

Climate change and land-use scenarios of crop pollination risk

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Abstract

Recent studies have highlighted rapid ongoing changes in insect biodiversity, in part driven by the interaction of land-use and climate change. Insect pollinator biodiversity specifically has been shown to be undergoing rapid changes, with potential consequences for the provision of crop pollination. Here, 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. We show that the combination of agricultural land use and recent climate change is associated with particularly large reductions in the abundance of insect pollinators. We further show that the tropics will likely experience the greatest risk of future pollination shortfalls, putting at risk the production of crops that depend on insect pollination. The risk to these crops is highest, and predicted to increase most rapidly, in regions of sub-Saharan Africa and northern South America, especially in areas used to produce cocoa, mango, pumpkin, melon, watermelon, and coffee. The health, well-being, and livelihoods of billions of people rely to some extent upon the availability and affordability of crops dependent on animal pollination. Climate change and agricultural land use could put these people's wellbeing at high risk.

One sentence summary

Climate change associated crop pollination risk is highest, and predicted to increase most rapidly, in regions of sub-Saharan Africa and northern South America, especially in areas used to produce cocoa, mango, pumpkin, melon, watermelon, and coffee.

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 and subtropical regions (9, 10), although see (11, 12) for two recent examples. Although a few studies have shown steep declines of insects in the tropics (3), evidence about insect biodiversity trends there often remains anecdotal (13), 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, 14–17). Climate change in particular is emerging as an increasingly important driver (8, 14, 18–21), as well as the interactive effects of land-use and climate change (22–26). For interactions, a key mechanism underpinning this effect is the altered microclimatic conditions in areas where vegetation has been modified for human land use (22). This results in synergistic effects of climate change and land use, leading to greater declines in biodiversity than if the pressures acted alone (22, 24–26). Tropical insects are expected to be more susceptible to climate change and interactive effects, given their narrower physiological tolerance compared to non-tropical species (27). Although evidence about the response of tropical insects to climate change interactions remains scarce (21), recent studies show greater effects in tropical than non-tropical insect biodiversity (26).

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, 28), and the productivity of certain crops (29–32), although there is no evidence yet that pollen limitation is causing wholesale reductions in yields of crops that rely on animal pollination (33). Evidence that insect biodiversity responds to human pressures more strongly in the tropics than elsewhere (17, 26) is noteworthy, given that the majority of animal-pollination-dependent crops are grown there (34). However, it is not only tropical countries that will experience the effects of pollinator losses and subsequent pollen limitation, with high income countries benefiting from imports of animal-pollination-dependent foods from tropical areas (35). Abundance, species diversity and functional diversity of pollinators have all been implicated as determinants of the delivery of pollination service (32, 36–40). Previous attempts to model the provision of crop pollination service are often 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 (41). A key uncertainty however relates to the shape of the functional relationship between pollinator abundance and crop production, which needs to be accounted for to predict how abundance change might relate to crop pollination provision (41).

Here, 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 (42), together with a list of species identified in the literature as likely pollinators (17). 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 temperature change between a baseline period (1901–1930) and the year prior to biodiversity sampling, standardized by monthly temperature variability in the baseline period (26). We standardised this temperature anomaly to up-weight regions that are experiencing novel temperatures beyond ordinary seasonal variation, which has previously been identified as important to insects (26). We then apply these models to predict which locations and crops are likely to be at greatest risk from pollination shortfalls, using estimated proportional reduction of pollinator total abundance as a proxy for relative risk to pollination services. This relative risk is then moderated according to estimates of where crops are grown (43), how dependent these crops are on animal pollination (34), projections of historical and future climate change, and a set of assumptions for the relationship between local pollinator abundance and crop pollination (e.g. from linear to highly convex or concave). Lastly, we then combine these projections with estimates of the trade in pollination dependent crop production (35), to predict regions of the world that may be vulnerable to the indirect consequences of crop pollination risk via trade connections.

83 Results and Discussion

84 The abundance of insect pollinators responded strongly to the interaction of recent climate change and land
85 use (Figure 1). Within cropland experiencing novel temperatures (Standardized Temperature Anomaly =
86 1), pollinator abundance is 38.9% of natural habitat that has not experienced temperature increases. The
87 causal mechanism underpinning this interaction is unclear, but potentially relates to the homogenisation of
88 microclimatic conditions on anthropogenic land (44). Our results are qualitatively consistent with recent
89 results for a sample of all functional groups of insects (26), but importantly we show that responses to the
90 interactive effects of climate change and land use are stronger for pollinating than non-pollinating insects
91 (Figure 1). We also show that the strength of the interactive effect varies among taxonomic groups, with
92 the strongest effects seen in dipteran and hymenopteran pollinators (Figure S05). Whether the sensitivity
93 of pollinating insects to the interaction of climate change and land use relates directly to their reliance on
94 floral resources, or to other correlated traits typical of pollinators, is unclear. Most likely some combination
95 of both is true. For example, selection of animal pollinated plants is thought to be highly sensitive to
96 climatic conditions (45), suggesting that plant-pollinator interactions are highly sensitive to thermal changes.
97 Pollinator pilosity (i.e. hairiness), on the other hand, likely affects an insect’s ability to adapt to changes
98 in climate (46), and given its nature as a trait typical of bees and hoverflies, tends to be correlated with a
99 reliance on floral resources (47).

