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Pollinator Deficits, Food Consumption, and Consequences for Human Health: A Modeling Study

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Background: Animal pollination supports agricultural production for many healthy foods, such as fruits, vegetables, nuts, and legumes, that provide key nutrients and protect against noncommunicable disease. Today, most crops receive suboptimal pollination because of limited abundance and diversity of pollinating insects. Animal pollinators are currently suffering owing to a host of direct and indirect anthropogenic pressures: land-use change, intensive farming techniques, harmful pesticides, nutritional stress, and climate change, among others.

Objectives: We aimed to model the impacts on current global human health from insufficient pollination via diet.

Methods: We used a climate zonation approach to estimate current yield gaps for animal-pollinated foods and estimated the proportion of the gap attributable to insufficient pollinators based on existing research. We then simulated closing the "pollinator yield gaps" by eliminating the portion of total yield gaps attributable to insufficient pollination. Next, we used an agriculture–economic model to estimate the impacts of closing the pollinator yield gap on food production, interregional trade, and consumption. Finally, we used a comparative risk assessment to estimate the related changes in dietary risks and mortality by country and globally. In addition, we estimated the lost economic value of crop production for three diverse case-study countries: Honduras, Nepal, and Nigeria.

Results: Globally, we calculated that 3%–5% of fruit, vegetable, and nut production is lost due to inadequate pollination, leading to an estimated 427,000 (95% uncertainty interval: 86,000, 691,000) excess deaths annually from lost healthy food consumption and associated diseases. Modeled impacts were unevenly distributed: Lost food production was concentrated in lower-income countries, whereas impacts on food consumption and mortality attributable to insufficient pollination were greater in middle- and high-income countries with higher rates of noncommunicable disease. Furthermore, in our three case-study countries, we calculated the economic value of crop production to be 12%–31% lower than if pollinators were abundant (due to crop production losses of 3%–19%), mainly due to lost fruit and vegetable production.

Discussion: According to our analysis, insufficient populations of pollinators were responsible for large present-day burdens of disease through lost healthy food consumption. In addition, we calculated that low-income countries lost significant income and crop yields from pollinator deficits. These results underscore the urgent need to promote pollinator-friendly practices for both human health and agricultural livelihoods. https://doi.org/10.1289/EHP10947

Introduction

Despite large increases in global food production over the past half-century, providing adequate nutrition on a global scale has remained elusive for many populations. Approximately 768 million people are undernourished worldwide, and that number has been growing steadily since 2015, following a decade of decline.[1] In addition to those suffering from hunger, 2 billion people globally have been estimated to experience micronutrient deficiencies, although global monitoring data is infrequently collected. The most commonly reported deficiencies are in iron[2,3] as well as widespread inadequate zinc,[4–6] vitamin A,[7,8] and protein for particular population groups.[9,10] Meanwhile, populations in many countries are also facing a pandemic of obesity and metabolic diseases from excess caloric intake, with >2 billion adults worldwide being overweight and obese.[11,12] Inadequate intake of healthy foods, such as fruits, vegetables, and nuts, is also driving large burdens of disease.[13] Considering these persistent challenges, strategies for global food and nutritional security have begun to shift from strictly producing adequate calories to providing more nutritious diets.[14,15]

Coincident with recognition of the need for more nutritious diets has been a growing awareness that we need to reduce the environmental toll of global food production. Agriculture is the single largest driver of biodiversity loss, land-use change, growing scarcity of freshwater, and land degradation globally.[16–19] It is also a significant contributor to climate change, responsible for one-fourth to one-third of global greenhouse gas emissions.[20] As such, growing more nutritious foods with lower environmental impact has become one of the great challenges of the 21st century.[16,18,19]

Pollinators Are Key for Healthy Foods

Ensuring an abundance and diversity of pollinators is one effective approach to address the nutritional and environmental challenges facing global food systems. Animal pollination increases the production of three-fourths of agricultural crop varieties[21] for several reasons. Pollinators are more efficient at delivering pollen

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than wind or self-pollination, which increases successful fertilization and improves seed and fruit set (transition of ovule/ovary to fruit/seed), resulting in greater yields. In addition, animal pollinators improve cross-pollination among different plants, thereby increasing genetic diversity by limiting inbreeding. Plants that rely on animal pollination include cash crops (coffee, cocoa, spices) and many food groups important for global health (fruits,[22] vegetables,[22] nuts,[23,24] legumes[23]) that, when eaten in greater amounts, have been shown in human epidemiological studies to be protective against a range of chronic noncommunicable diseases (NCDs), including heart disease, stroke, many cancers, and diabetes. Moreover, because wild pollinators increase yields without requiring regular external inputs, they can generate significant income for farmers, thereby improving farmers' livelihoods, with potential downstream implications for their health.[25] These benefits are realized without any associated negative environmental impacts. Multiple studies have estimated the contribution of animal pollination to the annual value of global agricultural output at USD $224–577 billion (in 2015 USD).[26,27]

Animal Pollinators are Under Pressure from Environmental Degradation

Yet global pollinators are increasingly in peril, mainly from anthropogenic alteration of their environment, nutrition, and biological networks.[28] Wild pollinators, in particular, are under growing threat. Pervasive land-use changes are fracturing, shrinking, and degrading suitable habitats for pollinators worldwide, not only reducing available areas for nesting but limiting pollinators' ability to migrate as an adaptation strategy in an increasingly disjointed landscape. Furthermore, reductions in wild lands and the dominance of farms growing large monocultures have shrunk the diversity of flowering plants and thereby the duration of flowering, causing nutritional stress. Intensive farming techniques, such as frequent tilling, disturb and destroy nesting sites and disrupt wild plant communities on farms. The ongoing use of pesticides, such as neonicotinoids, have inflicted lethal and sublethal harm to bees both on treated farms and in nearby areas.[28] In addition, the overarching impact of climate change is causing a host of deleterious effects: driving pollinators out of their historical range to find suitable new environmental conditions; causing novel predators, competitors, and pathogens to invade newly habitable environments; and increasing the asynchrony between pollinators and their coevolved plant species who may be motivated by different environmental cues.[29] Although scarce monitoring data currently limits our ability to definitively link individual drivers to pollinator declines, wherever measured, pollinator communities are decreasing in abundance, range, or diversity.[30–32]

Managed honeybees, facing sometimes catastrophic hive collapse caused by pest and nutrition pressures, have not been able to compensate for wild pollinator losses nor keep pace with the growth in pollinator-dependent crops that rely on them,[33] which makes the use of managed bees an increasingly risky solution to compensate for wild pollinator losses. Furthermore, managed pollinators are not fully interchangeable for wild pollinators,[34] and cropping systems with large managed honeybee industries (e.g., blueberries, cherries, apples) could still see additional yield benefit from even greater animal pollination.[35]

This lack of pollinators is already reducing food production. A 2016 study by Garibaldi et al.[36] used a global sample of 344 fields in 33 different pollinator-dependent farming systems across Africa, Asia, Latin America, and Europe to identify the yield penalty currently attributable to insufficient pollination (i.e., the pollinator deficit). To do this, they collected a range of data on farming practices, proximity to natural habitats, and crop yields, as well as pollinator visitation and richness in each location to isolate the role of pollination in supporting yields. They found that, of the yield gap between the low- and high-producing fields across all crop systems, roughly a quarter of the difference could be explained by insufficiently abundant and diverse pollinator populations.

However, this previous work[36] has not yet been extended to quantify the current burden of lost pollination for food intake, nutrition, incomes, and global health. In this study, we aimed to make an advance over earlier work by applying these empirically derived estimates of lost yields from inadequate pollination with the following motivating research questions:

- How much additional food would have been produced if global pollination were adequate (hereafter called the pollinator deficit)?
- Who would have consumed that food, and what health benefits would they have experienced? How many diet-related diseases and deaths could have been averted?
- For lower-income countries especially, what are the economic costs of insufficient pollination?

In this study, we explored the first two questions at a global scale and by country by applying and connecting well-established and vetted analytical tools using the following steps: *a*) comparing existing global agricultural yields with climate-specific theoretically attainable yields for the 63 most important pollinator-dependent crops to identify the total yield gap for each crop and country, *b*) using empirical relationships of the percentage of these yield gaps attributable to insufficient pollination[36] to quantify the pollinator deficit for each crop and country, *c*) employing an international economic trade model to identify who would be most likely to have consumed this additional food, and *d*) using relative risks (RRs) linking dietary risk factors to health outcomes to quantify the implications for global, regional, and country-specific mortality of closing the pollinator yield gap. To evaluate the economic penalty of insufficient pollination, we analyzed, as case studies, three developing countries of different size, geography, and crop specialty—Honduras, Nepal, and Nigeria—to quantify examples of the economic value lost to unrealized agricultural productivity for an individual country.

Methods

The model framework underpinning our analysis comprised several interconnected modules (Figure 1) that are discussed individually below. "Example: Poland" in the "Results" section contains a representative example of how the model works for a subset of crops.

