# *Globalisation and pollinators: pollinator declines are an economic threat to global food systems*

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# Globalisation and pollinators: Pollinator declines are an economic threat to global food systems

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## Abstract

1. Trade in animal-pollinated crops plays an important role in global food systems: in many low-income countries, export of pollinated crops such as coffee and cocoa plays a significant role in livelihoods, while food systems in many higher income nations depend on international trade in these crops to satisfy their local demands. Losses of pollination services therefore pose a significant risk to economies beyond the area directly affected.
2. Using a simple extension of a common economic model, we explore which countries are most affected by a loss of pollination services in three case study groups of 25 countries that are vulnerable to different risks: pesticide use, natural disasters and economic debts.
3. In all three cases, large, developed economies such as the United Kingdom, Germany and Japan, are estimated to suffer the greatest economic losses, even if pollinator losses only affect smaller, less-developed economies.
4. In cases where higher income countries are affected by pollinator losses, there is a significant shift in the value of global pollinated crop production towards other large, unaffected countries.
5. Our findings highlight the need for richer countries to invest in pollinator conservation beyond their own borders to maintain resilient food systems. We provide suggestions for further economic research to better understand and identify system vulnerabilities to pollinator losses.

**KEYWORDS**
agriculture, economic valuation, global value chain, globalisation, pollination services, trade

# 1 | INTRODUCTION

Animal pollination is a key process in the reproduction of many nutritious food crops (Aizen et al., 2008; Bailes et al., 2015). Pollinator populations are under pressure from human activities, including intensive use of agrochemicals, climate change and habitat losses, in turn resulting in pressures on the supply of pollination services to global crops (Potts et al., 2016). The relative risks and impacts of such losses are thought to vary strongly between global regions, but there remains considerable uncertainty around the scale and severity of these impacts (Dicks et al., 2021).

As consumer demands and new technology have created increasingly globalised food systems, many animal-pollinated crops, such as coffee and cocoa, have become globally important commodity crops (Talbot, 2002) often produced primarily for export (Gereffi & Lee, 2012). Trade in animal-pollinated crops is an important source of income for many countries on the UN list of least developed countries (LDCs), often from crops that are specifically grown for export (Silva et al., 2021). For example, over €3.4 billion in agri-food products (including tropical fruits, nuts and spices, coffee and cocoa) were imported from LDCs to the European Union alone in 2015 (European Commission, 2016). Shocks to global food systems, such as the global financial crisis, can therefore have disproportionate effects on these countries (Bekkers et al., 2017; Dissanayake, 2016). The loss of pollinators has geo-political implications with respect to production and international trade of cultivated crop species, the resilience of global food systems and related issues of global inequality and poverty (Dicks et al., 2021). However, global and local markets for many insect-pollinated crops are poorly understood, especially in developing countries, limiting research and policy capacity to explore the vulnerability of global crops systems to localised pollinator losses.

To encourage policy action, numerous studies have estimated the impacts of pollinator declines on human economies at a range of scales, with for example, estimates of the economic impacts of pollinators to global agri-food production estimated at US$235–577 billion per annum (Breeze et al., 2016; Lautenbach et al., 2012). Most of these studies use simple ‘dependence ratios’: quantitative measures of the proportion of crop production lost in the absence of pollination by animals, to estimate the impacts of pollination service losses. However, by ignoring the effect on trade, such studies inherently assume that all impacts of pollination service losses are confined to the area affected, missing the impacts of supply and price changes on other countries.

To date only one study, Bauer and Sue Wing (2016) has attempted to capture the effect of pollinator losses on global trade. This study used a general equilibrium model (GEM) approach. GEMs are complex economic models that use numerous metrics of substitution (i.e. replacing one item with a suitable alternative) between products (e.g. different brands), inputs (e.g. materials vs. labour) and countries (e.g. acquiring the same product from a number of countries) to capture the effect of global market changes on whole economies (see e.g. Bauer & Sue Wing, 2016; Farber et al., 2006; Jones, 1965). However, GEMs require large amounts of data on product and input substitutions, which can be very difficult to properly estimate, even for widely studied products in well-developed economies. This can make them impractical for evaluating global risks from localised pollinator losses as the extent of impacts can be lost among the numerous unvalidated assumptions about how markets will react. Furthermore, existing global analyses focus on total, global losses of pollination services rather focusing on countries that are vulnerable to particular risks. This makes them less useful for assessing threats or targeting responses.

Here, we use a simple extension of common economic analyses to identify which countries are most affected by a series of localised pollinator losses (e.g. in countries vulnerable to specific economic and environmental risks) in the wider food system. We focus on the relative impacts between countries rather than the absolute values of economic losses in order to highlight the relative vulnerability of different countries to different risks to global pollinators. We discuss the challenges in our approach and the identify key data required to improve it.

# 2 | MATERIALS AND METHODS

Based on past studies (Gallai et al., 2009; Lautenbach et al., 2012), we developed a computational framework in R (v3.5.2) to estimate the immediate economic impacts of shock pollination service losses at a national level on international food systems. We used data for 74 major animal-pollinated crops and crop categories using trade data from 140 countries for the years 2005–2014 (the full period available for all applicable data), recorded in the FAOSTAT database (FAOSTAT, 2017a). Ten years of aggregated trade data were used to minimise the effects of anomalies in individual years, such as abnormal yields or prices. The model estimates the change in production yields and market prices on a per-country basis following pollinator loss in one or more countries. The difference between the net monetary value of trade in animal-pollinated crops calculated with and without pollinators forms a measure of the economic benefits of the pollination services provided by pollinators to the sale and trade of each crop species.

Because we lack information on the marginal relationship between pollinator abundance and yield for most crops (but see e.g. Garratt et al., 2018), our model explores the presence of pollinators compared with their absence. As such, it reflects the maximum economic benefits/risks only.

## 2.1 | Model inputs: Dependence ratio and price elasticity

Crop pollinator dependence ratios were drawn from a global review by Klein et al. (2007) of the leading global crops on the world market included in the FAO crop production list at the time (the year 2004) (FAOSTAT, 2017a; Klein et al., 2007). We used this list of crop species

(74 single crops and 33 commodity crops) as the basis for our analysis. First, we removed crops where the impact of animal pollination was reported as 'no increase', 'unknown' or 'indirect', leaving a short list of 70 single crops and 18 commodity crops. In the case of the 18 commodity crops, these were pooled into four commodity groups (Beans, green; Fruit, fresh NES [Not Elsewhere Specified]; Fruit, tropical fresh NES; Nuts, NES) according to FAO conventions. This gave a final total of 74 different crop categories included in the analysis.