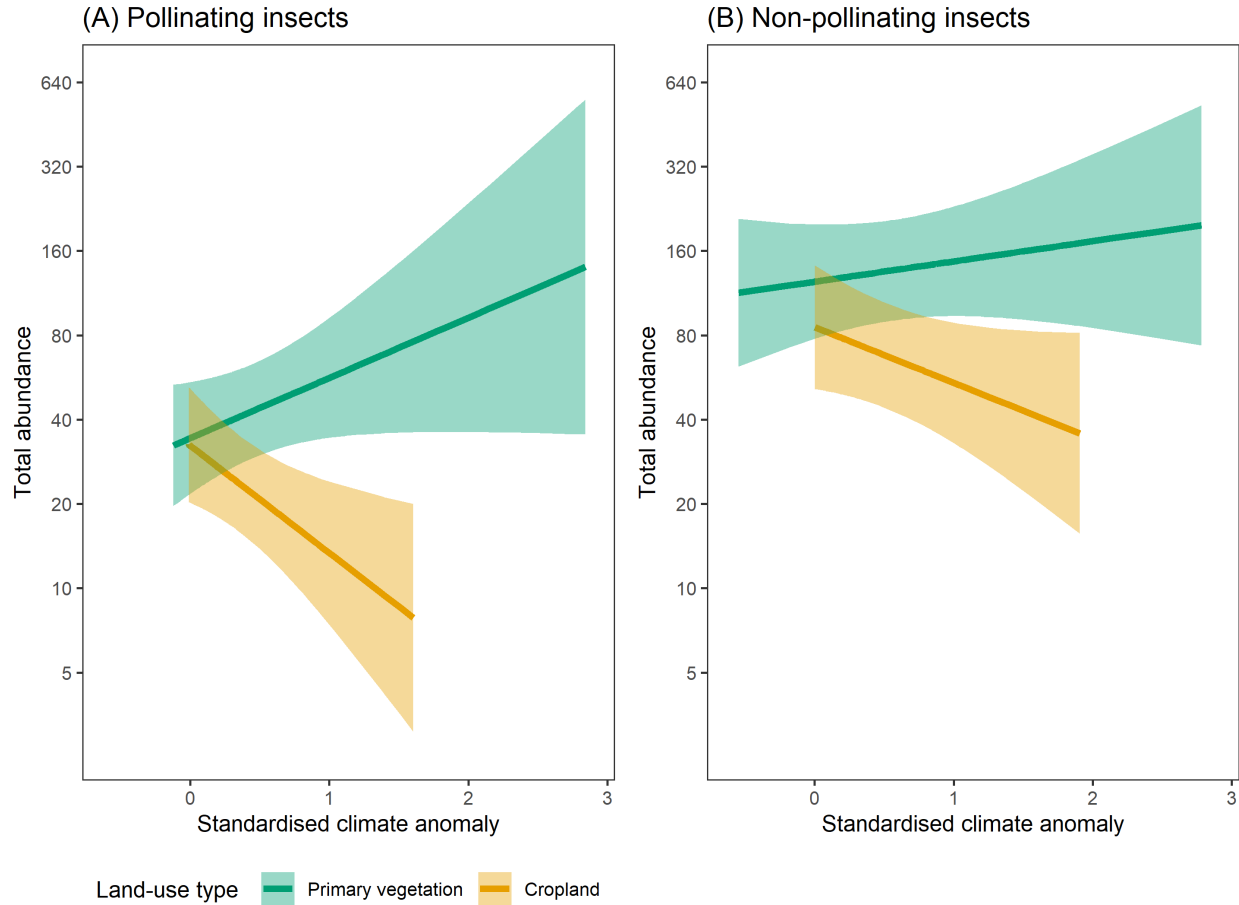


Figure 1: Response of pollinating (A) and non-pollinating (B) insect total abundance to the interactive effect of standardised temperature anomaly and land use (primary vegetation versus cropland) (A: $F = 23.3195$, $p < 0.001$; B: $F = 10.5764$, $p < 0.01$). Note that abundance is plotted on a \log_e scale. Results are based on linear mixed-effects models. Site numbers are as follows (also see Supplementary Material Table 2): Pollinating insects (primary vegetation = 1166, cropland = 1507); likely non-pollinating insects (primary vegetation = 1747, cropland = 922). Shading represents 95% confidence intervals around the mean fitted effect. Green = primary vegetation; yellow = cropland.

100 We predict that total pollination production risk will increase under all climate scenarios (Figure 2). For all
 101 scenarios, our projections use change in pollinating insect abundance as a proxy for the relative risk to the
 102 production of crops dependent on insects, incorporating information on where crops are grown worldwide
 103 (43) as well as the fractional dependence of crops on animal pollination (34). Our estimates of risk are based
 104 on the distribution of crops as grown in 2000, meaning we do not account for changes in the distribution of
 105 crops over time, which are likely to occur as a result of the direct impacts of climate change, indirect effects
 106 through the loss of pollinator biodiversity, and socio-economic factors such as price changes in the global
 107 markets for particular crops. Moreover, our estimates of both relative risk as well as absolute production
 108 risk should be interpreted as indices of risk, rather than predictions of the actual amount of production
 109 likely to be lost, given a very high uncertainty in how pollinator abundance changes will translate into actual
 110 production losses.