Yield Gap Analysis

Crop yield gaps for 63 pollinator-dependent crops (Excel Table S1) were calculated by subtracting circa 2000 yields[37] from circa 2000 climatically attainable yields, which were estimated using a climate zonation approach (Figure 1, module A).[38–40] The particular method used here was developed by Mueller et al.[40] and is described in the supplemental material therein. Globally, we established 100 zones of equal harvested area and similar climatic properties (i.e., annual precipitation and temperature characteristics derived from WorldClim[41]) for each crop. Within each zone, we determined an attainable yield defined as the area-weighted 90th percentile yield (i.e., the yield value, which is exceeded by only 10% of area within that zone, with maps of yield and area from Monfreda et al.[42]) The resulting map of yield ceilings, which has 10-km resolution, has 100 values for each crop, allocated according to the positions of the zones, which are in turn based on the distributions of the maps of crop yield and area from Monfreda et al.[42] These attainable yields were then summarized using area-weighted averages for each crop and country. The resulting attainable yield layers represent a ceiling of

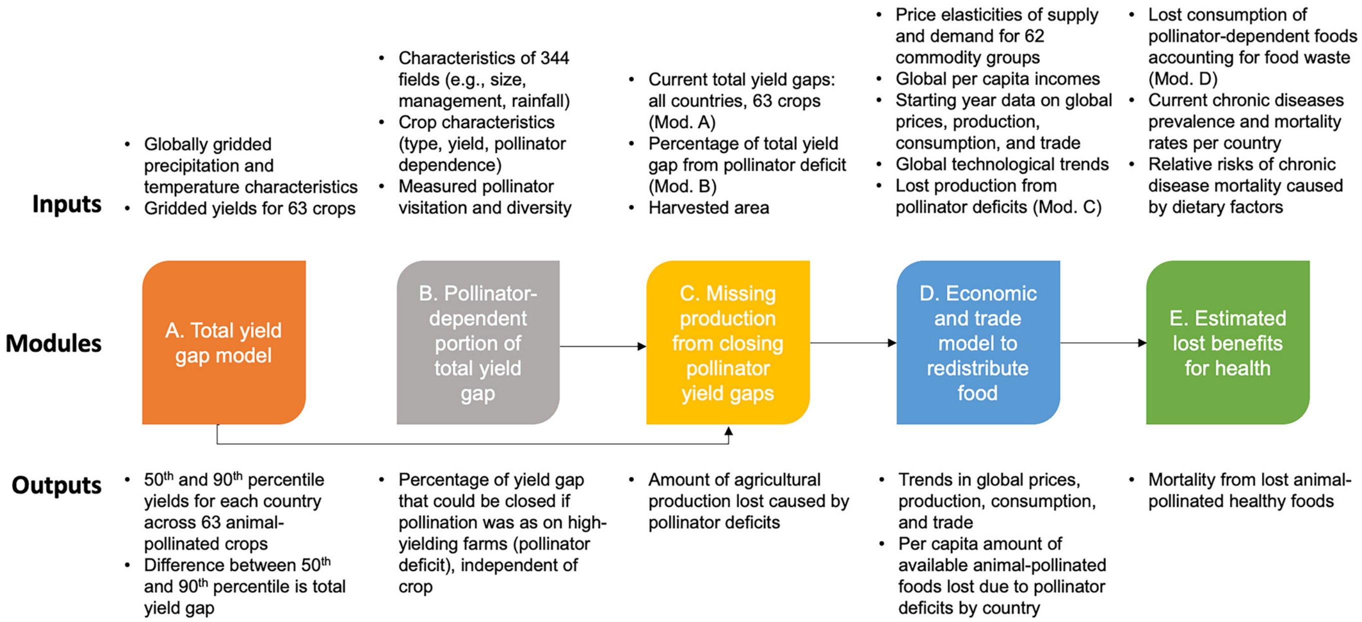

Figure 1. Schematic depicting the chain of modules that constituted our overall model. Arrows show where outputs of one module serve as inputs to another. Module C received inputs from both modules A and B, which connected to module D, then to module E. Note: mod, module.

regionally averaged actual yields, in contrast to agronomic potential yields that may be economically unrealistic. Yield gaps were estimated for all country–crop combinations where those crops were grown. For countries whose yields were currently greater than the 90th percentile attainable yield, the gap was set to zero. Yield gap modeling was performed in MATLAB (version 2018b; MathWorks). These methods are equivalent to the attainable yield modeling carried out by Mueller et al.[40] with the exception that the earlier analysis used a 95th percentile cutoff.

Closing the Pollinator Yield Gap

Next, we used data on the relationship between pollination and total yield gaps[36] to calculate the size of the yield gap for each crop attributable to insufficient pollination (Figure 1, module B). The model and data set used to quantify the proportion of the yield gap (i.e., difference between the 50th and 90th percentile yield of each crop and country) attributable to insufficient pollination were taken from an earlier study by Garibaldi et al. from 2016.[36] In their study, they collected data from 344 fields from 33 pollinator-dependent crop systems from both small and large farms within a 5-y window from 2010 to 2014. Regions were chosen to focus primarily on developing countries, although the inclusion of many large farms with industrialized practices common in developed countries allows for their results to be applied more broadly across income levels. Crops grown included a diversity of pollinator-dependent food groups (fruits, vegetables, nuts, oilseeds, spices), as well as inedible cash crops (coffee, cotton). Crop systems were chosen specifically to span the range of management styles (conventional agriculture, organic agriculture, traditional practices), field sizes, biotic/abiotic variables, and landscape settings. Data collection variables and methods were uniform at all sites to build a model that identified whether the availability of pollinating insects contributed significantly to the crop yield.

The following variables were collected from all sample sites: flower–visitor density, flower–visitor richness, crop yield, index of agricultural intensification (ranging from -3 to 5, with five variables of conventional intensification, each adding 1 to the index—presence of monoculture, synthetic fertilizers, herbicides, pesticides, and fungicides—and three agroecological variables, each subtracting 1 from the index—presence of polyculture, organic certification, and organic fertilizers), latitude, longitude, field size, and isolation from natural or semi-natural habitats. Additional calculated or external variables were also included: percentage pollinator dependence of each crop from Klein et al.,[21] baseline level of flower–visitor density (10th percentile: n per 100 flowers), yield gap within each crop system (10th/90th percentile), flower–visitor gap within each crop system (10th/90th percentile), and interaction terms between these variables. All variables were then included as inputs into a general linear mixed-effects model to predict the crop yield.

Their model found that several of these variables were significantly predictive of crop yields (sign in parentheses indicates direction of relationship): flower–visitor density (+), flower–visitor richness (+), field size (+), intensification index (+), isolation (in kilometers) from natural habitats (–), and flower–visitor gap percentage (+), as well as several interaction terms: flower–visitor density × field size (–), flower–visitor density × flower–density richness × field size (+), flower–visitor density × isolation (–). Many other model variables were not found to be significant: percentage pollinator dependence of each crop, latitude, longitude, baseline flower–visitor density (10th percentile), yield gap percentage, and several interaction terms. The lack of significance of the crop's percentage pollinator dependence was particularly surprising given that certain crops are believed to derive much more of their yield from animal pollination, although neither the percent dependence nor its interaction term with crop–visitor density were found to be significant.

Two additional findings from Garibaldi et al.[36] that are relevant to our present study were that the relationship between flower–visitor density and crop yield was significant for small farms regardless of their flower–visitor richness (number of species per field in the sampling window), whereas density was only significant for larger farms when flower–visitor richness was high (>3 species). This difference is presumed to be caused by the dominance of generalist honeybee species in large fields, given that they are less efficient pollinators than a diverse community of wild insects despite having high foraging ranges.[34]

Based on these findings, some additional steps were required before applying this previous work to our present study. First, we began with an assumption that our counterfactual high-pollinator scenario would need to include both a high density and richness of pollinating insects. This is because simply having more pollinators was only beneficial for yields on small fields (<2 ha), whereas having both higher density and diversity of pollinators also increased yields in large fields.[36] Therefore, we needed to use a subset of the original data to include only crop systems with species richness ≥ 3 from all field sizes. This subset is found in Excel Table S2. Notably, this subset preserves the diversity of management intensity, pollinator dependence, field size, and crop diversity as in the full original data set, lending confidence to our ability to apply these findings to developed countries where conventional intensely managed agriculture in large fields is more common.

We then fit a Gaussian distribution to the pollinator-attributable yield gap percentages from Excel Table S2 and identified the mean along with its 95% confidence interval (CI) (25.5%; 95% CI: 5.5%, 45.4%) for use in our model. Of note are two data points from Excel Table S2 that were anomalously high or low: −37% for agraz (native blueberry) in Colombia and 121% for sunflower in South Africa. All Excel Table S2 values were generated using the best mixed-effects model from Garibaldi et al.,[36] although these particular data points had very high or low values for some inputs, causing their irregularity: Colombian agraz was not at all isolated from natural areas (0 km) and South African sunflower had very high species richness given its large field size—eight species per 30-min sampling window. We preserved these extreme values to maintain congruency with the previous study although removing them would have only slightly altered our yield gap percentage for later steps (22.9%; 95% CI: 10.5%, 35.3%).

Percentage changes in production caused by closing the pollinator deficits were then multiplied by current production values to estimate the additional food that would be produced under scenarios of enhanced pollinator density and richness (Figure 1, module C). The percentage increase in production was capped at 100% to preclude unrealistically high modeled yield gains from greater pollination; country–crop combinations with yield increases >100% constituted a small percentage of all data points (~1%). Modeling of percentage production changes under high pollination scenarios was performed in MATLAB (version 2018a; MathWorks).

One caveat to our model is that we did not account for potential losses to agricultural productivity that might be necessary to achieve the adequate pollinator levels in our high-pollinator scenario. Many practices can boost on-farm pollinator populations without harming productivity, such as the installation of bordering hedgerows or the use of adjacent marginal lands for habitat. Nevertheless, where nearby pollinator habitat is not available, setting aside farmland to serve as undisturbed habitat may be necessary. Doing so would reduce the productive land for crops and could lessen our projected yield gains.

Trade and Economic Model

Changes in a country's crop production do not directly translate to equivalent changes in domestic consumption. That is because the place where a food will be eaten, regardless of where it is grown, is dictated by its price (itself governed by supply and demand for that food) and consumers' ability and willingness to pay for it. Furthermore, farmers change their own behavior—how much area to devote to which crop, the amount of effort to expend—based on crop prices in a given season, which feeds back to influence a crop's supply, price, and demand.