These data were used to calculate the change in production of animal-pollinated crops following pollinator loss in one or more countries (Equation 1). Production (tonnes per annum) of crops in the absence of pollinators, $Y_{t+1}$, is calculated as the production of crops with pollinators present, $Y_t$, multiplied by 1 minus the dependence ratio ($D$) for that crop species.

$$Y_{t+1} = Y_t \times (1 - D). \quad (1)$$

For each crop species, Klein et al. (2007) presented dependence ratio as a category with a range of values to capture the approximate highest and lowest estimated reduction in crop output in the absence of pollinators. We therefore created scenarios using values for $D$ at the upper and lower end of each range respectively, representing best-case and worst-case scenarios for pollinator dependence. For example, in the case of apples, are assigned a dependence ratio of 40% (best case) to 90% (worst case). See Table S1 for the full list of dependence ratio values used in this analysis.

As animal-pollinated crop production falls, prices would be expected to rise as available supplies of the crop fall relative to consumer demand. In this case, the economic concept of price elasticity of demand is a useful tool to quantify price sensitivity of demand for goods/services. Price elasticity of demand describes the relationship between demand for a particular commodity and its market price: reflecting a percentage change in quantity demanded relative to a 1% change in the price. This is generally a negative relationship, with demand decreasing in response to increasing price. For example, a commodity with a price elasticity of 0.07 means that a 10% increase in the price of the commodity is associated with a 7% decrease in the quantity demanded.

The inverse of this relationship was used to make a general estimate of the market prices of animal-pollinated crops under scenarios of reduced production due to pollinator loss, assuming that demand will stay constant, but prices will instead rise (Equation 2). We used this relationship to connect the dependence ratio ($D$) data from Klein et al. (2007) (to estimate the proportional decrease in production in the absence of pollinators) with price elasticity ($E_d$) information for the relevant food categories, to be able to estimate the response of crop prices to reduced production yields. The hypothetical price of each crop, $p_{t+1}$, assuming reduced production in the absence of pollinators, was estimated as a function of the current price, $p_t$, the price elasticity of demand ($E_d$) and the dependence ratio ($D$), as follows:

$$p_{t+1} = p_t \times \left(1.0 + \frac{D}{E_d}\right). \quad (2)$$

As price change is calculated on the inverse of the price elasticity of demand $\left(\frac{D}{E_d}\right)$ low elasticities will translate to high price changes. Price elasticities are typically estimated using linear modelling of a wide range of data over multiple decades and are thus mostly estimated for large economies (e.g. Andreyeva et al., 2010; Tian & Yu, 2017) or globally traded commodities (e.g. de Menezes & Piketty, 2012; Tothmihaly, 2018). As such, most past studies into the impact of pollinator losses on prices have used a realistic but arbitrary range for all insect-pollinated crops (Breeze et al., 2020; Gallai et al., 2009). Here, we use the values for price elasticity of demand for each crop species from Andreyeva et al. (2010) who reviewed 160 studies on the price elasticity of demand for major food categories in the United States for four major food categories (fruit, vegetables, fats/oils and sweets/sugars) (Table S1). Data were not available on regional variations in price elasticities, so this source was used as the most comprehensive available dataset. Two scenarios of price elasticity were modelled, using the upper and lower limits of the 95% confidence intervals reported by Andreyeva et al. (2010) for each food category. This, combined with the two scenarios for dependence ratio, resulted in a total of four separate scenarios being modelled for each crop: reflecting high/low pollinator dependence and high/low price elasticity.

## 2.2 | Demand for pollinated crops

The shortfall in production is represented as the difference ($\Delta Y$) between the production levels for the crop species (tonnes) with pollinators ($Y_t$) and without pollinators ($Y_{t+1}$):

$$\Delta Y = Y_t - Y_{t+1}. \quad (3)$$

The model calculates the net trade for each crop on a country-by-country basis as follows:

$$TB_t = p_{t,X}(X) - p_{t,Y}(M), \quad (4)$$

where $TB_t$ is the current trade balance or net exports as calculated from data in the FAO database on import and export prices ($p_{t,I}$ and $p_{t,Y}$) and quantities of imports ($M$) and exports ($X$) for each crop. Following pollinator loss, the updated trade balance is calculated as follows:

$$TB_{t+1} = p_{t+1,X}\left(X - \Delta Y\left(\frac{X}{X+M}\right)\right) - p_{t+1,Y}\left(M + \Delta Y\left(\frac{M}{X+M}\right)\right), \quad (5)$$

where $TB_{t+1}$ is the estimated trade balance for the crop following pollinator decline in the affected countries; $p_{t+1,x\,N}$ and $p_{T+1,x}$ are the updated prices per tonne for imports and exports respectively (see Equation 2), $X$ is export quantities (tonnes, source FAO), $M$ is import quantities (tonnes, source FAO) and $\Delta Y$ is the shortfall in national production (tonnes) assumed in the absence of pollinators using Klein's dependence ratio data (see Equation 3). The difference between the crop production with and without pollinators is defined as $\Delta Y$. This shortfall is balanced out by proportionally increasing the quantities of imports ($M$) and decreasing the quantities of exports ($X$) respectively for that particular crop.

The value ($Val$, in US$) of global pollination services to a particular country ($i$) is defined as the difference between the net trade balance before pollinator loss ($TB_t$) and after pollinator loss ($TB_{t+1}$) summed across all pollinated crops ($j$) traded by that country:

$$Val_i = \sum_j \left( TB_{t,j} - TB_{t+1,j} \right). \quad (6)$$

As suitable data on the substitutability, between different pollinated crops and/or non-pollinated produce in different countries is unavailable, the model assumes (a) no dietary changes in the event of pollinator loss and (b) countries retain the same distribution of imports and do not change their own patterns of crop production. Similarly, as we lack information on input substitution between pollination and other forms of natural or manufactured capital, the model ignores any constraints on supply, effectively assuming that production shortfalls can be compensated for by, for example, planting a greater area of crops (Aizen et al., 2009) in place of other agricultural activities or increasing other inputs. Such substitutions commonly occur in response to supply shocks, but usually after a variable time-lag (e.g. Santeramo et al., 2021), however, data on these changes are not available for most crops considered.