111 Increases in risk are seen for all assumed relationships between abundance loss and production risk (linear
 112 and varying degrees of convexity), although the magnitude of changes in relative risk and especially absolute
 113 production risk varied widely. The predicted rate of increase in average production risk was substantially

114 higher under RCP (Representative Concentration Pathway) 6.0 than RCP 2.6, suggesting that efforts to
115 mitigate climate change will reduce the risk to future crop production, alongside the many other bene-
116 fits (48). Relative production risk varied strongly between years under the convex abundance-production
117 relationships (Figure 2 and S13). This volatility may be explained by way in which the non-linearity of
118 abundance/production relationships interacts with inter-annual climate variability caused by the El Nino
119 Southern Oscillation (49), although at present this is unclear. Such climate effects would be some seen to
120 some extent under all abundance-production relationships, but magnified under highly convex scenarios as
121 regions undergo marked shifts from high to low production. While increasingly convex assumed relationships
122 between insect abundance loss and crop production risk led to steeper increases in relative production risk
123 with future climate change, absolute production risk was markedly lower owing to a lower baseline in the
124 present day (Figure 2). Results were robust to variation in climate predictions under different individual
125 climate models (Figure S06), do not change markedly when abundance loss is capped at the maximum model-
126 fitted value (Figure S02), do not change markedly when tested for sensitivity to data quality (Figure S04),
127 and likely hold across a set of plausible active season temperature thresholds (fitted through two different
128 approaches, see Figures S11 and S12) and abundance change slopes (Figure S10).