To capture the complexity of these market forces that intercede between production and consumption, we relied on the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), version 3 (Figure 1, module D).[43] Fuller descriptions of the IMPACT model and its core elements are available,[43–45] but a summary is given here, and a schematic of IMPACT, its components, and how they intersect, in Figure S1. IMPACT is a global, partial equilibrium multimarket model of the food system that links pixel-scale modeling of climate, hydrology, and crops to national level supply and demand and further to global-scale international markets through trade. IMPACT simulates national and global agricultural market behavior annually.[43] Starting with FAOSTAT data[37] that have been balanced globally using a Bayesian maximum entropy algorithm to reconcile imbalanced FAO-reported production and consumption data, IMPACT computes annual solutions that balance global agricultural supply and demand with prices that clear international trade markets such that global net trade equals zero. Food, feed, and industrial demand are determined through a combination of endogenous and exogenous drivers (prices and population/income growth, respectively) with market behavior determined by income and price elasticities derived from the literature and expert judgment. Therefore, any increases in crop production are distributed among consumers (either domestically or in other countries via trade) using a combination of model-generated food price changes, as well as per capita incomes and price elasticities, which govern a consumer's willingness to purchase a certain quantity of each food. The supply side is, likewise, simultaneously determined through a combination of endogenous and exogenous parameters. Producers react to price changes to make within-year adjustments to production systems that are defined by assumptions on technological potential and trends determined through analysis of historical data and expert judgment about likely structural change within the agricultural sector.[46,47]

Productivity impacts of levels of theoretically replete pollinator populations were translated into yield increases according to the food-group mapping found in Excel Table S1. In IMPACT, two types of scenarios were run: *a*) baseline scenarios, where production, trade, and consumption patterns proceeded as usual; and *b*) an alternative set, where production was increased assuming higher levels of pollination (i.e., a reduction in the pollinator deficit). Three levels of high-pollinator scenarios were run: a median case where production was increased assuming a median closure of the pollinator yield gap, as well as low and high 95% confidence-bound scenarios. Levels of yield increases for pollinated crops at aggregate world regions are detailed in Table S1.

In our higher-pollination scenarios, pollinated-yield boosts were introduced in the year 2010 and allowed to come into equilibrium until the comparison year 2020. The economic equilibrium modeling process includes simultaneous farmer and consumer responses to the changes in production and the ensuing international commodity prices, encompassing changes in farming intensity, crop choice, and farmed area to account for farmers' varying profit incentives; changing consumer diets after accounting for food prices and their elasticities of demand; and shifting trade markets to rebalance the flow of food from more or less productive regions. IMPACT is anchored to empirically derived data in year 2005 (an average of 2004–2006) and calibrated to available data up to 2012 using smoothed 3-y averages, after which it is then based on assumptions that change in 5-y increments. This multiyear smoothing limits the model's ability to account for volatile annual changes to crop production or price (e.g., the 2007–2008 global food price spike and crisis) but, instead, is designed to capture the behavior of the agricultural and food system in response to long-run trends, such as population and income growth, or the influence of sustained global temperature increases.

After 2012, simulations were run to 2020 using five global climate models [National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamic Laboratory model (GFDL), Hadley

Centre's Global Environment Model (HGEM), Institut Pierre Simon Laplace's Earth System Model (IPSL), Model for Interdisciplinary Research on Climate (MIRO), Norwegian Earth System Model (NORE)] under a moderate radiative forcing model [Representative Concentration Pathway (RCP) 4.5][48] and a moderate shared socioeconomic pathway scenario (SSP2).[49] The various SSPs do not diverge significantly until after 2020, and SSP2 was used solely to bridge 2010 to 2020 by accounting for changes in population and gross domestic product (GDP), as well as elasticities calibrated to a business-as-usual future. This allowed for the model to resolve changes in global food production, consumption, and trade that flow from these demographic and economic drivers. The average and standard deviation from among the five global climate models were used for each of the four scenarios—namely, the baseline and three high-pollinator scenarios—in subsequent health modeling.

Nut consumption, unlike other food categories, required additional steps before being used as an input to health models. Groundnuts were explicitly reported in IMPACT, whereas tree nuts were included in a broader IMPACT category of "other crops" that included other pollinator-benefitting crops (cloves and "spices, other"), and nonpollinated or inedible crops (e.g., jute, tobacco, rubber). To estimate the food availability of tree nuts, we used per capita estimates from the FAO food balance sheet estimates[37] as our baseline values. We then calculated the difference between current and high-pollinator production and consumption values for the "other crops" category in each country from IMPACT. Separately, using FAO data, we estimated the percentage that tree nuts constituted in the production and consumption of pollination-benefitting "other crops" in each country. For example, if Country X consumes 9 g/d of tree nuts, 1 g/d of cloves, and 5 g/d of "spices, other," we would estimate that tree nuts account for 60% of the consumption of pollination-benefitting "other crops"; a similar calculation was also made for production in each country. We then multiplied these percentages by the total absolute change in production and consumption of "other crops" under high-pollinator scenarios from IMPACT to approximate the pollinator-attributable change in tree nut production and consumption. Tree nut production and consumption values were added to groundnut values and used as inputs in estimating the health implications.

Health Outcomes

We used a global risk–disease model focused on dietary and weight-related risk factors to quantify what impacts the changes in pollination could have on mortality in each country (Figure 1, module E). The model is based on a comparative risk assessment framework with eight risk factors and five disease endpoints.[50] In comparative risk assessments, one compares different levels of risk exposure—for example, a situation where lead levels in municipal water are high compared with a counterfactual case where lead in the water is zero—and calculates the consequences of that relative level of risk in terms of health outcomes, using an empirically established relationship between risk and outcome. Risks can be binary (e.g., lead exposure exceeding a certain threshold) or continuous (e.g., functions equating higher lead levels to increasingly severe cognitive or developmental consequences). Based on several variables—an exposure variable (e.g., lead concentrations), the RR of a health outcome given a certain risk exposure (e.g., empirical relationship between lead levels and developmental impairment), and the current occurrence of health outcomes under consideration (e.g., prevalence of developmental impairment in the community)—one can then compute what amount of existing health burden is attributable to the current risk exposure.

In our study, the risk factors included high consumption of red meat and low consumption of fruits, vegetables, nuts, and legumes, as well as being underweight [body mass index $(\mathrm{BMI}) < 18.5$], overweight ($25 < \mathrm{BMI} < 30$), and obese ($\mathrm{BMI} > 30$). The disease endpoints included coronary heart disease, stroke, type-2 diabetes mellitus, cancer (in aggregate and as site-specific ones, such as colon and rectum cancers), and an aggregate endpoint of all-cause mortality associated with changes in weight.[50] Further information on RRs associated with each of these endpoints is described below. A table showing the groupings of individual foods into health-related food groups is found in Excel Table S1 ("other crops," "palm crop," and "other grains," also included in Excel Table S1, were not included in the health modeling).

For specifying the exposure levels of the dietary and weight-related risk factors, we used and adjusted the food availability estimates from IMPACT. For the dietary risk assessment, we used regional data on food wastage at the consumption level (Excel Table S3), combined with conversion factors into edible matter[51] to convert food availability estimates into proxies for food consumption. For reference, consumption values of major food groups after removing waste are listed in Excel Table S4. For the weight-related risk assessment, we used current weight levels and the historical relationship between food availability and BMI to estimate changes in weight levels in the different scenarios. The mortality and disease burden attributable to dietary and weight-related risk factors were then estimated by calculating population impact fractions (PIFs) and applying those to age and country-specific mortality rates.[52–54] PIFs represent the proportions of disease cases that would be avoided when the risk exposure was changed from a baseline situation (the current diet) to a counterfactual situation (the pollination scenarios). For specifying the exposure levels of the dietary and weight-related risk factors, we used and adjusted the food availability estimates from IMPACT.

RR estimates that relate the risk factors to the disease endpoints were adopted from meta-analyses of prospective cohort studies for dietary risks[22–24,55–59] and pooled cohort studies for weight-related risks.[52,60] RRs used in our calculations are provided in Excel Table S5. In line with the meta-analyses, we included nonlinear dose–response relationships for fruits and vegetables[22] and nuts[24] and assumed linear dose–response relationships for the remaining risk factors.[23,57,58] Because our analysis was primarily focused on mortality from chronic diseases, we focused on adults ≥ 20 years of age, and we adjusted the RR estimates for attenuation with age based on a pooled analysis of cohort studies focused on metabolic risk factors[53] in line with other assessments.[54,61] In addition to changes in total mortality, we also calculated years of life lost. Health modeling was performed in GAMS (version 38; GAMS).

Sources and Treatment of Uncertainty in the Global Model

Three main sources of uncertainty were propagated through the model to capture the full range of possible outcomes. The first and largest quantifiable source was introduced by the relationship between insufficient pollination and crop yields. For this, we used the empirically derived distribution of possible pollinator yield gaps (Excel Table S2) and, described above, as inputs into a Monte Carlo simulation ($N = 1{,}000$) to quantify the possible percentage loss of each pollinated food caused by insufficient pollination. A randomly chosen pollinator-attributable yield gap percentage was chosen for each iteration, the total yield gap for that food and country was closed by that amount, and a percentage change in food production was calculated. We then identified the median, 2.5th percentile, and 97.5th percentile values from among the 1,000 Monte Carlo runs for each food and country.

Additional uncertainty was also introduced from the global trade and health modeling. As mentioned previously, IMPACT used multiple climate and socioeconomic models to bridge the

Table 1. Modeled lost production and consumption (95% UIs) of healthy food groups due to insufficient pollination.