## 2.3 | Evaluating economic risks

As a global loss of pollinators is illustrative but unlikely to occur, we applied our model to three case study groups of countries that are vulnerable to different environmental and economic risk factors. Although a global index of available pollination supply (derived from Chalpin-Kramer et al., 2019) has formed part of a Biodiversity and Ecosystem Services index (SRI, 2020), this is not separately or publicly available. As such we chose groups of 25 countries based on two existing risk classifications and a metric of known pressures on pollinators (full lists of countries see Table S2):

a. HIPC risk: countries classed by the world bank as 'heavily indebted poor countries' (HIPCs—World Bank, 2018). These countries have low capacity to deal with economic shocks and are unlikely to be able to pursue effective sustainable agriculture policies and practices due to economic necessity. This list contains 37 countries, but crop data were not available for 12 of them.
b. Disaster risk: the 25 countries, for whom trade data are available, that are at the greatest total risk of natural disasters (e.g. severe weather, drought) according to the World Risk Index 2019 (IFHV, 2019). This reflects countries that are potentially vulnerable to sudden environmental shocks that could cause severe damage to pollinator populations.
c. Pesticide risk: The 25 countries, for whom data were available, that have the highest average (2005–2014) use of chemical pesticides per hectare of cropland, based on data from the FAOs statistical database (FAOSTAT, 2021). We use the sum of all pesticides as insecticides and some fungicides and herbicides have all been demonstrated to have degrees of lethal and sublethal effects on pollinators, while herbicides can also reduce available forage (Cullen et al., 2019; Iwasaki & Hogendoorn, 2021).

These risks are only three of many possible factors that could be associated with sudden or long-term pollinator losses. We encourage readers to explore other subsets of countries using the model.

## 2.4 | Model pipeline

The main steps in the R pipeline (Figure 1) were as follows: Step 1 involved extraction of production data, and import/export data (values in 1,000s US$, and quantities in tonnes) by crop type, country and year from the UN FAOSTAT database. The main data sources were crop production data (from 'Crops' and 'Crops Processed' data tables), and trade data (from the 'Detailed Trade Matrix' data table; FAOSTAT, 2017b). These data were downloaded from the FAOSTAT database in July 2017, for the years 2005–2014. A list of animal-pollinated crop species was then used to filter the data and import it into R data frames for further processing and analysis. In total, 140 countries were included in the analysis for between 31 and 63 animal-pollinated crops and commodities each. For comparative purposes, we also calculate a dependence ratio only analysis (following Lautenbach et al., 2012) of the impacts of pollinator losses that does not include trade or price changes.

In Step 2, the net trade in animal-pollinated crops (total across the study years 2005–2014) for each country was calculated by subtracting the value of imports (1,000 US$) from the value of exports (1,000 US$) (Equation 4).

Step 3 involved applying scenarios of pollinator loss and simulating the impact this would have on the production of crops and their market prices (see Equations 1 and 2). Production figures for each crop were calculated by applying the dependence ratios from Klein et al. (2007) to calculate the percentage reduction in yields in the absence of pollinators (two scenarios: high and low dependence). The current market prices ($p_t$) for each crop species were derived from trade data (value and quantity) in the FAOSTAT database. If there were insufficient data to calculate separate import and export prices for a single crop, then the same market price was assumed for both imports and exports. Note that the market price represents the value of the goods as recorded for crossing between countries (including transportation costs).

The hypothetical price of each crop, assuming reduced supply under scenarios of pollinator loss was calculated using Equation 2. Two alternative scenarios were applied, representing the higher and lower values from the 95% confidence intervals calculated by Andreyeva et al. (2010). As noted above, lacking information on the market substitutability of pollinated and non-pollinated crops, we

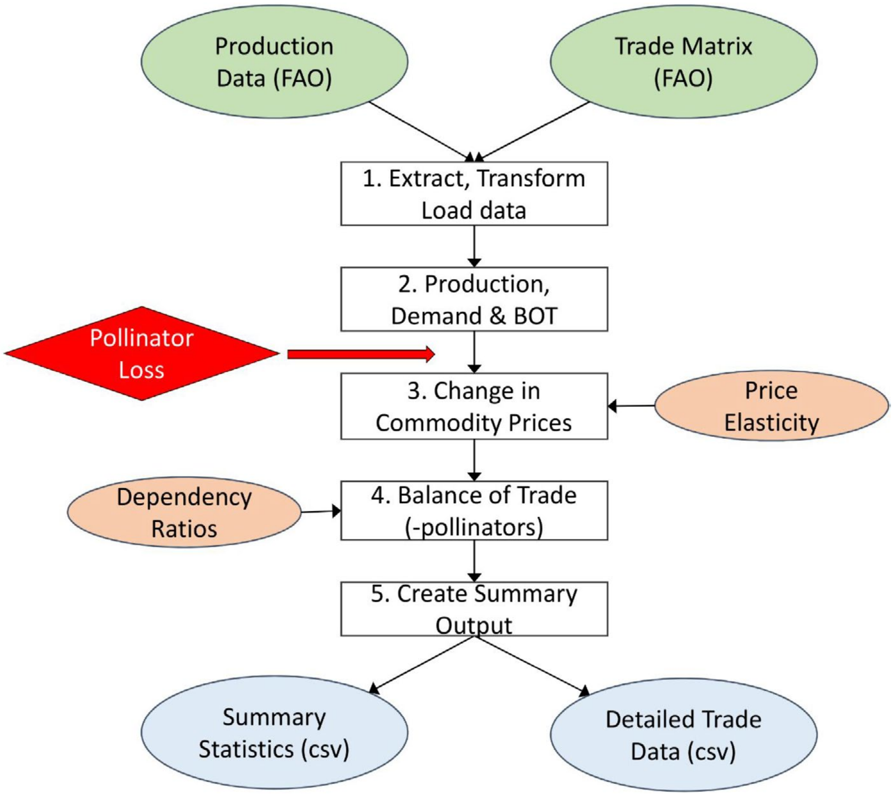


**FIGURE 1** Summary of the main stages in the model for calculating the balance of trade for pollinator dependent crops under scenarios of pollinator loss using production and trade data from the FAOSTAT

inherently assume that the supply curve for animal-pollinated crops retains the same shape and slope even if prices were to rise. In other words, the market still tries to supply as much as it can at the new, higher price, rather than trying to change what is produced. As such, the model only represents the immediate impacts of pollinator loss, not the long-term response of the market.

This resulted in the following four scenarios of global pollinator loss

1. LDLE: low pollinator dependence (DR), low Elasticity of Demand ($E_d$);
2. LDHE: low DR, high $E_d$;—this scenario represents the lowest changes in total crop prices
3. HDLE: high DR, low $E_d$;—this scenario represents the highest changes in total crop prices
4. HDHE: high DR, high $E_d$.