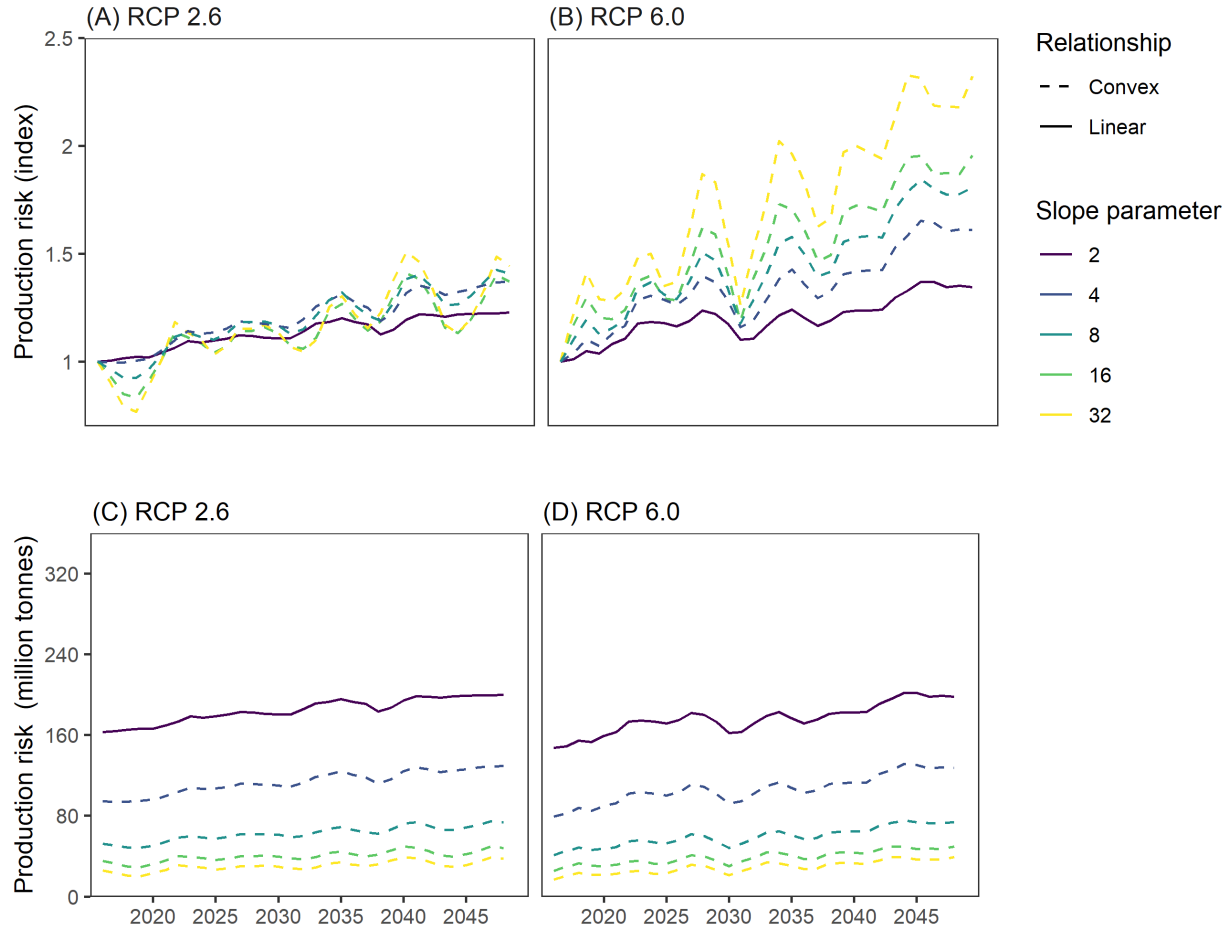


Figure 2: Projected change in total production risk under two RCP scenarios (2.6 and 6.0) and a set of different pollinator abundance-crop production relationships (linear and varying degrees of convexity). Results are shown both for an index of change in relative risk (A and B) and for absolute total production at risk (in tonnes) (C and D). For each year into the future, the standardised temperature anomaly was projected globally for all cells with production of crops dependent on animal pollination, using a 3-year rolling average of temperature anomaly estimates in each cell, from an ensemble of different climate models. We used data on crop production from the year 2000 (the latest year when such data are available for all crops). For each annual projection of standardised temperature anomaly, insect pollinator abundance on cropland was predicted according to the model shown in Figure 1A, 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, the total production of each crop (43) was multiplied by dependence on animal pollination (34), and then adjusted for the predicted percentage reduction in insect pollinator abundance in that cell. These estimates of crop production at risk were summed across crops, and then across all terrestrial cells globally. Lines show different assumed relationships between insect pollinator abundance and crop production: dashed = convex relationships (of differing degrees, indicated by different colours: yellow = most convex; purple/blue = least convex); and solid = linear relationship.

129 Production risk from insect pollinator abundance losses is highest, and predicted to increase most rapidly,
 130 in regions of sub-Saharan Africa, northern South America, and southeast Asia (Figure 3A and Figure 3C).
 131 Somalia, Guinea Bissau, and Ivory Coast emerge as particularly vulnerable, given their high and increasing

production risk, and the high dependence of their economy on agriculture (Figure 3C). A number of countries in Asia, South America, and the Caribbean have high and increasing levels of production risk, but lower levels of agricultural dependence, making their economies less vulnerable overall. For example, the Philippines, Indonesia, Papua New Guinea, Puerto Rico, Haiti, and Suriname all have high and increasing levels of production risk (Figure 3C), but relatively low GDP adjusted pollination dependent production. Among crops, cocoa is estimated to be at highest risk by a large margin, followed by mango and watermelon (Figure 3B). The risk to cocoa production is all the more significant from a social and economic perspective, as most cocoa is produced on small farms (two to four hectares) that provide income to between 40 and 50 million people globally (50). Coffee is also expected to have a combination of relatively high production risk and high value, suggesting that regions in which it is grown may experience economic difficulties, unless the pollination service can be replaced cost effectively. Similarly to cocoa, coffee production provides income to millions of small-scale farmers and their families in the tropics (51). Therefore, the increased production risk due to loss of pollinators could lead to increased income insecurity for some of the most vulnerable people globally. Projections of local crop production risk are sensitive to the assumed abundance-production relationship (Figure S08), with the exception of South East Asia which is consistently resolved as high risk, and the temperate realm which is consistently predicted as low risk (Figure S09).

For both countries and crops it is difficult to predict how the consequences of our production risk measure will play out in the real world. In part this is due to the push and pull of multiple uncertainties, some of which we do explore here (e.g. the relationship between pollinator abundance and crop production), but many of which we do not or cannot (e.g. the changing distribution of crops, the economic viability of hand pollination, the buffering effects of managed pollinators, the effects of climate change alone, and other technological solutions such as the breeding or engineering of pollinator independent cultivars). Regardless, at the global scale independent of changes in agricultural intensity, it's not unreasonable to state that the distribution of standardised temperature anomaly and animal-pollinator dependent crop production should predict a substantial portion of the variation in pollinator-mediated losses to crop production. For cocoa, recent research has focused on the direct effects of climate change on crop production (52, 53), often overlooking those that might be pollinator-mediated. Given the difficulties in teasing these mechanisms apart, and that the direct effects of climate change are easier to intuit, it is probable that this trend continues. However, and importantly, solutions to direct and pollinator-mediated effects will differ. For example, shade trees might protect crops from extreme temperatures (52), but might not for the ceratopogonid fly pollinators on which cocoa pollination depends. This is particularly pertinent given that some cocoa varieties are limited more by pollination availability than resource availability (54).