	Lost food due to insufficient pollination (percentage change relative to high-pollinator scenarios)					
	Production			Consumption		
Country groups	Fruit	Vegetables	Nuts	Fruit	Vegetables	Nuts
Income group						
Low	−4.7 (−8.2, −0.5)	−26.0 (−32.5, −16.5)	−8.4 (−14.0, −1.9)	−1.5 (−2.3, −0.9)	−3.1 (−4.0, −2.1)	−6.5 (−8.9, −3.5)
Lower middle	−10.3 (−12.5, −5.3)	−13.0 (−18.2, −5.4)	−1.8 (−3.8, 0.6)	−4.0 (−5.4, −2.0)	−3.3 (−4.9, −1.3)	−5.4 (−7.0, −3.2)
Upper middle	−4.5 (−6.8, −2.0)	1.6 (−3.4, 4.9)	−5.3 (−8.8, 2.1)	−4.9 (−6.7, −2.1)	−3.0 (−4.7, −0.9)	−3.7 (−5.3, −1.5)
High	5.3 (1.9, 8.6)	1.2 (−2.1, 4.9)	7.1 (−4.6, 16.4)	−4.8 (−6.3, −2.9)	−3.1 (−4.2, −1.8)	−11.9 (−15.7, −6.7)
Region						
East Asia and Pacific	−4.2 (−7.4, −1.3)	4.6 (−0.9, 7.7)	−5.4 (−8.7, 1.4)	−5.7 (−8.0, −2.1)	−3.0 (−4.8, −0.6)	−3.6 (−5.2, −1.3)
Europe and Central Asia	−5.3 (−8.7, −0.5)	−11.1 (−16.7, −4.7)	−0.8 (−18.2, 15.4)	−4.8 (−6.1, −3.3)	−3.0 (−3.9, −2.1)	−11.2 (−14.2, −7.8)
Latin America	−2.3 (−4.3, −0.2)	−5.3 (−10.7, 0.0)	0.0 (−9.6, 11.0)	−2.4 (−3.7, −1.1)	−3.1 (−4.7, −1.4)	−10.6 (−15.6, −4.6)
Middle East/N. Africa	−6.7 (−9.6, −2.9)	−8.9 (−15.4, −1.7)	−5.6 (−20.7, 17.1)	−5.2 (−7.4, −2.7)	−2.1 (−3.0, −1.3)	−4.4 (−5.9, −2.6)
North America	11.8 (1.7, 19.2)	7.5 (1.1, 12.5)	12.4 (0.6, 19.2)	−5.7 (−8.6, −1.1)	−4.4 (−7.0, −0.7)	−11.3 (−16.9, −2.4)
South Asia	−13.4 (−16.1, −3.8)	−1.9 (−8.2, 5.0)	0.1 (−2.5, 3.1)	−4.5 (−6.5, −1.1)	−3.9 (−6.1, −0.7)	−3.9 (−5.7, −0.6)
Sub-Saharan Africa	−1.7 (−3.9, 0.4)	−36.1 (−41.6, −19.8)	−6.9 (−10.4, −3.0)	−1.3 (−1.9, −0.6)	−3.4 (−4.5, −2.1)	−7.0 (−9.2, −4.6)
World	−4.7 (−7.1, −0.8)	−3.2 (−5.3, −0.4)	−4.7 (−6.9, −0.5)	−4.6 (−7.0, −0.8)	−3.2 (−5.3, −0.4)	−6.1 (−9.5, −0.8)

Note: Positive values in production indicate where production is currently higher than it would be if pollination were sufficient given that they would likely import these foods rather than grow them domestically. Definitions for each food category are found in Excel Table S1. Supporting data on the population and current production tonnage by food group for each income group and region are found in Table S2. Income and region classifications are from the World Bank.[62]

gap between the base year in IMPACT (2010) and our analysis year (2020). Because of the complexity and time required to run IMPACT, it was not feasible to use all Monte Carlo model output from module C (Figure 1) to generate 1,000 IMPACT model (module D) outputs. Instead, we used three high-pollinator scenario outputs from among the 1,000 outputs from module C: median, 2.5th percentile ("low pollinator") and 97.5th percentile ("high pollinator"). Therefore, IMPACT was run four times (benchmark plus three high-pollinator scenarios) and the average and standard deviation of the output (driven by the various general circulation models) was calculated.

Finally, the outputs of these four scenarios (plus standard deviations) were passed on to be used as inputs in health modeling, module E. Here, additional uncertainty was introduced from the RR parameters of each food–outcome pair. Using averages and 95% CIs from previously reported RRs, we ran three comparisons between each high-pollinator scenario and the benchmark to estimate the change in mortality that would be caused by changes in diet. We used 95% RR CIs associated with RR estimates using error propagation methods. Final median values in Tables 1 and 2 reflect the average of the "average" scenario, whereas the 95% uncertainty interval (UI) reflects the upper bound of the high-pollinator scenario and the lower bound of the low-pollinator scenario.

It is worth mentioning that not all model components had associated uncertainties, and our final estimates do not reflect a true encapsulation of all potential outcomes. Specifically, most IMPACT model (module D) inputs—such as price elasticities, intrinsic productivity growth rates, and farmer planting/effort choices—did not have quantifiable uncertainties attached. Likewise, our global yield gap measurements (module A) were not capable of reporting uncertainties. Therefore, our reported uncertainties are likely too narrow.

Economic Analysis for Case-Study Countries

To quantify the economic penalty of insufficient pollination, we chose three case-study countries—Honduras, Nepal, and Nigeria—to identify the implications for the lost economic value of

Table 2. Excess mortality (95% UIs) attributable to insufficient pollination by risk factor.

	Current excess annual deaths attributable to insufficient pollination, total and by dietary risk factor (thousands)					Current deaths from insufficient pollination as percentage of total mortality
Country groups	Fruit	Vegetables	Nuts	Other risk factors	Total	
Income group						
Low	2 (0, 4)	2 (0, 3)	2 (0, 3)	2 (0, 4)	9 (2, 15)	0.3 (0.1, 0.5)
Lower middle	44 (9, 71)	43 (8, 72)	18 (4, 26)	6 (1, 9)	110 (22, 179)	0.6 (0.1, 1.0)
Upper middle	111 (21, 180)	78 (16, 129)	32 (7, 50)	−12 (−20, −2)	208 (41, 338)	1.0 (0.2, 1.6)
High	31 (6, 50)	28 (6, 46)	47 (10, 72)	−5 (−8, −1)	101 (21, 159)	1.0 (0.2, 1.5)
Region						
East Asia and Pacific	98 (19, 160)	59 (12, 97)	21 (4, 32)	−6 (−9, −1)	171 (34, 278)	1.0 (0.2, 1.7)
Europe and Central Asia	37 (7, 58)	35 (7, 59)	42 (9, 65)	−7 (−12, −1)	107 (22, 169)	1.2 (0.2, 1.9)
Latin America and Caribbean	8 (1, 13)	5 (1, 9)	4 (1, 6)	−2 (−4, −0)	14 (3, 25)	0.4 (0.1, 0.7)
Middle East and North Africa	10 (2, 16)	5 (1, 9)	4 (1, 5)	−2 (−4, −0)	16 (3, 27)	0.8 (0.2, 1.3)
North America	9 (2, 15)	12 (2, 19)	16 (3, 26)	−1 (−2, −0)	36 (7, 57)	1.1 (0.2, 1.8)
South Asia	23 (5, 37)	30 (6, 52)	8 (2, 10)	6 (1, 10)	67 (13, 109)	0.6 (0.1, 1.0)
Sub-Saharan Africa	4 (1, 6)	4 (1, 6)	4 (1, 7)	4 (1, 6)	16 (3, 26)	0.3 (0.1, 0.5)
World	189 (37, 305)	151 (31, 251)	99 (21, 151)	−9 (−14, −2)	427 (86, 691)	0.8 (0.2, 1.3)

Note: "Other risk factors" include changes in red meat and legume consumption, as well as changes in overweight, underweight, and obese populations. Negative values indicate current risk-attributable deaths that may increase under higher-pollination scenarios, such as those caused by a greater prevalence of overweight and obese populations and increases in red meat consumption.

agricultural production due to inadequate pollination in an individual country. Case-study countries were chosen based on the following criteria: low or lower-middle income; diverse population size, economy, agricultural system, and geography; being economically reliant on pollination-dependent crops (including cash crops); and a stated interest or strategy to protect pollinators. An exception to these criteria was that Honduras did not have an established plan nor official interest to protect pollinators. However, very few Latin American countries have officially prioritized protecting pollinators, and Honduras's reliance on coffee production for their national economy, coupled with increasingly narrow profit margins driven by escalating climate change, suggested that identifying opportunities to increase yields that did not further degrade the environment may be salient. Finally, they were chosen to be illustrative of more typical response behavior for different categories of lower-income regions globally, instead of outliers to represent the upper bound of potential losses.

For these countries, we performed the counterfactual high-pollinator scenario only in each country of interest individually, and all other countries were parameterized as in the baseline scenario. As in the production and consumption modules, global markets were allowed to come into equilibrium between the production boost in 2010 and the comparison year 2020. To give an overall indication of the economic impact associated with the high-pollinator scenario, the economic value of production was calculated as the product of the estimated international price of each commodity multiplied by its total production. This metric gives a conservative indication of the benefits of increased pollinator populations with a focus on the supply side while consumer-side benefits, although likely positive but more complicated to estimate in this limited modeling exercise, are left aside.

Results

Globally, we estimated that the world is currently losing 4.7% (0.8%, 7.1%) of total production of fruit, 3.2% (0.4%, 5.3%) of vegetables, and 4.7% (0.5%, 6.9%) of nuts due to insufficient pollination (Table 1). All parenthetical ranges in Results indicate 95% UIs. Had these foods been produced, distributed through the global food trade system, and consumed (assuming current percentage rates of food loss and waste), we estimated that 427,000 (86,000, 691,000) excess global annual deaths, mostly from chronic NCDs, would have been averted (Table 2).

Our model showed that lost food production was greatest in lower-income countries, primarily because these countries had the largest yield gaps based on our estimates and would experience greater absolute yield increases from adequate pollination than countries with smaller overall yield gaps (Table 1). Importantly, this result was underpinned by the earlier finding that the contribution of insufficient pollinators to a farm's overall yield gap was independent of its geography, degree of agricultural intensification, and several other agronomic and landscape characteristics.[36] In some areas, pollinator deficits in our models were found to be substantial; an estimated 26% (17%, 33%) of vegetable production and 8% (2%, 14%) of nut production in low-income countries was estimated lost due to inadequate pollination, as well as 10% (5%, 13%) of fruit production and 13% (5%, 18%) of vegetable production in lower–middle-income countries.

