Projecting climate change and land-use scenarios of crop pollination risk (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*
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- ☐ 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*
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- ☐ 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*
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- ☐ Uhler et al. (2021). *Nature Communications*
- ☐ Oliver et al. (2016). *Landscape Ecology*
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- ☐ 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*
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- ☐ 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*
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- ☒ 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*).

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 (see Shiny app for full extended predictions, https://joemillard.shinyapps.io/pollinator_dependence_visualisation/). 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*), projections of historical and future climate change, and a set assumptions for the relationship between local pollinator abundance and crop pollination, we predict which locations and crops are likely to be at greatest risk from pollination shortfalls. We then combine these projections with estimates of the trade in pollination dependent production, to predict regions of the world that may be vulnerable to the indirect consequences of crop pollination risk via trade routes.

4 Results and Discussion

The abundance of insect pollinators responded strongly to the interaction of recent climate change and land use (Figure 1). Within cropland in areas experiencing novel temperatures (Standardized Temperature Anomaly = 1), pollinator abundance is X% lower than areas of natural habitat that have not experienced temperature increases. Our results are qualitatively consistent with recent results for a sample of all insects (*25*), but importantly we show that responses to the interactive effects of climate change and land use are stronger for pollinating than non-pollinating insects (Figure 1). Whether the sensitivity of pollinating insects to the interaction of climate change and land use relates directly to their reliance on floral resources, or to other correlated traits such as dispersal ability, body size, voltinism, or specialism, is unclear. Most likely some combination of both is true. For example, insect-pollinated plants have been shown to respond more strongly to warming than wind-pollinated plants, suggesting that plant-pollinator interactions are highly sensitive to thermal changes (Fitter & Fitter, 2002).