Step 4 involved calculated the net trade ($TB_{t+1}$) for each crop species on a country-by-country basis under the four scenarios to illustrate the total benefits of pollination to international trade and evaluate model sensitivity. The difference between net trade values with and without pollinators represents the hypothetical total cost to a country of maintaining its current level of consumption of animal-pollinated crops in the face of global pollinator decline and therefore the avoided economic losses from the presence of pollination. For comparative purposes, we also calculated the effects of a global loss of pollinators, presented in Supporting Information 2—Global Analysis.

## 3 | RESULTS AND DISCUSSION

The results of our analysis indicate that the benefits of pollination services vary substantially between countries depending on their initial balance of trade in animal-pollinated crops and the impact of price changes on the crops grown in each country. Initial analysis of FAO data indicates that China, Germany, Japan, the United Kingdom, India, Russia, France, The Netherlands, Belgium and Italy are greatest net importers of pollinated crops. Brazil, Indonesia, Argentina, Malaysia, the United States, Canada, Spain, Cote d'Ivore, Ukraine and Chile are the greatest net exporters.

Analysis of the three risk case studies showed substantial variation in the extent to which countries are affected by pollinator losses and the overall global scale of economic impacts (Table 1). The Supplementary materials contain a full breakdown of the results per country in absolute values (Tables S3–S5) and as a % of GDP (Tables S7–S9).

### 3.1 | Heavily indebted poor countries (HIPCs)

Pollinator losses in HIPC resulted in net total losses of $4.8–16.3 billion (Figure 2). In total, 90–100 countries suffer economic losses while the remaining 40–50 countries experience gains, depending on the scenario (Table S4). However, most (86%–96%) of these economic losses are concentrated in high or upper middle countries which are unaffected by pollinator loss. The countries affected by

**TABLE 1** Total impacts of pollinator losses due to global risk factors

| | | Heavily indebted poor countries | | | | Disaster risk | | | | Pesticide risk | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LDLE | LDHE | HDLE | HDHE | LDLE | LDHE | HDLE | HDHE | LDLE | LDHE | HDLE | HDHE |
| Economic impacts[a] | Net global changes | −$12.67 | −$4.83 | −$16.31 | −$6.24 | −$7.12 | −$3.05 | −$12.74 | −$6.52 | −$53.18 | −$40.42 | −$135.25 | −$97.19 |
| | Total losses | −$21.80 | −$7.30 | −$34.60 | −$12.30 | −$15.10 | −$5.23 | −$25.20 | −$10.50 | −$64.50 | −$44.90 | −$168.60 | −$111.20 |
| | Total gains | $9.10 | $2.50 | $18.30 | $6.00 | $7.90 | $2.18 | $12.40 | $3.90 | $11.40 | $4.60 | $33.40 | $14.10 |
| | Affected countries | $2.90 | −$0.68 | $2.82 | −$1.10 | −$0.44 | −$1.23 | −$2.67 | −$3.68 | −$54.55 | −$41.01 | −$143.19 | −$100.67 |
| | Unaffected countries | −$15.56 | −$4.16 | −$19.13 | −$5.14 | −$6.68 | −$1.82 | −$10.07 | −$2.84 | $1.37 | $0.59 | $7.94 | $3.48 |

Key: LDLE: low pollinator dependence (DR), low Elasticity of Demand (Ed); LDHE: low DR, high Ed; HDLE: high DR, low Ed; HDHE: high DR, high Ed.

[a]Negative numbers indicate economic losses as a result of price rises.

pollinator losses collectively only suffer economic losses in the low elasticity scenarios (LDLE and HDLE) and these losses are equivalent to only 14%–18% of the total net global losses. In high elasticity scenarios, affected countries collectively experience net economic gains.

Across all four dependence/elasticity scenarios, Germany, The Netherlands, Japan, China, the United States, Malaysia, France and the United Kingdom are always among the 10 countries suffering the greatest absolute economic losses. In total, these eight countries alone account for between 58% (HDHE) and 71% (LDLE) of total losses. Of the countries affected by pollinator losses Cote d'Ivoire, Ghana and Cameroon only suffer in the high elasticity scenarios. In both cases, these losses only represent 10% (US$0.7 billion, LDHE) and 8% ($1 billion, HDHE) of the total global losses. In the low elasticity scenarios, these countries instead experience significant economic gains notably Cote d'Ivore which experiences gains of $1.43 billion (LDLE) and $1.27 billion (HDLE), equivalent to 2.74% and 2.43% of its average annual GDP respectively. Under these scenarios, the increase in price of cocoa, the main pollinated export in all three countries rises fast enough to compensate for the overall reduction in yields. In reality, however, such a niche market would likely experience a degree of re-orientation so any significant gains from price spikes would ultimately result in long-term economic losses as competition within the market intensifies. When considering the change in balance of trade as a percentage of GDP, many high-income countries (Germany, The Netherlands, Belgium, Switzerland, Norway) suffer, on average, the greatest losses (Table S7). Among the countries affected by pollinator losses, only Togo and Malawi are suffering the greatest % GDP losses.

Although a country's economic status does not in itself affect pollinator populations, nonetheless, many of the countries affected in this scenario have highly agriculture-oriented economies (World Bank, 2020; GDP PPP and Agriculture, forestry, and fishing, value added [% of GDP]) and often have loose regulations on agrochemical use (e.g. Schreinemachers & Tipraqsa, 2012) and/or limited resources to support agri-environment management. There are concerns that increased demand for environmental protection in wealthier countries can result in exporting the environmental impacts of food production to smaller nations, in turn accelerating the loss of habitats and ecosystem services in those countries (Balogh & Jambor, 2020; Schmitz et al., 2012), while their relatively low incomes may curtail efforts to instigate positive management. Our findings demonstrate the need for higher income countries to support pollinator conservations efforts (e.g. through funds, knowledge exchange etc.) in these lower income countries in part for the benefit of their own food systems.