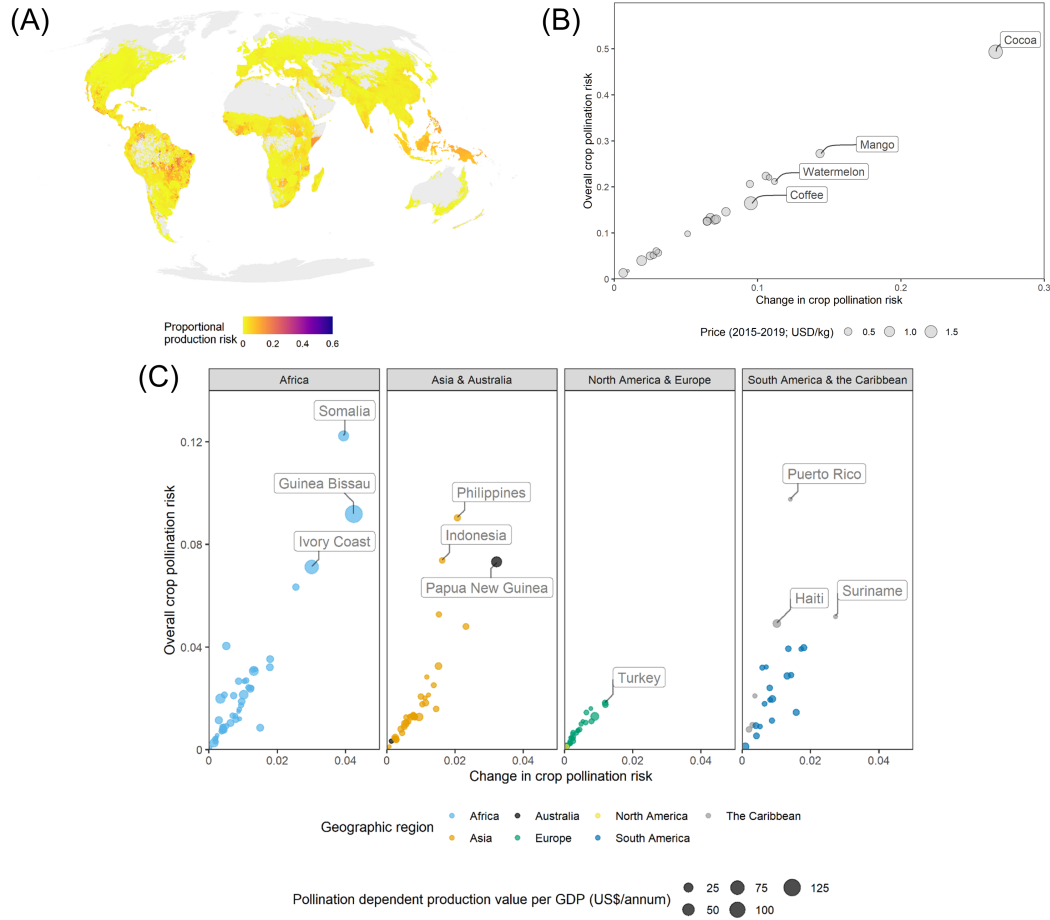


Figure 3: Projected change globally in the fraction of crop production estimated to be at risk in 2050 under the RCP 6.0 climate scenario, assuming a linear relationship between insect pollinator abundance loss and production loss for crops dependent on animal pollination. All projections are based on mean projections of the standardized temperature anomaly based on temperature estimates from an ensemble of individual climate models. (A) The sum of crop production at risk across all crops with some dependence on animal pollination (in each spatial cell), as a proportion of the production of all crops grown in that spatial cell (i.e. proportional production risk; see Figure S08 to see how cell-level risk differs among abundance-production scenarios). (B) Proportional production risk for the 20 crops with the highest total pollination dependent production globally (see Figure S01 for the top 20 crops). Overall risk here is the median of proportional production risk for all spatial cells in which that crop appears, 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 (55). (C) 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 adjusted for GDP, calculated from the product of total pollination dependent production per annum according to (43) and (34), and the per kg value of each crop (55). 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.

164 Countries besides those with high production risk will feel the impact of losses of pollinator biodiversity
 165 and the crops that depend on them, through disruption to imports, especially as the most vulnerable crops

166 tend to be valuable export products such as coffee and cocoa. In absolute terms, large countries such as
167 China and the United States have the highest total import risks. The exception is the Netherlands which
168 has the third largest overall import risk, much higher than expected based on its size but consistent with
169 its status as the greatest importer of cocoa beans worldwide (56). Import risk per capita highlights the
170 challenges that could be faced by nations with limited agricultural production capacity, such as many island
171 countries (e.g. Cayman Islands, Aruba, Singapore, the first, second and fourth highest import risk per capita,
172 respectively) or countries with unfavourable environmental conditions for agriculture (e.g., Mongolia, 19th
173 in import risk per capita). Total import risk per capita tends to be high also in northern and high income
174 countries, particularly continental western Europe, which has large processing industries for crops such as
175 coffee and cocoa. High income and unfavourable environment for agriculture could both account for high
176 import risk per capita for some countries in the Middle East (United Arab Emirates, Kuwait, Saudi Arabia,
177 which are 5th, 8th and 27th highest pollination import risk per capita). Our predictions of import risk are
178 based on trade patterns from the present day (35), meaning we do not account for changes in trade flows
179 that will likely occur in the future.