These modeled production losses, when mediated by the global trade system, led to decreases in fruit and vegetable consumption that ranged from 2% to 5% compared with high-pollinator scenarios, and from 4% to 12% less nut consumption. On average, our model estimated that trade would have transferred production from lower-income countries to higher-income countries. This was especially evident when looking across regions (Table 1), where, for example, we saw that North America consistently experienced the greatest reductions in consumption (in percentage terms) across all food categories. Meanwhile, sub-Saharan Africa saw much more modest impacts on estimated consumption of fruits and vegetables.

Calculated Mortality Burden Resulting from Lost Pollination

Our model-generated results of reduced production and consumption of pollinator-dependent crops drove large mortality burdens (Table 2). Pollinator deficits were estimated to be responsible for 1% of total annual mortality in both upper–middle- and high-income countries. Globally, decreased fruit and vegetable intakes accounted for the highest amount of increased mortality, 189,000 (37,000, 305,000) and 151,000 (31,000, 251,000) deaths respectively, primarily due to stroke, coronary heart disease, and cancer (Figure 2). Low nut intake also contributed an estimated 99,000 deaths annually (21,000–151,000) Other minor beneficial factors under high-pollinator scenarios (higher legume consumption, fewer underweight) as well as detrimental factors (higher obese and overweight, higher red meat consumption), reduced our final mortality estimates relative to a high-pollinator scenario by 9,000 (2,000, 14,000) annual deaths, or $\sim 2\%$. For total avoidable deaths, the largest number was found in upper–middle-income countries and the lowest number in low-income countries. This was due in part to the very large populations in upper–middle-income countries (3 billion people; including China, Indonesia, and Brazil) compared with low-income countries (675 million people), coupled with the higher baseline rates of chronic diseases in upper–middle-income countries that could have been ameliorated by eating more healthy foods.

Our modeled health effects of inadequate pollination were not evenly distributed. Figure 3 and Table 2 show the regional distribution of the health burden from the pollinator deficit. Areas with particularly high health burdens included China, India, Central Asia, Eastern Europe, and Russia and parts of Southeast Asia and North Africa. These regions shared high baseline prevalence rates of underlying dietary-affected NCDs, as well a greater loss of the protective effect from consumption of pollinator-dependent foods. Much of Southern and Eastern Africa, Latin America, Western Europe, and Australia would have seen relatively little difference in mortality under higher-pollination scenarios compared with the present day.

Calculated Economic Losses Resulting from Lost Pollination

When comparing current and modeled yields assuming replete pollination, the annual lost economic value across all agricultural commodities—represented here as a commodity's annual production quantity multiplied by its international price—for our three case-study countries amounted to −12% (−3%, −19%) in Honduras, −17% (−5%, −22%) in Nigeria, and −31% (−13%, −32%) in Nepal (Table S3). These economic losses were attributable to crop production losses of −3% (−1%, −5%) in Honduras, −15% (−5%, −18%) in Nigeria, and −19% (−7%, −20%) in Nepal. The greater percentage economic loss compared with production loss (by weight) suggests that pollinated crops constituted high-value commodities for these countries.

Dividing modeled economic losses (Table S3) by the 2020 population related to the agricultural sector[62,63] amounted to an annual lost value per person in Honduras of USD $209 ($42, $363), USD $250 ($83, $264) for Nepal, and USD $325 ($81, $442) for Nigeria (all in 2005 USD). Although lost agricultural

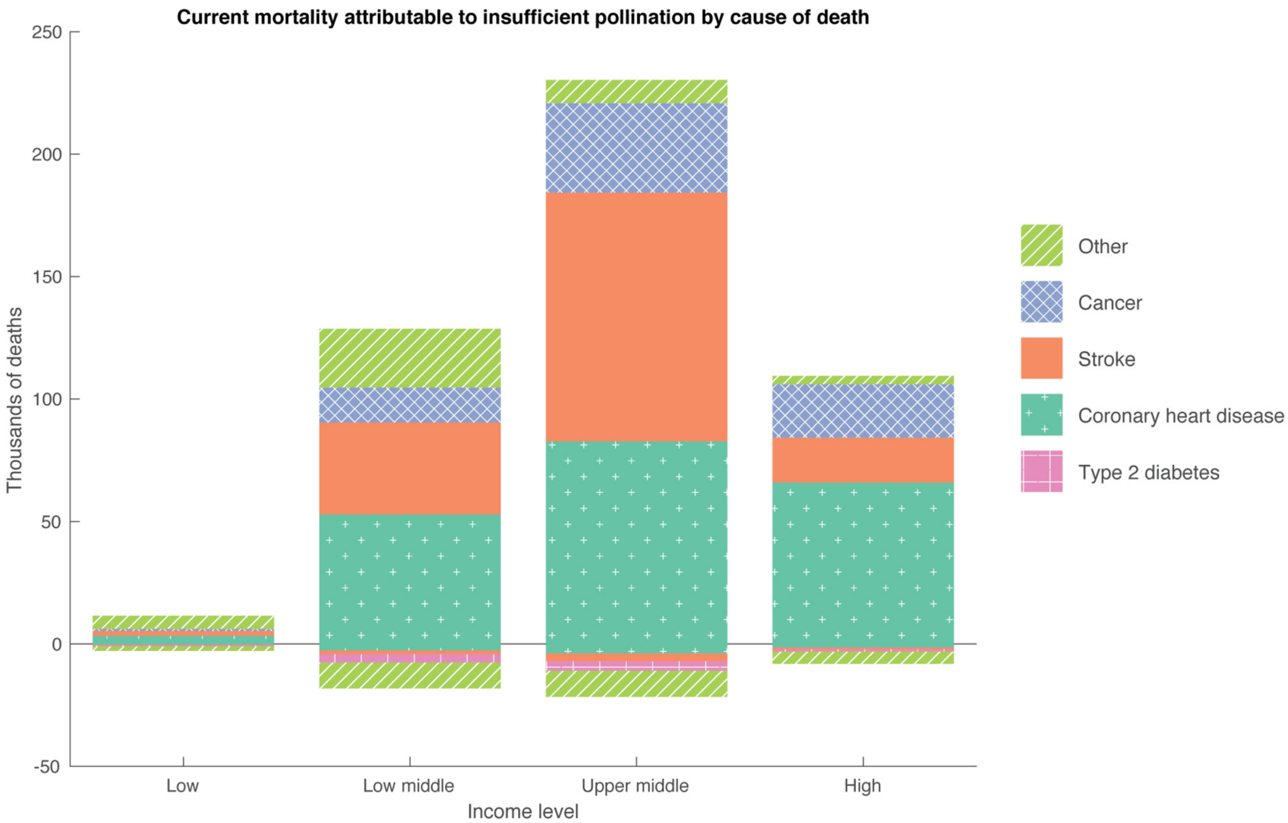

Figure 2. Current annual mortality estimated to be attributable to inadequate pollination and its dietary effects, by cause of death and country income. Inadequate pollination is defined as a combination of too-little flower visitation and scant pollinator diversity to achieve optimal yields. More information of "other risk factors" and causes of negative values may be found in the caption for Table 2. Source data may be found in Excel Table S6.

value is only a rough proxy for lost income, for reference the total 2019 Nepalese agricultural GDP divided by the population employed in agriculture was USD $326 (all in constant 2010 USD). Honduras's 2019 agricultural per capita GDP is USD $799 and Nigeria's is USD $1,486, also suggesting a considerable potential loss to incomes. Because such a large share of the population is employed in agriculture in these countries—30% in Honduras, 35% in Nigeria, and 64% in Nepal[62]—this effect could be substantial for these countries and for other agriculture-dependent nations globally.

In all countries, the lost value of production was dominated by fruits and vegetables: 84% (84%, 85%) of total lost production value

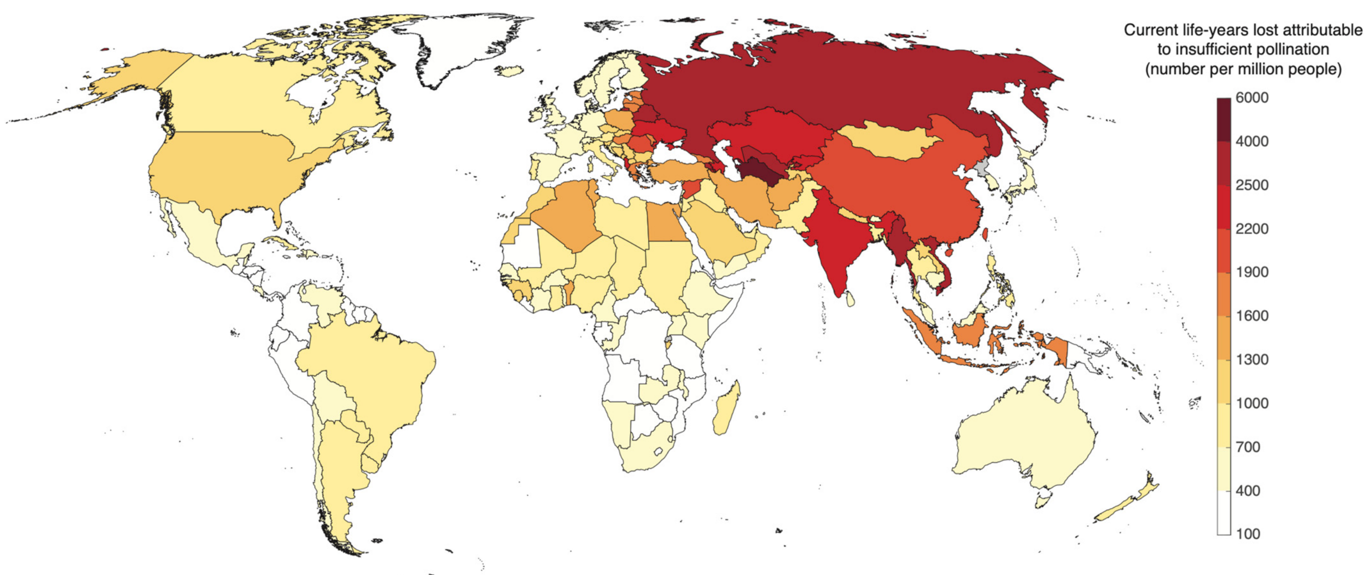

Figure 3. Life-years lost per capita estimated to be attributable to insufficient pollination. Insufficient-pollination–related health conditions include dietary and weight factors. Values represent median of model runs. Source data may be found in Excel Table S7. Map outline sourced from https://thematicmapping.org/downloads/world_borders.php.