## 3.2 | Disaster risk

The absolute impacts of pollinator losses in the countries most at risk of natural disasters are the lowest of the three risk case studies (net total: $3.05–12.74 billion). In total 94–99 countries suffer

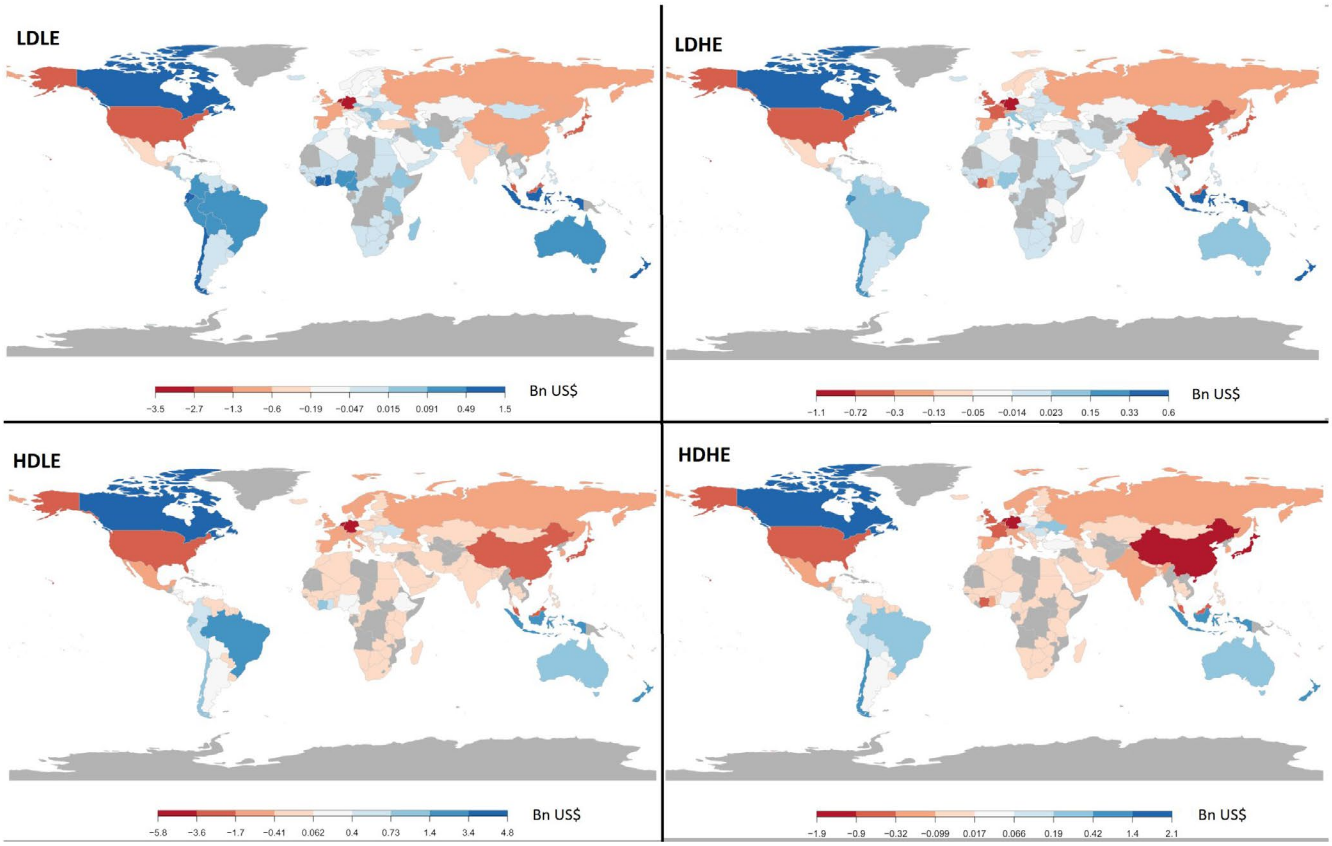


**FIGURE 2** Economic losses in the HIPC case study. Key: LDLE: Low pollinator dependence (DR), low elasticity of demand (ED); LDHE: Low DR, high ED; HDLE: High DR, low ED; HDHE: High DR, high ED. *: Negative numbers indicate economic gains as a result of price rises

economic losses (Figure 3; Table S5). Again, the greatest absolute losses are in high- and upper middle-income countries that are not affected by pollinator losses (60%–90% of total losses), with Germany, The Netherlands, France, Japan, Malaysia, the United Kingdom, Italy and Russia consistently among the 10 countries suffering the greatest economic losses. In total these eight countries alone account for between 40% (HDHE) and 61% (LDLE) of total global economic losses. Between 16 and 21 of the countries affected by pollinator loss suffer economic losses, the majority (79%–93%) of which occur in The Philippines and Indonesia, which are among the 10 countries that suffer the greatest losses in all but the LDLE scenario, where the comparatively high change in price helps offset the fall in production from their main pollinated crops (coconuts and coffee respectively). When considering losses as a percentage of national GDP, many of the smaller nations affected suffer the greatest economic losses, notably Fiji, Togo, Jamaica and the Philippines, although unaffected high-income countries such as Germany, The Netherlands, Singapore and Belgium also suffer among the greatest losses (Table S8).

Of the 41–46 countries that experience economic gains following pollinator losses in affected countries, many experience relatively large gains (totalling $2.2–12.4 billion) that substantially offset the net global losses. Notably Cote d'Ivore, Ghana, Brazil, Colombia, Ecuador, Peru and Bolivia are always among the countries that experience economic gains, accounting for 72%–89% of the total economic gains collectively. Of special note is the Cote d'ivore which experiences very high gains of $3.8 billion (LDLE) and $4.4 billion (HDLE) in the low elasticity scenarios, (48% and 36% of total global gains), equivalent to 7.3% and 8.4% of its total national GDP. This is driven by the high price increase for cocoa following pollinator losses in Indonesia and Cameroon—two of the other major producers of the crop. Finally, the United States suffers among the highest economic losses in the low elasticity, low dependence scenario (LDLE) as the rising costs of crops it imports exceeds the increased value of its exports. However, it experiences among the highest economic gains ($0.05 and $0.5 billion in LDHE and HDHE respectively, in both cases <0.01% GDP) in the high elasticity scenarios where the reverse is true.

Although substantial, these losses are likely to be small compared to the impacts of infrastructure damage caused by disasters in affected countries. To date, although studies have explored the impacts of serious stochastic effects on pollinators (e.g. Potts et al., 2005) and crop markets (Bras et al., 2019), the impacts of such events on pollination service delivery are largely unknown (Nicholson & Egan, 2020). Although a national scale loss of pollinators due to an extreme event is unlikely, localised, short-term shocks are feasible and could have severe effects on prices, akin to the effects of so called 'colony collapse disorder' in the United States in the early 2000s (Lee et al., 2018). The lasting effects of such shocks are of particular concern for lower income communities, who may have