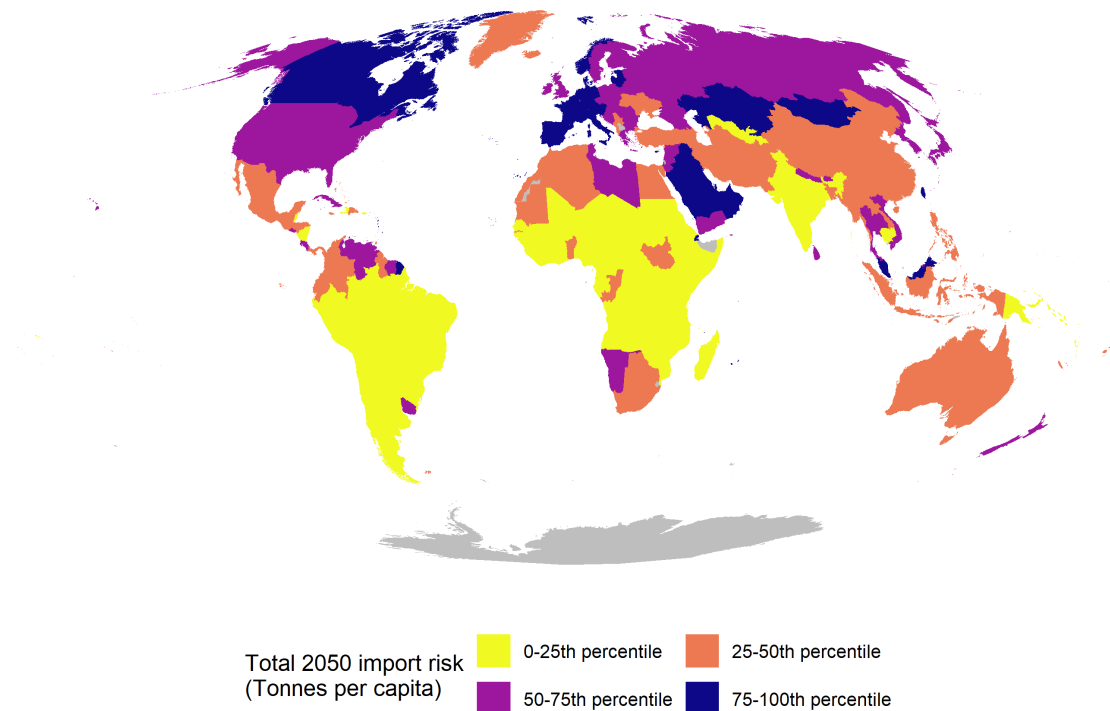


Figure 4: Projected total import risk for 2050 under the RCP 6.0 scenario, assuming a linear relationship between insect pollinator abundance loss and production loss. Projections are based on changes in the mean standardized temperature anomaly based on projections from an ensemble of individual climate models. 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 (35). For each yearly time step into the future, local production risk in each spatial cell is attributed to importers according to the quantity of pollination trade imported from each country. For example, if an importer is dependent on 3 countries for imports, at a proportion of 30%, 50%, and 20%, then any change in import risk should scale as a function of the local production risk aggregated at those same proportions. Total import risk here has been adjusted for country population size 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.

180 Interacting effects of climate change and anthropogenic land use are rapidly restructuring biodiversity (26,
 181 57). Here we show that the combination of agricultural land use and recent climate change is associated
 182 with particularly large reductions in the abundance of insect pollinators. We further show that the tropics
 183 will likely experience the greatest risk of future pollination shortfalls, putting at risk the production of crops
 184 that depend on insect pollination. The risk to these crops is highest, and predicted to increase most rapidly,
 185 in regions of sub-Saharan Africa and northern South America, especially in areas used to produce cocoa,
 186 mango, pumpkin, melon, watermelon, and coffee. Given the many factors that determine crop production
 187 and crop price (58), the likely effects of insect pollinator losses on crop production are unclear, and even if
 188 they do occur, conclusive attribution is likely to be challenging. Such complications likely in part explain
 189 why identifying a strong effect of pollinator losses on global crop yield and price has thus far been so

difficult (33, 59, 60). Regardless, there is sufficient evidence to suggest that declining insect pollinator abundance will influence crop production risk, particularly for those in the global south (61). Such risk could manifest in the form of direct and immediate losses to crop production through pollinator shortfall and fluctuations in the stability of production, as well through decreased resilience to changes that will happen in conjunction (e.g. the effects of extreme temperature and drought on crop growth). The health, well-being, and livelihoods of billions of people, from small farmers to consumers, relies to some extent upon the availability and affordability of crops dependent on animal pollination, and therefore on those pollinators (62). Climate change and agricultural land use could put these people’s well-being at very high risk.

References

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. S. A. Khan, M. Tanveer, S. Ahmad, M. Mars, M. Naeem, Z. Naveed, W. Schuett, C. Drees, D. Goulson, Declining abundance of pollinating insects drives falls in loquat (*Eriobotrya japonica*) fruit yields in the Pothwar region of Pakistan. *Agriculture, Ecosystems & Environment*. **339**, 108138 (2022).
12. T. M. Lewinsohn, K. Agostini, A. V. Lucci Freitas, A. S. Melo, Insect decline in Brazil: an appraisal of current evidence. *Biology Letters*. **18**, 20220219 (2022).
13. D. H. Janzen, W. Hallwachs, Perspective: Where might be many tropical insects? *Biological Conservation*. **233**, 102–108 (2019).