in Honduras, 84% (63%, 86%) in Nigeria, and 100% (99%, 100%) in Nepal (Table S3). The importance of these food categories in economic terms reflected their current dominance in each country: In Honduras and Nepal, fruits and vegetables are currently the highest-value agricultural commodity category, and they are the second-most valuable commodity in Nigeria behind roots and tubers. Following fruits and vegetables, several additional crops were estimated to contribute to significant economic losses: Honduras lost most value from pulses (10% of total loss; 11%, 11%) and "other crops" (7% of total loss; 6%, 7%), primarily coffee. Nigeria lost significant value from underperforming vegetable oil (8% of total loss; 7%, 26%) and oil crop (7%; 5%, 10%) categories, led by palm fruit and oil, as well as smaller losses among "other crops" (2%; 2%, 3%), mainly cocoa. Nepal was estimated to lose nearly all its value from fruits and vegetables, but these estimates have large accompanying error bars due to the poor specificity of its reporting of specific fruit and vegetable production.

Example: Poland

Here we expand our analysis in a single country in detail to help demonstrate how the models operate individually and together. Unless otherwise noted, all data is derived from sources listed in the "Methods" section above. Furthermore, because values are presented to inform the reader of how our individual models interconnect rather than to highlight Poland's results per se, all numbers represent median values of our modeled uncertainties for simplicity.

Three-quarters of Poland's animal-pollinated crop production, excluding oilseeds, comes from three crops: apples (53%), cucumbers (11%), and tomatoes (10%).[37] To understand Poland's missing potential due to insufficient pollination, we first compared Poland's average crop yields with its potential yield based on a selection of yields globally grown on cropland that has a similar climate to Poland's. Poland's average reported yield[1] for apple is 12.1 metric tons (t)/ha compared with an attainable yield of 15.8 t/ha; cucumbers, 11.5 t/ha on average vs. 18.9 t/ha attainable; and tomatoes, 15.5 t/ha on average vs. 37.8 t/ha attainable.

Of the gap between the average and estimated climatically attainable yields, we relied on robust field-based empirical work to assume that roughly a quarter of the difference is caused by insufficient pollination after controlling for other potential variables (e.g., industrialized farming techniques, input use, irrigation, soil properties, proximity to natural areas) (for details, see "Closing the pollinator yield gap" the "Methods" section above). From this, we estimated that if pollinators were abundant and diverse, Poland could produce 8% more apples, 12% more cucumbers, and 28% more tomatoes. Widening the lens to both animal- and nonpollinated crops, we estimate that, under greater pollination, Poland could produce 13% more fruit and 3% more vegetables than at present. The larger value for fruit reflects that animal-pollinated vegetables make up a smaller proportion of total production based on our calculations.

If Poland and the rest of the world were producing greater volumes of fruit and vegetables (among other crops) in a more pollinated world, economic principles that underpin our IMPACT global economic model would predict that farmers would follow new price incentives by changing what they plant or the effort they expend. Global consumers would also buy and eat differently based on food prices, accommodated by shifts in global trade flows. These local and global forces combine in our modeled results for Poland by driving up exports of surplus fruit to meet new demand elsewhere, increasing imports of now less expensive vegetables to meet domestic demand, and increasing domestic consumption of fruits by 6% and vegetables by 4%. Interestingly, nut intake is estimated to increase from 4.2 to 5.0 g/d, driven entirely by increased imports caused by higher supply and lower prices (very few nuts are grown domestically).

Our model suggests that these relatively modest diet changes nevertheless would have the benefit of reducing avoidable mortality from chronic disease. Higher fruit intake could be estimated to help avoid 1,400 deaths annually in Poland due to decreased risk of stroke (900 deaths avoided), cancer (300 deaths), and coronary heart disease (200 deaths). Furthermore, higher vegetable intake could lead to reduced mortality from coronary heart disease (1,000 deaths), cancer (500 deaths), and stroke (200 deaths). Higher nut intake could help avoid 1,700 deaths, all from coronary heart disease. All together, these beneficial changes to the diet could be estimated to avoid 4,700 deaths per year.

Discussion

Our results suggest that suboptimal pollination appears to be already driving significant excess mortality globally and loss of economic value in producing regions. Furthermore, they suggest that it is also likely widening inequality in diets and health outcomes given that a reduced supply of pollinated foods would raise prices and narrow access within and across countries. Today's estimated health impacts of insufficient pollination would be comparable to other major global risk factors: those attributable to substance use disorders, interpersonal violence, or prostate cancer.[64] We found that in percentage terms, this health burden was estimated to be borne disproportionately by upper–middle- and high-income countries, and much of the absolute burden was estimated to be suffered in middle-income countries with large populations, namely, China, India, Indonesia, and Russia. In addition, our analysis showed that the lower-income countries we examined could also be losing considerable agricultural income from depressed yields, potentially on the order of 10%–30% of total agricultural production value.

It is worth noting that our estimates of the health impacts of global pollinator deficits are likely to be conservative. In this analysis, we focused on a single pathway: the impact of lost pollinator-dependent crop production and consumption on deaths from NCDs. However, the loss of pollinator-dependent crops is likely to impact health in other important ways not addressed by our analysis. One way is increased prevalence of micronutrient deficiency, particularly for vitamin A and folate. Although falling globally, there are still substantial global burdens of disease from these deficiencies,[8] and pollinator-dependent crops are responsible for a large share of these nutrients in the global diet.[65] Another pathway is the indirect effect of reduced income among farmers in low and lower–middle-income countries. Presumably, the higher incomes associated with higher per capita crop yields in producing regions would translate into health benefits, particularly for lower-income countries. Finally, other health opportunities, such as reduced access to health-benefitting bee products (e.g., honey, propolis, royal jelly) and pollinated medicinal plants that are important in both industrialized and traditional medicines, may be lost. Analysis of these effects, however, was beyond the scope of this paper.

This study represents a unique, cross-disciplinary combination of data and modeling to quantify the health implications of inadequate pollination on a global scale. A previous analysis[66] investigated more extreme theoretical future scenarios of 50%, 75%, and 100% removal of global pollinators and their implications on diets and health, finding a predictably more severe impact on agricultural production and health. With 100% removal of pollinators, they found that supplies of fruit, vegetables, nuts, and seeds could fall by 16%–23%, leading to 1.4 million additional annual deaths globally due to the ensuing dietary and nutritional changes. However, unlike this prior study, which examined the implications for extreme hypothetical scenarios of severe or complete pollinator loss, the present analysis aimed to quantify the present-day penalty being paid by inadequate global pollination compared with our achievable potential. As such, it serves to inform and target strategies aimed at boosting pollinating insect populations by quantifying the potential health and economic benefits of adopting such policies.

We provide four accompanying notes to explain and justify our results. First, our data sets for both the total yield gap of each crop and country, as well as the pollinator-attributable yield gap,[36] are derived from recorded or empirical measurements, making them congruent and applicable to our research question. Our second note is a justification for the use of a single percentage—25.5% (95% UI: 5.5%, 45.4%)—to characterize the pollinator-attributable yield gap for all pollinator-dependent crops globally. This percentage was identified from an empirically derived regression model after controlling for many other confounding variables: location (latitude and longitude), management intensity, isolation from semi-natural or natural habitats, the estimated percentage pollinator dependence of each crop from Klein et al.,[21] baseline floral density, and the size of the total yield gap. Some of these variables were also found to be significantly correlated with yields—such as management intensity, isolation from natural habitats—whereas most were not, most importantly, the crop's estimated pollinator dependence percentage. This last finding can also make intuitive sense given that farmers of highly pollinator-dependent crops may recognize the necessity of pollinators and therefore manage them, whereas farmers of low-to-intermediate pollinator-dependent crops may not cultivate pollinators so aggressively. In this case, a pumpkin farmer (high pollinator-dependent crop) near a peanut farmer (low pollinator-dependent crop) may have similar pollinator deficits despite very different crop pollinator dependence. Because the pollinator yield relationship was found to be independently significant after controlling for a large slate of predictor variables, we believe it is a robust empirical finding that we could confidently apply broadly. Third, we address how our model results may underestimate the true effect. Given that many agricultural inputs will continue to be optimized globally over time (e.g., fertilizers, other agrochemicals, improved seed, increased mechanization), whereas pollinator populations are expected to continue their decline, these countervailing trends are likely to increase the pollinator-attributable portion of the yield gap globally. Therefore, it is possible that our results may ultimately underestimate the true effect of insufficient pollination on global health and diets. Fourth and finally, we note that our estimates of global food production and consumption are underpinned by FAO data drawn from nationally reported accounts, which can be unreliable in some countries given a low prioritization of agricultural data collection or poor quality data. It is difficult to estimate the magnitude or direction of these errors because of a slim literature systematically assessing data quality. Most available studies comparing FAO data with more reliable survey data have found that FAO tends to produce higher estimates of fruit and vegetable consumption. This includes non-starchy vegetable consumption in sub-Saharan Africa,[67] although fruit and total fruit/vegetable intakes did not show a consistent and significant bias when measured by FAO compared with different methods. However, we have attempted to correct for this in our estimates by removing retail and domestic food waste, which is included in FAO food availability estimates but not others.