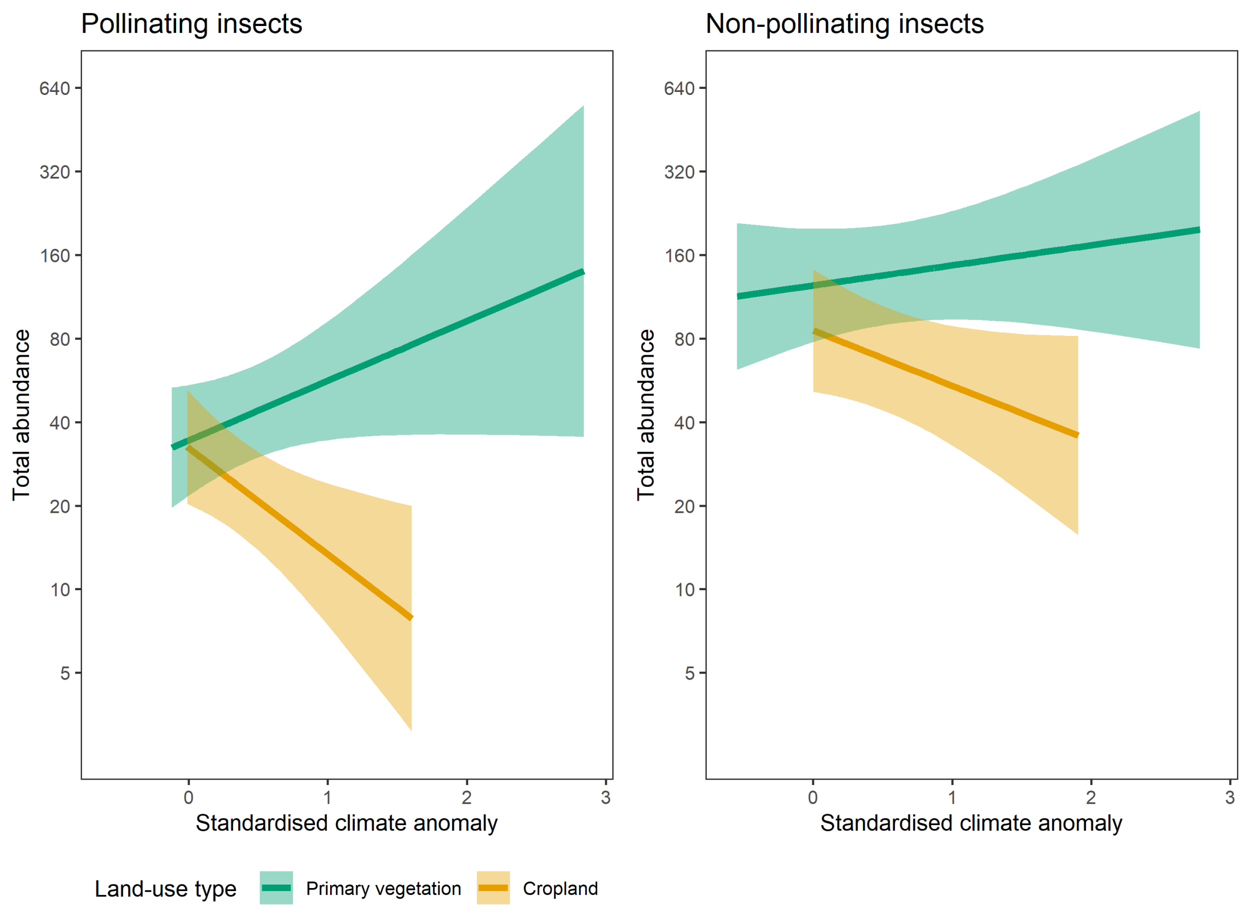

Figure 1: Response of pollinating (A) and non-pollinating (B) insect total abundance to the interactive effect of standardised temperature anomaly and land use (primary vegetation versus cropland) (A: $F = 23.3195$, $p < 0.001$; B: $F = 10.5764$, $p < 0.01$). Note that abundance is plotted on a $\log_e$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

Using the projected changes in pollinating insect abundance as a proxy for the relative risk to the production of crops dependent on insects (incorporating information on where crops are grown worldwide (Earthstat ref) as well as the fractional dependence of crops on animal pollination (Klein ref)), we predict that total production risk will increase under all climate scenarios (Figure 2). Our estimates of risk are based on the distribution of crops as grown in 2000. We do not account for changes in the distribution of crops over time, which are likely to occur as a result of the direct impacts of climate change as well as indirect effects such as through the loss of pollinator biodiversity. Our estimates of both relative risk as well as absolute production risk should be interpreted as indices of risk, rather than predictions of the actual amount of production likely to be lost, given a very high uncertainty in how pollinator abundance changes will translate into actual production losses. Increases in risk are seen for all assumed relationships between abundance loss and production risk (linear and varying degrees of convexity), although the magnitude of changes in relative risk and especially absolute production risk varied widely. The predicted rate of increase in average production risk was substantially higher under RCP 6.0 than RCP 2.6, suggesting that efforts to mitigate climate change will reduce the risk to future crop production, alongside the many other benefits (refs). Relative production risk varied strongly between years under the convex abundance-production relationships, owing to the non-linearity of these relationships combined with inter-annual climate variability caused by the El Nino Southern Oscillation (*reference*). While increasingly convex assumed relationships between insect abundance loss and crop production risk led to steeper increases in relative production risk with future climate change, absolute production risk was markedly lower owing to a lower baseline in the present day (Figure 2). Results were robust to variation in climate predictions under different individual climate models (Figure S06), do not change markedly when abundance loss is capped at the maximum model-fitted value (Figure S02), do not change markedly when tested for sensitivity to data quality (Figure S04), and likely hold across a set of plausible active season temperature thresholds, fitted through two different approaches (Figures S11 and S12).