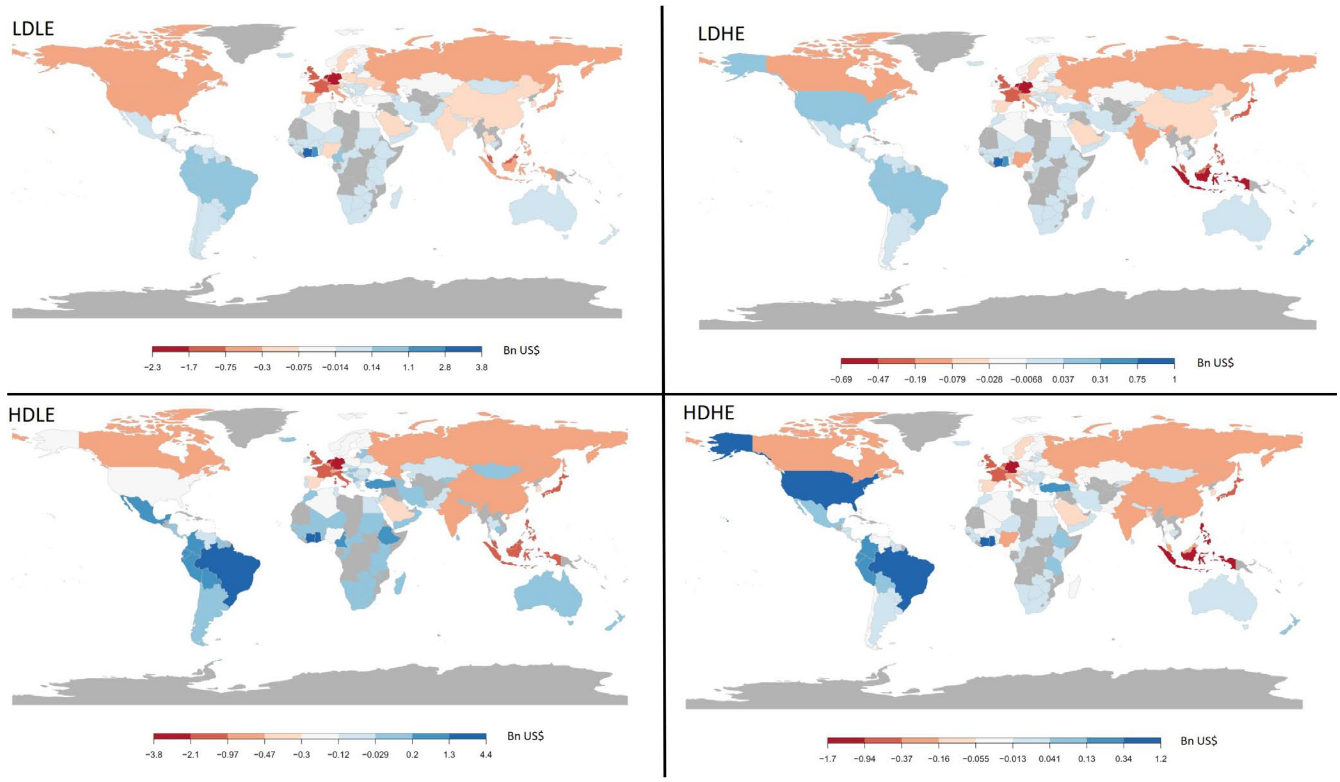


**FIGURE 3** Economic losses in the disaster risk case study. Key: LDLE: Low pollinator dependence (DR), low elasticity of demand (ED); LDHE: Low DR, high ED; HDLE: High DR, low ED; HDHE: High DR, high ED. *: Negative numbers indicate economic gains as a result of price rises

less capacity to recover from such events than wealthier countries (e.g. Sakai et al., 2017). As such events are increasing in frequency, countries that are less likely to be affected should support work to mitigate such risks, including reducing their contribution to climate change, in order to protect their own food supply chains.

## 3.3 | Pesticide risk

Pollinator losses in countries with the greatest pesticide use per hectare resulted in the largest global economic losses of the three case studies (net total: $40.4-135 billion, Figure 4). In total, 91–100 countries suffer economic losses. Unlike other risks, most (85%–91%) of the losses are concentrated in high- and upper middle-income countries affected by pollinator loss, many of which are major net producers of pollinated crops (Table S6). China, Japan, Italy, South Korea, the Netherlands, Malaysia and Belgium accounting for between 96%–97% of the total losses in affected countries and 81%–88% of the total global economic losses. By far the most significant losses are in China which experiences 8.1–10 times greater losses than any other country, representing 62%–69% of total global losses alone. Several large economies, including the United Kingdom, Germany, France and Russia were also among the most negatively impacted under every scenario, despite not being affected by pollinator losses. Affected countries also suffer the greatest losses as a percentage of national GDP, although countries of a wide range of income categories (e.g. Zimbabwe, Switzerland) are also among the most negatively affected (Table S9).

Although economic gains are relatively much smaller than the losses, a number of countries that produce large areas of high-value insect-pollinated crops experience economic gains in every scenario. Unaffected countries that are already among the biggest exporters of pollinated crops: Argentina, Brazil, Ukraine, Spain, the United States, Chile and Cote d'Ivore are among the greatest beneficiaries in every scenario, accounting for 68%–72% of these total gains. Here, the economic impacts (gains and losses) are more affected by pollinator dependence than price elasticity due to the large quantities of highly pollinator dependent fruit crops grown in many affected countries, which must not be replaced with imports (notably China). Of the affected countries, only Costa Rica sees a very small gain in value (<$0.01 billion, <0.01% GDP) and only the low elasticity scenarios (LDLE, LDHE).

Pesticide use is among the most significant threats to pollinators globally (Dicks et al., 2021) and the over-use of pesticides in some areas has resulted in near total pollinator losses (Partap & Ya, 2012). Here, we applied a simple metric of pesticide use per hectare of cropland as data on the use of pesticides in specific crops is not available for most of the countries in the FAO database (López-Ballesteros et al., in press). In reality, pesticide use is likely to vary significantly between crops and cropping systems (e.g. FERA, 2020).