- 225 14. 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,
226 Rapid responses of British butterflies to opposing forces of climate and habitat change. *Nature*. **414**,
65–69 (2001).
- 227 15. 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. Tschardtke, 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
228 changes: Effects of geographic and taxonomic biases. *Scientific Reports*. **6**, 31153 (2016).
- 229 16. I. Oliver, J. Dorrough, H. Doherty, N. R. Andrew, Additive and synergistic effects of land cover, land
230 use and climate on insect biodiversity. *Landscape Ecology*. **31**, 2415–2431 (2016).
- 231 17. J. Millard, C. L. Outhwaite, R. Kinnersley, R. Freeman, R. D. Gregory, O. Adedaja, S. Gavini, E.
Kioko, M. Kuhlmann, J. Ollerton, Z.-X. Ren, T. Newbold, Global effects of land-use intensity on local
232 pollinator biodiversity. *Nature Communications*. **12**, 2902 (2021).
- 233 18. R. Hickling, D. B. Roy, J. K. Hill, R. Fox, C. D. Thomas, The distributions of a wide range of
234 taxonomic groups are expanding polewards. *Global Change Biology*. **12**, 450–455 (2006).
- 235 19. 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
236 trends. *Ecography*. **40**, 1139–1151 (2017).
- 237 20. 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
238 (2020).
- 239 21. C. A. Halsch, A. M. Shapiro, J. A. Fordyce, C. C. Nice, J. H. Thorne, D. P. Waetjen, M. L. Forister, In-
sects and recent climate change. *Proceedings of the National Academy of Sciences*. **118**, e2002543117
240 (2021).
- 241 22. 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*
242 *Climate Change*. **8**, 713–717 (2018).
- 243 23. 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.
244 *Scientific Reports*. **9**, 15039 (2019).
- 245 24. 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
246 climate warming. *Global Change Biology*. **23**, 2272–2283 (2017).

- 247 25. 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. Gerschlauser, 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
248 shape tropical mountain biodiversity and ecosystem functions. *Nature*. **568**, 88–92 (2019).
- 249 26. C. L. Outhwaite, P. McCann, T. Newbold, Agriculture and climate change are reshaping insect
250 biodiversity worldwide. *Nature*. **605**, 97–102 (2022).
- 251 27. 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
252 National Academy of Sciences*. **105**, 6668–6672 (2008).
- 253 28. 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
254 flowering plant seed production to pollinator declines. *Science Advances*. **7**, eabd3524 (2021).
- 255 29. A. Klein, I. Steffan–Dewenter, T. Tschardtke, Fruit set of highland coffee increases with the diversity
of pollinating bees. *Proceedings of the Royal Society of London. Series B: Biological Sciences*. **270**,
256 955–961 (2003).
- 257 30. T. H. Ricketts, G. C. Daily, P. R. Ehrlich, C. D. Michener, Economic value of tropical forest to coffee
258 production. *Proceedings of the National Academy of Sciences*. **101**, 12579–12582 (2004).
- 259 31. A. Holzschuh, C. F. Dormann, T. Tschardtke, I. Steffan-Dewenter, Expansion of mass-flowering crops
leads to transient pollinator dilution and reduced wild plant pollination. *Proceedings of the Royal
260 Society B: Biological Sciences*. **278**, 3444–3451 (2011).
- 261 32. 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. Ouyard, 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**,
262 1481 (2019).
- 263 33. 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
264 Biology*. **18**, 1572–1575 (2008).
- 265 34. A.-M. Klein, B. E. Vaissière, J. H. Cane, I. Steffan-Dewenter, S. A. Cunningham, C. Kremen, T.
Tschardtke, Importance of pollinators in changing landscapes for world crops. *Proceedings of the
266 Royal Society B: Biological Sciences*. **274**, 303–313 (2007).
- 267 35. 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
268 Advances*. **7**, eabe6636 (2021).
- 269 36. 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).
270
- 271 37. C. Brittain, C. Kremen, A.-M. Klein, Biodiversity buffers pollination from changes in environmental
conditions. *Global Change Biology*. **19**, 540–547 (2013).
272

- 273 38. M. A. Genung, J. Fox, N. M. Williams, C. Kremen, J. Ascher, J. Gibbs, R. Winfree, The relative
274 importance of pollinator abundance and species richness for the temporal variance of pollination
services. *Ecology*. **98**, 1807–1816 (2017).
- 275 39. R. Winfree, J. R. Reilly, I. Bartomeus, D. P. Cariveau, N. M. Williams, J. Gibbs, Species turnover
276 promotes the importance of bee diversity for crop pollination at regional scales. *Science*. **359**, 791–793
(2018).
- 277 40. 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. Tschardtke, 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. Četković, 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. Plečáček, 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.
278 *Science Advances*. **5**, eaax0121 (2019).
- 279 41. E. Lonsdorf, C. Kremen, T. Ricketts, R. Winfree, N. Williams, S. Greenleaf, Modelling pollination
280 services across agricultural landscapes. *Annals of Botany*. **103**, 1589–1600 (2009).
- 281 42. L. N. Hudson, T. Newbold, S. Contu, S. L. L. Hill, I. Lysenko, A. De Palma, B. Collen, R. M. Ewers,
G. M. Mace, D. W. Purves, J. P. W. Scharlemann, A. Purvis, The database of the PREDICTS
(Projecting Responses of Ecological Diversity In Changing Terrestrial Systems) project. *Ecology and*
282 *Evolution*. **7**, 145–188 (2017).
- 283 43. C. Monfreda, N. Ramankutty, J. A. Foley, Farming the planet: 2. Geographic distribution of crop
284 areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochemical*
Cycles. **22**, GB1022 (2008).
- 285 44. T. H. Oliver, M. D. Morecroft, Interactions between climate change and land use change on biodi-
286 versity: Attribution problems, risks, and opportunities. *Wiley Interdisciplinary Reviews: Climate*
Change. **5**, 317–335 (2014).
- 287 45. A. R. Rech, B. Dalsgaard, B. Sandel, J. Sonne, J.-C. Svenning, N. Holmes, J. Ollerton, The macroecol-
288 ogy of animal versus wind pollination: Ecological factors are more important than historical climate
stability. *Plant Ecology & Diversity*. **9**, 253–262 (2016).
- 289 46. M. K. Peters, J. Peisker, I. Steffan-Dewenter, B. Hoiss, Morphological traits are linked to the cold
290 performance and distribution of bees along elevational gradients. *Journal of Biogeography*. **43**, 2040–
2049 (2016).
- 291 47. J. R. Staver, G. Liñán-Cembrano, J. R. Beggs, B. G. Howlett, D. E. Pattemore, I. Bartomeus,
292 Hairiness: The missing link between pollinators and pollination. *PeerJ*. **4**, e2779 (2016).
- 293 48. D. Ürge-Vorsatz, S. T. Herrero, N. K. Dubash, F. Lecocq, Measuring the co-benefits of climate change
294 mitigation. *Annual Review of Environment and Resources*. **39**, 549–582 (2014).

