Effects of decreases of animal pollinators on human nutrition and global health: a modelling analysis

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Summary

Background Anthropogenic declines of animal pollinators and the associated effects on human nutrition are of growing concern. We quantified the nutritional and health outcomes associated with decreased intake of pollinator-dependent foods for populations around the world.

Methods We assembled a database of supplies of 224 types of food in 156 countries. We quantified nutrient composition and pollinator dependence of foods to estimate the size of possible reductions in micronutrient and food intakes for different national populations, while keeping calorie intake constant with replacement by staple foods. We estimated pollinator-decline-dependent changes in micronutrient-deficient populations using population-weighted estimated average requirements and the cutpoint method. We estimated disease burdens of non-communicable, communicable, and malnutrition-related diseases with the Global Burden of Disease 2010 comparative risk assessment framework.

Findings Assuming complete removal of pollinators, 71 million (95% uncertainty interval 41–262) people in low-income countries could become newly deficient in vitamin A, and an additional 2·2 billion (1·2–2·5) already consuming below the average requirement would have further declines in vitamin A supplies. Corresponding estimates for folate were 173 million (134–225) and 1·23 billion (1·12–1·33). A 100% decline in pollinator services could reduce global fruit supplies by 22·9% (19·5–26·1), vegetables by 16·3% (15·1–17·7), and nuts and seeds by 22·1% (17·7–26·4), with significant heterogeneity by country. In sum, these dietary changes could increase global deaths yearly from non-communicable and malnutrition-related diseases by 1·42 million (1·38–1·48) and disability-adjusted life-years (DALYs) by 27·0 million (25·8–29·1), an increase of 2·7% for deaths and 1·1% for DALYs. A 50% loss of pollination services would be associated with 700 000 additional annual deaths and 13·2 million DALYs.

Interpretation Declines in animal pollinators could cause significant global health burdens from both non-communicable diseases and micronutrient deficiencies.

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Introduction

In the past decade, worldwide decreases in the number, range, and species diversity of both wild and managed animal pollinators have been well documented.[1] Since 2006, managed honey bee colonies in the USA have seen sustained and significant annual winter colony losses at around 30%,[2] while Europe has seen smaller but substantial losses (15%).[3] For non-managed wild pollinators, for which quantitative abundance data are more sparse, numerous studies have documented significant declines in their diversity and range over the past three decades throughout North America, Europe, and Asia,[4,5] with many species going extinct. Additionally, bird and mammal pollinator species have also experienced increasing scarcity, extinction, and narrowing ranges globally over the past 25 years.[6] Despite recent investigations, the exact cause of these trends remains poorly understood, although a consensus is forming to attribute decreased insect pollination—the predominant type of animal pollination—to a combination of causes, including pest infestations, disease, increased use of pollinator-harming pesticides, and loss of habitat and forage.[4]

Pollinators contribute to the agricultural yield for an estimated 35% of global food production[7] and are directly responsible for up to 40% of the world's supply of some micronutrients, such as vitamin A.[8] Regions where pollinators contribute most heavily to nutrient production are often also those where populations have the largest burdens of micronutrient deficiency diseases.[9] In addition, insufficient intakes of the key foods affected by pollinator species—fruits, vegetables, nuts, and seeds—are each risk factors for non-communicable diseases, including cardiovascular diseases, diabetes, oesophageal cancer, and lung cancer.[10] Micronutrients vital for children and pregnant women—vitamin A and folate—are also affected, and inadequate intakes can lead to increased mortality from infectious disease and increased incidence of blindness and neural tube defects.[10] Thus, pollinator declines could lead to substantial new disease burdens from both micronutrient deficiencies and chronic diseases.

Few studies have assessed the potential effect of pollinator decreases on health. One analysis in four low-income countries showed that human vulnerability to animal pollinator decreases from micronutrient deficiencies requires that the population receive

Research in context

Evidence before this study

Animal pollinators are declining globally, including managed and wild insect pollinators, as well as bird and mammal species. Additionally, the action of pollinators greatly benefits food crops and nutrients important in diets, and low intakes of highly pollinator-affected foods and nutrients (fruits, vegetables, nuts and seeds, vitamin A, folate) are major risk factors for disease.

Few studies have attempted to link the loss of pollinator-related foods to health outcomes. One study assessed the increased risk of micronutrient deficiency following pollinator removal in four countries with non-nationally representative dietary datasets and found that 0–56% of populations became newly at risk for vitamin A deficiency. Another study used global agricultural production maps coupled with nutrient densities to investigate the relationship between reliance on pollinator-dependent crops and prevalence of micronutrient deficiency, finding that those at risk for pollinator-related nutrient losses are commonly also the most deficient.

Added value of this study

This study adds a dimension that has been missing in previous global assessments by estimating per-person intakes of nutrients and food commodities under both full pollinator and partial pollinator decline scenarios and quantifying the health effect of such declines, thereby providing a novel global analysis of the contribution of pollination to human health and nutrition.