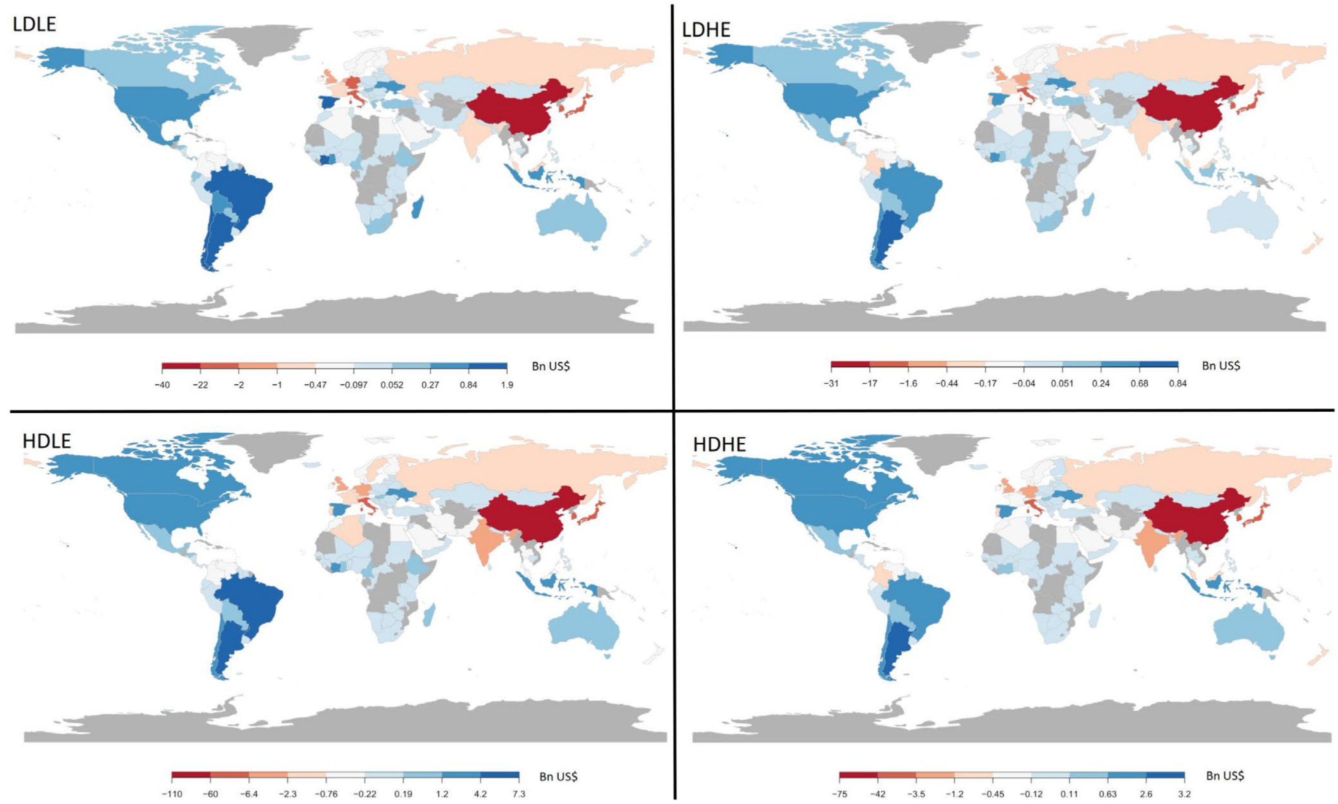


**FIGURE 4** Economic changes in the pesticide risk case study. Key: LDLE: Low pollinator dependence (DR), low elasticity of demand (ED); LDHE: Low DR, high ED; HDLE: High DR, low ED; HDHE: High DR, high ED. *: Negative numbers indicate economic losses as a result of price rises

Furthermore, we lack information on the quantities of different substances used, which, along with their co-formulants, may have different toxicity to pollinators (Heard et al., 2017; Straw et al., 2021), and can have synergistic effects on pollinator health (Siviter et al., 2021). This is especially significant in less developed countries which may have weaker regulation on pesticide use, allowing for over-use or the application of banned substances (Schreinemachers & Tipraqsa, 2012). However, research on pesticide impacts in field conditions remains fairly limited and focused on a small number of bee species and chemicals widely applied in developed countries, limiting our understanding of impacts of pesticide use (Franklin & Raine, 2019). Nonetheless, our findings highlight the need for large, developed countries to review pesticide use on pollinated crops and aim to reduce their impacts (e.g. through the promotion of immigrated pest management) to avoid negative effects on local and international food systems.

## 3.4 | Methodological applications

Previous global assessments of the economic impacts of pollinator losses that do not account for trade, inherently assume that shocks in pollinator supplies only affect those countries. By accounting for the effects on international trade, our method captures the potential extent of impacts across global trade networks and highlights the importance that pollinators in one country can play in the food systems of others. Our work is a first step towards better accounting (in economic and non-economic terms) for the impact of shocks to biodiversity and natural capital on global food systems.

The model was more sensitive to price elasticity than pollinator dependence ratio in two of the three case studies, as the price rise resulting from falling production under the high elasticity scenarios (LDHE, HDHE) compensates for a greater proportion of the losses, even under the high pollinator dependence scenario (HDHE). However, in the pesticide risk case study, pollinator dependence has a much greater impact on the final estimates, with the high dependence scenarios generating estimates 2.5 (HDLE) and 2.4 (HDHE) times their respective low dependence scenarios using the same elasticities (LDLE and LDHE respectively). Here, many of the countries affected are significant global producers of high price, medium dependence crops, where the range of possible pollinator dependence is much broader and consequently, price changes become less impactful than the fall in production.

Our case studies collectively highlight the reliance that food systems in large, developed countries have on the continued supply of crops (Silva et al., 2021) and ecosystem services in smaller, developing countries. Notably, the United Kingdom, Germany and Japan are almost always among the 10 most affected countries in all case studies even though none are affected by pollinator losses. However, most international action on pollinators remains focused on intra-national management, rather than strategically providing support for pollinators that influence their wider food systems. Similarly, the three countries which are the largest exporters of cocoa (Cote d'Ivore, Indonesia, Ghana), often see the greatest net benefits when pollinator declines affect other cocoa producers—highlighting the sensitivity of niche crop markets to shocks in pollination services.

### 3.5 | Challenges and further work

Although illustrative, our modelling work is limited by a number of challenges in data availability, especially at a global scale, each of which alter the estimates we generate. Although we have addressed some of the most immediate challenges, here we highlight three major challenges that will need to be addressed by future work to better understand the economic risks of pollinator losses to global food systems.

Challenge 1—Over-generalisation: Key to our model outputs are the metrics of pollinator dependence and price elasticity. However, in both cases, although we present a range of possible values, we are forced to over-generalise due to limited data available. In the case of pollinator dependence, while Klein et al. (2007) is the most comprehensive global review, it does not take into account any regional variations in variety or growing conditions which may in turn affect the benefits of pollination services (e.g. Bishop et al., 2020; Garratt et al., 2014). Similarly, the dependence ratios are assumed to be at their peak levels, meaning crops are not currently experiencing pollination deficit but in reality, such deficits have been observed in several countries (e.g. Garratt et al., 2014; Reilly et al., 2020). Similarly, for crop price elasticity, while Andreyeva et al. (2010) is a comprehensive review of price elasticities, it only applies to the United States. In reality, different countries will have differences in their price elasticities for a given product based on a number of factors such as national food demands, income and local concentration of production (Catao & Chang, 2015; Cornelson et al., 2015; Field & Pagoulatos, 1998). By applying these elasticities across all countries, our model may over or under-estimate the impacts of pollinator losses on prices, and thus the value of the service, particularly if elasticities are higher or lower in affected countries than the global average.