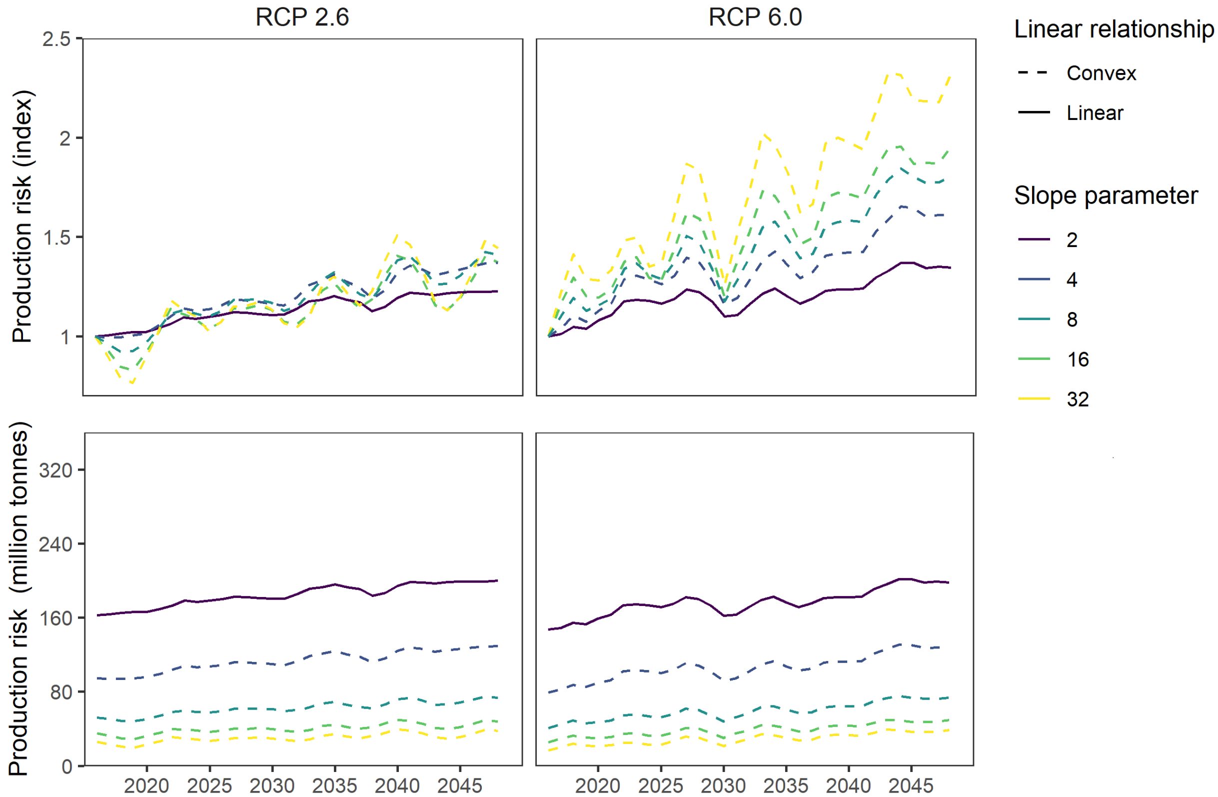

Figure 2: Projected change in total production risk under two RCP scenarios (6.0 and 2.6) and a set of different abundance-production relationships (linear and varying degrees of convexity). Results are shown both for an index of change in relative risk (A) and for absolute total production at risk (in tonnes) (B). 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. Temperature projections are the mean across 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 crops (estimated according to (Earthstat ref)) was adjusted to account for dependence on animal pollination (using ratios from (Klein ref)), and then adjusted according to 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.

Production risk from insect pollinator abundance losses is highest, and predicted to increase most rapidly, in regions of sub-Saharan Africa, northern South America and southeast Asia (Figure 3). Somalia, Guinea Bissau, and Ivory Coast emerge as particularly vulnerable, given their high and increasing production risk, and the dependence of their economy on agriculture (Figure 3X). Within Asia, the Philippines, Indonesia and Papua New Guinea, while within South America and the Caribbean, Puerto Rico, Haiti and Suriname have high and increasing levels of production risk. However, these countries have a lower dependence on crops dependent on animal pollination for their GDP (Figure 3X). Among crops, cocoa is estimated to be at highest risk by a large margin, followed by mango and watermelon (Figure 3X). 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.

