pineda, J. Pino, J. Pizarro-Araya, A. J. Plumptre, S. L. Poggio, N. Politi, P. Pons, K. Poveda, E. F. Power, S. J. Presley, V. Proença, M. Quaranta, C. Quintero, R. Rader, B. R. Ramesh, M. P. Ramirez-Pinilla, J. Ranganathan, C. Rasmussen, N. A. Redpath-Downing, J. L. Reid, Y. T. Reis, J. M. Rey Benayas, J. C. Rey-Velasco, C. Reynolds, D. B. Ribeiro, M. H. Richards, B. A. Richardson, M. J. Richardson, R. M. Ríos, R. Robinson, C. A. Robles, J. Römbke, L. P. Romero-Duque, M. Rös, L. Rosselli, S. J. Rossiter, D. S. Roth, T. H. Roulston, L. Rousseau, A. V. Rubio, J.-C. Ruel, J. P. Sadler, S. Sáfián, R. A. Saldaña-Vázquez, K. Sam, U. Samnegård, J. Santana, X. Santos, J. Savage, N. A. Schellhorn, M. Schilthuizen, U. Schmiedel, C. B. Schmitt, N. L. Schon, C. Schüepp, K. Schumann,

41. C. Monfreda, N. Ramankutty, J. A. Foley, Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochemical Cycles*. **22**, GB1022 (2008).