Challenge 2—Time insensitivity: By not including cross-price or input elasticities, our model is fundamentally time insensitive, meaning that it assumes a total loss of pollinators and pollination in affected countries and assumes that other countries will pay more to maintain consumption levels. In reality, pollinator loss is likely to be a gradual decline until a tipping point is crossed, resulting in a gradual loss of services, greater yield instability (Garibaldi et al., 2011) and subsequent price adjustments, and there is the possibility of gradual population recovery. Estimating these effects will require crop specific data relating pollinator visitation (e.g. Garratt et al., 2018) and interactions with other inputs (e.g. Raderschall et al., 2021; Bishop et al., 2020) to final crop yield, which is absent for most crops. Furthermore, both consumers and producers are highly likely to substitute between different crops as prices change, meaning that any gains in economic value may be offset in later years as consumers switch to different products or produce from different countries (Kargbo, 2000; Tian & Yu, 2017). Again, this challenge is caused by limited information on cross-price elasticity for pollinator dependent produce and particularly for produce within the same crop categories where substitution is more likely to occur (e.g. substituting apples for pears).

Challenge 3—Limited understanding of the whole food system: While our analysis is a valuable step towards illustrating the benefits of pollination on international trade, ultimately it does not include many aspects of broader food systems. For instance, FAO trade data only concern the prices paid directly to growers, usually by wholesalers. It therefore does not account for price transmission to end consumers who, especially in high-income countries, may be insulated from such changes if wholesalers actively factor such changes into their profit margins (Bekkers et al., 2017; Dissanayake, 2016). By considering only raw produce, we also do not account for impacts on processed foods, an increasingly important aspect of global trade between developed and developing countries (Baiardi et al., 2015; Suanin, 2021), beyond the FAOs 'crops processed' category. Similarly, lacking information on how price influences production substitutions for many crops (but see Iqbal & Babcock, 2018; Santeramo et al., 2021), we implicitly assume that land use changes to meet this increased demand by increasing the area of crop planted. At a global scale this would result in radical shifts in overall food production patterns that are likely to affect supplies of other, non-pollinated foods (Aizen et al., 2009) or drive further losses of pollinator habitats. Finally, we only consider the economic impacts of food trade and consumption and do not include any dietary or health impacts of pollination that could theoretically result from this altered access to pollination services (Cornelson et al., 2015; Smith et al., 2015). As such, our model is likely under-estimate the impacts of pollinator losses on the whole food system, which would have to re-orient at several levels, and cannot determine the relative vulnerability of different actors within the system.

Addressing these challenges will require a focused programme of data generation. For pollination service benefits this will require a series of field studies in different biomes using standardised methods (e.g. Fijen & Kleijn, 2017; Garratt et al., 2014) and accounting for differences in growing conditions (Bishop et al., 2020). This allows for more refined estimations of pollination service benefits under different conditions and under different marginal levels of pollination services. Estimating price elasticities of demand for crops on a per country basis is more complex as (a) the specific data required to estimate elasticity for particular crops may be limited, necessitating the use of broad groups of crops with differing sensitivities to pollinator loss (Andreyeva et al., 2010) and (b) beyond demand, price and cross-price elasticities are influenced by a large number of wider factors such as income, produce quality, logistics and trade policies (Cornelson et al., 2015; Field & Pagoulatos, 1998; Kargbo, 2000; Tian & Yu, 2017). A standardised method for estimating such elasticities, for individual crops at a national level, based on publicly available data that accounts for at least some of these factors (e.g. Suanin, 2021), would be a key step to generating such data. Finally, detailed national analyses of different aspects of national food systems, including consumption patterns (e.g. Chalpin-Kramer et al., 2014) and price transmission (Bekkers et al., 2017) would allow for a more comprehensive assessments of the impacts of pollinator losses on national economies and livelihoods.

## 4 | CONCLUSIONS AND RECOMMENDATIONS

The scale of the potential financial costs associated with pollinator loss is considerable. In an era of globalised markets and global supply chains, the effects of pollinator loss in one country can have far-reaching global impacts via a complex network of trade connections. Consequently, the loss of pollination services in subsets of countries can have disproportionately large impacts on the welfare of consumers in other, often wealthier, nations. Declines in pollinators also risk reinforcing global inequalities in trade and prosperity by exposing developing nations with reduced economic capacity to absorb costs and a reliance on pollinated crops for trade with the developed world. Therefore, from a purely economic perspective, maintaining healthy pollinator populations should be a priority for both national and international food policy in order to maintain both domestic and international food systems. Given the apparent importance of crops produced in developing economies with little resources to adapt, the emphasis should be on the developed world to provide the necessary resources and expertise to help meet this global challenge.

Based on the findings of our model and the challenges that need to be overcome to further understanding in this area, we make the following recommendations:

1. **Invest in pollinator conservation worldwide**. Following the IPBES assessment on Pollinators (Potts et al., 2016), a growing number of mostly high-income countries are implementing pollinator strategies. However, these are mostly focused on the countries themselves and not the wider aspects of their food systems. In order to truly maintain national pollinator security, these high-income countries should look to support pollinator security in their lower income trade partners through knowledge development and exchange as well as financial support where appropriate.
2. **Primary data generation on pollination and crop markets is still crucial**: Our work has been able to highlight some of the potential risks from pollinator losses to global food systems. However, we lack much of the fundamental information on how marginal changes in pollination affect food systems and how, in turn food, systems are likely to respond to long-term declines in pollination services. A programme of standardised ecological and economic research would enable a much stronger understanding of the risks around pollinator decline.
3. **Further research into the role of pollinated crops in food systems is essential to understand the full extent of risks and benefits**: The scale and accuracy of our projections are limited by a lack of fundamental data on how crop markets operate at both national and global scales, including how imports are used in processing and household consumption. Better understanding global patters of crop consumption and how this affects consumer welfare and livelihoods will be instrumental in understanding the full extent of pollinator impacts world-wide and supporting holistic action on pollinators through whole food systems.

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## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## AUTHORS' CONTRIBUTIONS

J.T.M. and T.D.B. jointly and equally contributed to the design, analysis and writing of the manuscript; J.C.S. contributed to developing and writing the paper; J.T.M. developed, coded and tested the model; T.D.B. and B.W. added further model refinements and ran the regional vulnerability analysis. All authors contributed to the final MS draft.

## DATA AVAILABILITY STATEMENT

All crop data used in this study are publicly available from the UN Food and Agriculture Organisation https://www.fao.org/faostat/en/#home and information in the cited references (reproduced in the Supporting Information).

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