Our results underscore the importance of pollinators for human health and increase the urgency of implementing pollinator-friendly policies to halt and reverse the trends of pollinator declines. Diverse research investigating the optimal policies to benefit pollination have shown remarkable consensus around a short list of highly effective strategies: increase flower abundance and diversity on farms, reduce pesticide use, and preserve or restore nearby natural habitat.[28,68–71] This encouraging scientific agreement has already spurred action worldwide, with many countries creating and implementing their own national pollinator protection strategies. Despite this promising momentum, immense challenges remain for the restoration of pollinator populations globally. In this analysis, we have demonstrated that the protection of animal pollinators is not solely an ecological or environmental issue but also has significant implications for human health and economic well-being.

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References

1. FAO (Food and Agriculture Organization of the United Nations), IFAD (International Fund for Agricultural Development), UNICEF (United Nations Children's Fund), WFP (World Food Program), WHO (World Health Organization). 2022. *The State of Food Security and Nutrition in the World 2022*. Rome, Italy: FAO.
2. Stoltzfus RJ. 2003. Iron deficiency: global prevalence and consequences. Food Nutr Bull 24(suppl 4):S99–S103, PMID: 17016951, https://doi.org/10.1177/15648265030244S206.
3. Zimmermann MB, Hurrell RF. 2007. Nutritional iron deficiency. Lancet 370(9586):511–520, PMID: 17693180, https://doi.org/10.1016/S0140-6736(07)61235-5.
4. Brown KH, Wuehler SE, Peerson JM. 2001. The importance of zinc in human nutrition and estimation of the global prevalence of zinc deficiency. Food Nutr Bull 22(2):113–125, https://doi.org/10.1177/156482650102200201.
5. Caulfield LE, Black RE. 2004. Zinc deficiency. In: *Comparative Quantification of Health Risks: Global and Regional Burden of Disease Attributable to Selected Major Risk Factors*, vol 1. Ezzati M, Lopez AD, Rodgers A, Murray CJL, eds. 257–280.
6. Wessells KR, Brown KH. 2012. Estimating the global prevalence of zinc deficiency: results based on zinc availability in national food supplies and the prevalence of stunting. PLoS One 7(11):e50568, PMID: 23209782, https://doi.org/10.1371/journal.pone.0050568.
7. World Health Organization. 2009. *Global Prevalence of Vitamin A Deficiency in Populations at Risk 1995–2005: WHO Global Database on Vitamin A Deficiency*. https://apps.who.int/iris/bitstream/handle/10665/44110/9789241598019_eng.pdf [accessed 30 September 2020].
8. Stevens GA, Bennett JE, Hennocq Q, Lu Y, De-Regil LM, Rogers L, et al. 2015. Trends and mortality effects of vitamin A deficiency in children in 138 low-income and middle-income countries between 1991 and 2013: a pooled analysis of population-based surveys. Lancet Glob Health 3(9):e528–e536, PMID: 26275329, https://doi.org/10.1016/S2214-109X(15)00039-X.
9. de Onís M, Monteiro C, Akré J, Glugston G. 1993. The worldwide magnitude of protein–energy malnutrition: an overview from the WHO Global Database on Child Growth. Bull World Health Organ 71(6):703–712, PMID: 8313488.
10. Medek DE, Schwartz J, Myers SS. 2017. Estimated effects of future atmospheric CO_2 concentrations on protein intake and the risk of protein deficiency

by country and region. Environ Health Perspect 125(8):087002, PMID: 28885977, https://doi.org/10.1289/EHP41.
11. NCD-RisC (NCD Risk Factor Collaboration). 2016. A century of trends in adult human height. eLife 5:e13410, PMID: 27458798, https://doi.org/10.7554/eLife.13410.
12. Development Initiatives Poverty Research Ltd. 2020. *2020 Global Nutrition Report: Action on Equity to End Malnutrition*. https://globalnutritionreport.org/reports/2020-global-nutrition-report/ [accessed 30 September 2020].
13. GBD 2017 Risk Factor Collaborators. 2018. Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks for 195 countries and territories, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. Lancet 392(10159):1923–1994, PMID: 30496105, https://doi.org/10.1016/S0140-6736(18)32225-6.
14. FAO, IFAD, UNICEF, WFP, WHO. 2021. *The State of Food Security and Nutrition in the World 2021*. Rome, Italy: FAO.
15. GLOPAN (Global Panel on Agriculture and Food Systems for Nutrition). 2020. *Future Food Systems: For People, Our Planet, and Prosperity*. https://www.glopan.org/wp-content/uploads/2020/09/Foresight-2.0_Future-Food-Systems_For-people-our-planet-and-prosperity.pdf [accessed 5 October 2020].
16. Godfray HCJ, Garnett T. 2014. Food security and sustainable intensification. Philos Trans R Soc Lond B Biol Sci 369(1639):20120273, PMID: 24535385, https://doi.org/10.1098/rstb.2012.0273.
17. Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, et al. 2019. Food in the anthropocene: the EAT-*Lancet* Commission on healthy diets from sustainable food systems. Lancet 393(10170):447–492, PMID: 30660336, https://doi.org/10.1016/S0140-6736(18)31788-4.
18. Myers SS. Food and nutrition on a rapidly changing planet. 2020. In: *Planetary Health: Protecting Nature to Protect Ourselves*. Myers SS, Frumkin H, eds. Washington, DC: Island Press, 536.
19. Rockström J, Edenhofer O, Gaertner J, DeClerck F. 2020. Planet-proofing the global food system. Nat Food 1(1):3–5, https://doi.org/10.1038/s43016-019-0010-4.
20. Mbow C, Rosenzweig C, Barioni LG, Benton TG, Herrero M, Krishnapillai M, et al. 2019. Food security. In: *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. Shukla PR, Skea J, Calvo Buendia E, Masson-Delmotte V, Pörtner HO, Roberts DC, et al., eds. https://www.ipcc.ch/srccl/chapter/chapter-5/ [accessed 8 December 2020].
21. Klein AM, Vaissière BE, Cane JH, Steffan-Dewenter I, Cunningham SA, Kremen C, et al. 2007. Importance of pollinators in changing landscapes for world crops. Proc Biol Sci 274(1608):303–313, PMID: 17164193, https://doi.org/10.1098/rspb.2006.3721.
22. Aune D, Giovannucci E, Boffetta P, Fadnes LT, Keum N, Norat T, et al. 2017. Fruit and vegetable intake and the risk of cardiovascular disease, total cancer and all-cause mortality—a systematic review and dose-response meta-analysis of prospective studies. Int J Epidemiol 46(3):1029–1056, PMID: 28338764, https://doi.org/10.1093/ije/dyw319.
23. Afshin A, Micha R, Khatibzadeh S, Mozaffarian D. 2014. Consumption of nuts and legumes and risk of incident ischemic heart disease, stroke, and diabetes: a systematic review and meta-analysis. Am J Clin Nutr 100(1):278–288, PMID: 24898241, https://doi.org/10.3945/ajcn.113.076901.
24. Aune D, Keum N, Giovannucci E, Fadnes LT, Boffetta P, Greenwood DC, et al. 2016. Nut consumption and risk of cardiovascular disease, total cancer, all-cause and cause-specific mortality: a systematic review and dose-response meta-analysis of prospective studies. BMC Med 14(1):207, PMID: 27916000, https://doi.org/10.1186/s12916-016-0730-3.
25. Garibaldi LA, Gemmill-Herren B, D'Annolfo R, Graeub BE, Cunningham SA, Breeze TD. 2017. Farming approaches for greater biodiversity, livelihoods, and food security. Trends Ecol Evol 32(1):68–80, PMID: 27793463, https://doi.org/10.1016/j.tree.2016.10.001.
26. Lautenbach S, Seppelt R, Liebscher J, Dormann CF. 2012. Spatial and temporal trends of global pollination benefit. PLoS One 7(4):e35954, PMID: 22563427, https://doi.org/10.1371/journal.pone.0035954.
27. Gallai N, Salles JM, Settele J, Vaissière BE. 2009. Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. Ecol Econ 68(3):810–821, https://doi.org/10.1016/j.ecolecon.2008.06.014.
28. IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services). 2016. *The Assessment Report on Pollinators, Pollination and Food Production: Summary for Policymakers*. http://digitallibrary.un.org/record/1664349 [accessed 30 September 2020].
29. Vasiliev D, Greenwood S. 2021. The role of climate change in pollinator decline across the Northern Hemisphere is underestimated. Sci Total Environ 775:145788, PMID: 33618305, https://doi.org/10.1016/j.scitotenv.2021.145788.
30. Potts SG, Imperatriz-Fonseca V, Ngo HT, Aizen MA, Biesmeijer JC, Breeze TD, et al. 2016. Safeguarding pollinators and their values to human well-being. Nature 540(7632):220–229, PMID: 27894123, https://doi.org/10.1038/nature20588.
31. Wagner DL, Grames EM, Forister ML, Berenbaum MR, Stopak D. 2021. Insect decline in the anthropocene: death by a thousand cuts. Proc Natl Acad Sci USA 118(2):e2023989118, PMID: 33431573, https://doi.org/10.1073/pnas.2023989118.
32. Zattara EE, Aizen MA. 2021. Worldwide occurrence records suggest a global decline in bee species richness. One Earth 4(1):P114–P123, https://doi.org/10.1016/j.oneear.2020.12.005.
33. Aizen MA, Harder LD. 2009. The global stock of domesticated honey bees is growing slower than agricultural demand for pollination. Curr Biol 19(11):915–918, PMID: 19427214, https://doi.org/10.1016/j.cub.2009.03.071.
34. Garibaldi LA, Steffan-Dewenter I, Winfree R, Aizen MA, Bommarco R, Cunningham SA, et al. 2013. Wild pollinators enhance fruit set of crops regardless of honey bee abundance. Science 339(6127):1608–1611, PMID: 23449997, https://doi.org/10.1126/science.1230200.
35. Reilly JR, Artz DR, Biddinger D, Bobiwash K, Boyle NK, Brittain C, et al. 2020. Crop production in the USA is frequently limited by a lack of pollinators. Proc Biol Sci 287(1931):20200922, PMID: 33043867, https://doi.org/10.1098/rspb.2020.0922.
36. Garibaldi LA, Carvalheiro LG, Vaissière BE, Gemmill-Herren B, Hipólito J, Freitas BM, et al. 2016. Mutually beneficial pollinator diversity and crop yield outcomes in small and large farms. Science 351(6271):388–391, PMID: 26798016, https://doi.org/10.1126/science.aac7287.
37. FAOSTAT. 2020. Food balance sheets. http://www.fao.org/faostat/en/#data/FBSH/report [accessed 19 November 2020].
38. Licker R, Johnston M, Foley JA, Barford C, Kucharik CJ, Monfreda C, et al. 2010. Mind the gap: how do climate and agricultural management explain the 'yield gap' of croplands around the world? Glob Ecol Biogeogr 19(6):769–782, https://doi.org/10.1111/j.1466-8238.2010.00563.x.
39. Johnston M, Licker R, Foley J, Holloway T, Mueller ND, Barford C, et al. 2011. Closing the gap: global potential for increasing biofuel production through agricultural intensification. Environ Res Lett 6(3):034028, https://doi.org/10.1088/1748-9326/6/3/034028.
40. Mueller ND, Gerber JS, Johnston M, Ray DK, Ramankutty N, Foley JA. 2012. Closing yield gaps through nutrient and water management. Nature 490(7419):254–257, PMID: 22932270, https://doi.org/10.1038/nature11420.
41. Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A. 2005. Very high resolution interpolated climate surfaces for global land areas. Int J Climatol 25(15):1965–1978, https://doi.org/10.1002/joc.1276.
42. Monfreda C, Ramankutty N, Foley JA. 2008. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Global Biogeochem Cycles 22(1):GB1022, https://doi.org/10.1029/2007GB002947.
43. Robinson S, Mason-D'Croz D, Islam S, Sulser TB, Robertson RD, Zhu T, et al. 2015. *The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description for Version 3*. International Food Policy Research Institute Discussion Paper 1483. Washington, DC: IFPRI.
44. Mason-D'Croz D, Bogard JR, Herrero M, Robinson S, Sulser TB, Wiebe K, et al. 2020. Modelling the global economic consequences of a major African swine fever outbreak in China. Nat Food 1(4):221–228, PMID: 33634268, https://doi.org/10.1038/s43016-020-0057-2.
45. Springmann M, Mason-D'Croz D, Robinson S, Garnett T, Godfray HCJ, Gollin D, et al. 2016. Global and regional health effects of future food production under climate change: a modelling study. Lancet 387(10031):1937–1946, PMID: 26947322, https://doi.org/10.1016/S0140-6736(15)01156-3.
46. Mason-D'Croz D, Sulser TB, Wiebe K, Rosegrant MW, Lowder SK, Nin-Pratt A, et al. 2019. Agricultural investments and hunger in Africa modeling potential contributions to SDG2 – Zero Hunger. World Dev 116:38–53, PMID: 30944503, https://doi.org/10.1016/j.worlddev.2018.12.006.
47. Rosegrant MW, Koo J, Cenacchi N, Ringler C, Robertson R, Fisher M, et al. 2014. *Food Security in a World of Natural Resource Scarcity: The Role of Agricultural Technologies*. Washington, DC: International Food Policy Research Institute.
48. van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, et al. 2011. The representative concentration pathways: an overview. Clim Change 109(1–2):5–31, https://doi.org/10.1007/s10584-011-0148-z.
49. Riahi K, van Vuuren DP, Kriegler E, Edmonds J, O'Neill BC, Fujimori S, et al. 2017. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Glob Environ Change 42:153–168, https://doi.org/10.1016/j.gloenvcha.2016.05.009.
50. Springmann M, Wiebe K, Mason-D'Croz D, Sulser TB, Rayner M, Scarborough P. 2018. Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. Lancet Planet Health 2(10):e451–e461, PMID: 30318102, https://doi.org/10.1016/S2542-5196(18)30206-7.
51. Gustavsson J, Cederberg C, Sonesson U, van Otterdijk R, Meybeck A. 2011. *Global Food Losses and Food Waste: Extent, Causes and Prevention; Study Conducted for the International Congress Save Food! At Interpack2011*