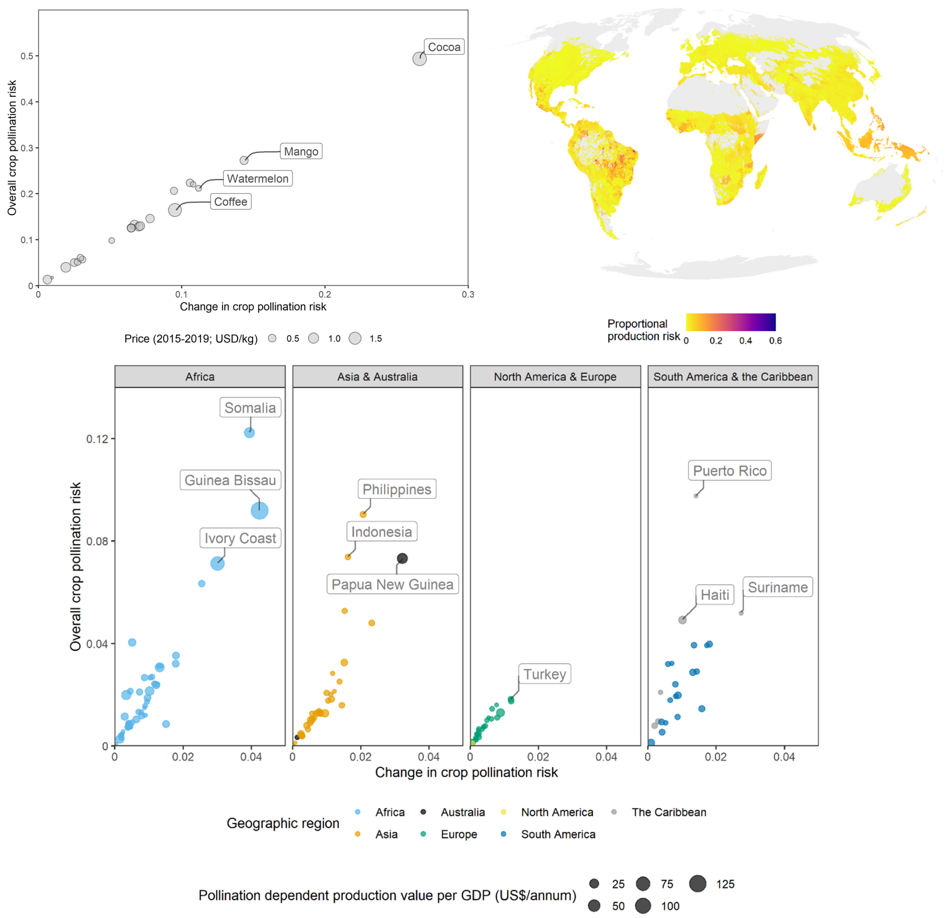

Figure 3: Projected change globally in the fraction of crop production estimated to be at risk in 2050 under the RCP 6.0 climate scenario, assuming a linear relationship between insect pollinator abundance loss and production loss for crops dependent on animal pollination. All projections are based on mean projections of the standardized temperature anomaly based on temperature estimates from an ensemble of individual climate models. 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.

Countries besides those with high production risk will feel the impact of losses of pollinator biodiversity and the crops that depend on them, through disruption to imports. Total import risk per capita tends to be highest in northern countries, particularly continental western Europe, Canada, and parts of the Middle East. Some of the countries with the highest levels of import risk are those that have a high dependence on food imports, such as the Cayman Islands, Singapore, and Aruba. Interestingly, the Netherlands has the third highest per capita import risk, consistent with its status as the greatest importer of cocoa beans worldwide (reference).

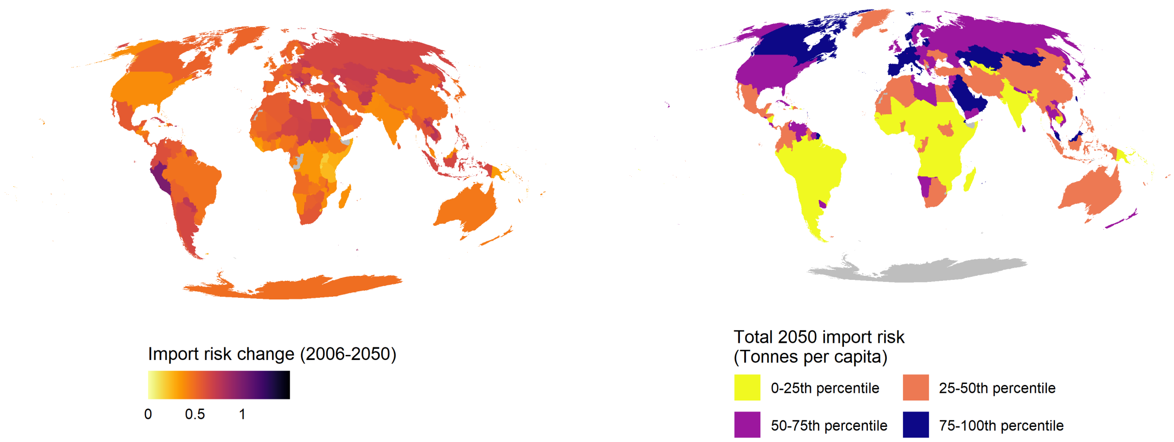

Figure 4: Projected change in import risk for 2050 under the RCP 6.0 scenario, assuming a linear relationship between insect pollinator abundance loss and production loss. The projections are based on chnages in the mean standardized temperature anomaly based on projections from an ensemble of individual 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 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.

Interacting effects of climate change and anthropogenic land use are rapidly restructuring biodiversity (*refs*). Here 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. Given the many factors that determine crop production and crop price, the likely effects of insect pollinator losses on crop production are unclear (*refs*), and even if they do occur conclusive attribution is likely to be challenging (Khanal et al., 2018; Santeramo et al., 2018). Such complications likely in part explain why identifying a strong effect of pollinator losses on global crop yield and price has thus far been so difficult (Aizen et al., 2008, 2009; Garibaldi et al.,2011). Regardless, there is sufficient evidence to suggest that declining insect pollinator abundance will influence crop production risk, particularly for those in the global south (Dicks et al., 2021). The health, well-being, and livelihoods of billions of people to some extent depends upon the availability and affordability of crops dependent on animal pollination (Potts et al., 2016). Climate change and agricultural land use could put these people's wellbeing at very high risk.

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