- 295 49. A. Timmermann, S.-I. An, J.-S. Kug, F.-F. Jin, W. Cai, A. Capotondi, K. M. Cobb, M. Lengaigne,
296 M. J. McPhaden, M. F. Stuecker, others, El Niño–southern oscillation complexity. *Nature*. **559**,
535–545 (2018).
- 297 50. M. S. Beg, S. Ahmad, K. Jan, K. Bashir, Status, supply chain and processing of cocoa-a review.
298 *Trends in food science & technology*. **66**, 108–116 (2017).
- 299 51. Y. Pham, K. Reardon-Smith, S. Mushtaq, G. Cockfield, The impact of climate change and variability
300 on coffee production: A systematic review. *Climatic Change*. **156**, 609–630 (2019).
- 301 52. G. Schroth, P. Läderach, A. I. Martinez-Valle, C. Bunn, L. Jassogne, Vulnerability to climate change
302 of cocoa in West Africa: Patterns, opportunities and limits to adaptation. *Science of the Total
Environment*. **556**, 231–241 (2016).
- 303 53. K. Ofori-Boateng, B. Insah, The impact of climate change on cocoa production in West Africa.
304 *International Journal of Climate Change Strategies and Management* (2014).
- 305 54. J. H. Groeneveld, T. Tschardtke, G. Moser, Y. Clough, Experimental evidence for stronger cacao
306 yield limitation by pollination than by plant resources. *Perspectives in Plant Ecology, Evolution and
Systematics*. **12**, 183–191 (2010).
- 307 55. Food and Agriculture Organization of the United Nations (FAO), Producer prices & crops and live-
308 stock products (2022).
- 309 56. A. J. G. Simoes, C. A. Hidalgo, in *Workshops at the twenty-fifth AAAI conference on artificial intel-
310 ligence* (2011).
- 311 57. C. Ganuza, S. Redlich, J. Uhler, C. Tobisch, S. Rojas-Botero, M. K. Peters, J. Zhang, C. S. Benjamin,
312 J. Englmeier, J. Ewald, others, Interactive effects of climate and land use on pollinator diversity differ
among taxa and scales. *Science advances*. **8**, eabm9359 (2022).
- 313 58. S. F. Gaetano, L. Emilia, C. Francesco, N. Gianluca, S. Antonio, Drivers of grain price volatility: A
314 cursory critical review. *Agricultural Economics*. **64**, 347–356 (2018).
- 315 59. M. A. Aizen, L. A. Garibaldi, S. A. Cunningham, A. M. Klein, How much does agriculture depend
316 on pollinators? Lessons from long-term trends in crop production. *Annals of botany*. **103**, 1579–1588
(2009).
- 317 60. L. A. Garibaldi, M. A. Aizen, A. M. Klein, S. A. Cunningham, L. D. Harder, Global growth and sta-
318 bility of agricultural yield decrease with pollinator dependence. *Proceedings of the National Academy
of Sciences*. **108**, 5909–5914 (2011).
- 319 61. L. V. Dicks, T. D. Breeze, H. T. Ngo, D. Senapathi, J. An, M. A. Aizen, P. Basu, D. Buchori, L.
320 Galetto, L. A. Garibaldi, others, A global-scale expert assessment of drivers and risks associated with
pollinator decline. *Nature Ecology & Evolution*. **5**, 1453–1461 (2021).
- 321 62. S. G. Potts, V. Imperatriz-Fonseca, H. T. Ngo, M. A. Aizen, J. C. Biesmeijer, T. D. Breeze, L. V.
322 Dicks, L. A. Garibaldi, R. Hill, J. Settele, others, Safeguarding pollinators and their values to human
well-being. *Nature*. **540**, 220–229 (2016).

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340 **Competing interests**

341 All authors declare that they have no competing interests.

342 **Data and materials availability**

343 All data will be made available on FigShare, and all code on both Zenodo and GitHub.

344 **Supplementary Materials**

345 Materials and Methods

346 Figs. S1-S13

347 Tables

348 References