Düsseldorf, Germany. Düsseldorf, Germany. Food and Agriculture Organization of the United Nations.

52. Berrington de Gonzalez A, Hartge P, Cerhan JR, Flint AJ, Hannan L, MacInnis RJ, et al. 2010. Body-mass index and mortality among 1.46 million white adults. N Engl J Med 363(23):2211–2219, PMID: 21121834, https://doi.org/10.1056/NEJMoa1000367.
53. Singh GM, Danaei G, Farzadfar F, Stevens GA, Woodward M, Wormser D, et al. 2013. The age-specific quantitative effects of metabolic risk factors on cardiovascular diseases and diabetes: a pooled analysis. PLoS One 8(7):e65174, PMID: 23935815, https://doi.org/10.1371/journal.pone.0065174.
54. Micha R, Shulkin ML, Peñalvo JL, Khatibzadeh S, Singh GM, Rao M, et al. 2017. Etiologic effects and optimal intakes of foods and nutrients for risk of cardiovascular diseases and diabetes: systematic reviews and meta-analyses from the Nutrition and Chronic Diseases Expert Group (NutriCoDE). PLoS One 12(4): e0175149, PMID: 28448503, https://doi.org/10.1371/journal.pone.0175149.
55. Chan DSM, Lau R, Aune D, Vieira R, Greenwood DC, Kampman E, et al. 2011. Red and processed meat and colorectal cancer incidence: meta-analysis of prospective studies. PLoS One 6(6):e20456, PMID: 21674008, https://doi.org/10.1371/journal.pone.0020456.
56. Chen GC, Lv DB, Pang Z, Liu QF. 2013. Red and processed meat consumption and risk of stroke: a meta-analysis of prospective cohort studies. Eur J Clin Nutr 67(1):91–95, PMID: 23169473, https://doi.org/10.1038/ejcn.2012.180.
57. Feskens EJM, Sluik D, van Woudenbergh GJ. 2013. Meat consumption, diabetes, and its complications. Curr Diab Rep 13(2):298–306, PMID: 23354681, https://doi.org/10.1007/s11892-013-0365-0.
58. Micha R, Michas G, Mozaffarian D. 2012. Unprocessed red and processed meats and risk of coronary artery disease and type 2 diabetes—an updated review of the evidence. Curr Atheroscler Rep 14(6):515–524, PMID: 23001745, https://doi.org/10.1007/s11883-012-0282-8.
59. Zheng J, Huang T, Yu Y, Hu X, Yang B, Li D. 2012. Fish consumption and CHD mortality: an updated meta-analysis of seventeen cohort studies. Public Health Nutr 15(4):725–737, PMID: 21914258, https://doi.org/10.1017/S1368980011002254.
60. Prospective Studies Collaboration, Whitlock G, Lewington S, Sherliker P, Clarke R, Emberson J, et al. 2009. Body-mass index and cause-specific mortality in 900 000 adults: collaborative analyses of 57 prospective studies. Lancet 373(9669):1083–1096, PMID: 19299006, https://doi.org/10.1016/S0140-6736(09)60318-4.
61. GBD 2013 Risk Factors Collaborators, Forouzanfar MH, Alexander L, Anderson HR, Bachman VF, Biryukov S, et al. 2015. Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks in 188 countries, 1990–2013: a systematic analysis for the Global Burden of Disease Study 2013. Lancet 386(10010):2287–2323, PMID: 26364544, https://doi.org/10.1016/S0140-6736(15)00128-2.
62. World Bank Country and Lending Groups. https://datahelpdesk.worldbank.org/knowledgebase/articles/906519 [accessed 5 November 2020].
63. United Nations. 2022. Population Division: World Population Prospects 2022. https://population.un.org/wpp/ [accessed 8 November 2022].
64. IHME (Institute for Health Metrics and Evaluation). 2019. GBD Results Tool. http://ghdx.healthdata.org/gbd-results-tool [accessed 8 November 2022].
65. Eilers EJ, Kremen C, Smith Greenleaf S, Garber AK, Klein AM. 2011. Contribution of pollinator-mediated crops to nutrients in the human food supply. PLoS One 6(6):e21363, PMID: 21731717, https://doi.org/10.1371/journal.pone.0021363.
66. Smith MR, Singh GM, Mozaffarian D, Myers SS. 2015. Effects of decreases of animal pollinators on human nutrition and global health: a modelling analysis. Lancet 386(10007):1964–1972, PMID: 26188748, https://doi.org/10.1016/S0140-6736(15)61085-6.
67. Mensah DO, Nunes AR, Bockarie T, Lillywhite R, Oyebode O. 2021. Meat, fruit, and vegetable consumption in sub-Saharan Africa: a systematic review and meta-regression analysis. Nutr Rev 79(6):651–692, PMID: 32556305, https://doi.org/10.1093/nutrit/nuaa032.
68. Kennedy CM, Lonsdorf E, Neel MC, Williams NM, Ricketts TH, Winfree R, et al. 2013. Global quantitative synthesis of local and landscape effects on wild bee pollinators in agroecosystems. Ecol Lett 16(5):584–599, PMID: 23489285, https://doi.org/10.1111/ele.12082.
69. Garibaldi LA, Carvalheiro LG, Leonhardt SD, Aizen MA, Blaauw BR, Isaacs R, et al. 2014. From research to action: enhancing crop yield through wild pollinators. Front Ecol Environ 12(8):439–447, https://doi.org/10.1890/130330.
70. Dicks LV, Viana B, Bommarco R, Brosi B, Arizmendi MDC, Cunningham SA, et al. 2016. Ten policies for pollinators. Science 354(6315):975–976, PMID: 27884996, https://doi.org/10.1126/science.aai9226.
71. Sardiñas H, Code A, Cruz JK, et al. 2021. *Bee Better Certified: Background to the Production Standards*. Portland, OR: Xerces Society for Invertebrate Conservation.