Implications of all the available evidence

Many regions are especially at risk for the health outcomes associated with a potential loss of pollinators: central and eastern Europe, south and southeast Asia, and sub-Saharan Africa. These regions also lack data about the status and trends for local pollinators. We have shown that most pollination-dependent foods that contribute to human health are grown locally rather than imported, meaning that greater emphasis should be placed on local pollination and its relationship to agricultural yield. Therefore, countries identified as at risk might benefit from increased monitoring and protection of their local pollinators to preserve economic, agricultural, and public health wellbeing.

significant nutritional value from pollinator-dependent crops and that the population be near a threshold of dietary intake at which decreases would affect risk for deficiency.[11] The study's findings, however, were limited by the use of dietary data from small, non-nationally representative samples. Furthermore, the investigation did not assess the additional potential effect on non-communicable disease, the major cause of death and disability worldwide.[10] The study was restricted to four countries, and potential health effects of pollinator decreases in other nations and worldwide are unknown. By modelling how losses in pollination could affect food and nutrient intake on a global scale, we aim to provide quantitative estimates of the contribution of pollination to overall human health on a broad scale.

Methods

Study design

We first quantified the effect of pollinator declines on the risk of non-communicable diseases associated with reduced consumption of specific food groups—fruits, vegetables, nuts, and seeds—by use of established relative risks and estimated reductions in intake for 156 countries. Second, we quantified reduced intake of vitamin A and folate in these countries. We modelled changes in risk of deficiency of these nutrients and their associated health sequelae.

Because of uncertainty about the size of pollinator losses globally, and the likely heterogeneity of future pollinator declines in different regions, any attempt to model theoretically likely pollinator losses would be speculative. Rather, our goal was to estimate the size of health effects directly attributable to reduced pollination and to provide guidance about how those effects would change under different scenarios of pollinator loss. We made no assumptions about human adaptation to pollinator-related food or nutrient losses (eg, use of alternative modes of pollination, dietary or crop variety substitution, nutrient supplementation, increased imports of affected foods) because of the high uncertainty and country-specific variability associated with each possible intervention. To remove ambiguity, we make only the simplest assumption that calories will be conserved after the removal of pollinator-dependent foods through a proportional increase in consumption of staple foods (cereals, roots, and tubers). The resulting estimates enable us to have a much clearer sense of what is at stake in our management of both national and global animal pollinator populations.

Estimating national food and micronutrient supplies

We took data for national food supplies per person for 177 countries from 2009 Food and Agriculture Organization (FAO) food balance sheets, which provide information for 89 of the most produced and traded commodities.[12] To disaggregate broad food groups (eg, "Fruits, other") and quantify supplies of subgroups that are differently affected by pollinators, we incorporated additional FAO production and trade data to replicate the FAO residual method (production + imports − exports) and estimated per-person supplies for additional individual food types, and identified the relative size of contributions from indigenous (in-country) versus exogenous (imported) sources for each food. After disaggregation, our dataset included estimates of food supply per person for 224 food commodities. Many countries had particularly imprecise reporting at this level of food specificity—eg, nearly all fruit and vegetable supplies were listed as "Fruits, other" or "Vegetables, other". For six countries, we used additional agricultural census data to apportion "other" fruits and vegetables to specific types. Another 21 countries without census data were omitted, leaving 156 countries in total.

To estimate the contributions of calories, vitamin A, and folate from each food, we matched food supplies per person to nutrient densities from five regional food composition databases[13–17] of regionally grown or sourced foods and calculated nutrient supplies for each food and country.

Effect of pollinator losses on crops

Klein and colleagues[7] assessed the effects of pollinator losses on each individual type of fruit, vegetable, and nut or seed through a meta-analysis that sorted the pollinator-yield dependence of crops into six groupings from 0–100%. We matched these with each FAO food category and decreased the food supply of each crop accordingly (appendix pp 11–16). In addition to modelling full removal of pollinators, we also modelled the dietary and health effects for both 50% and 75% losses as sensitivity analyses.

Effect of loss of pollinators on food and nutrient intake

We aggregated estimated losses of individual fruit, vegetable, and nut or seed types to estimate percentage reduction in each country for each of the three food groups. Because of the potentially large differences between national food availability and dietary intake, both overall and by age and sex,[18–20] we applied the country-specific percentage declines in fruits, vegetables, and nuts and seeds to actual country-specific, age-specific, and sex-specific nationally representative dietary survey intake and imputed data used in the Global Burden of Disease 2010 study.[10,21]

To estimate losses of vitamin A and folate from the diet, we used the nutrient supplies provided by current food balance sheets and pollinator-affected food estimates, assuming that calories were conserved through the proportional increase of the current mix of staple foods (cereals, roots, tubers). This assumption is supported by evidence of increased intake of cheap staple foods as a coping strategy during food shortages and subsequent price shocks in low-income countries.[22]

Changes in prevalence of micronutrient deficiency

Next, we estimated the proportion of each population that had nutrient supplies below the population-weighted estimated average requirement before and after pollination removal by using the mean per-person supply calculated above (as a proxy for intake) and assuming a 25% coefficient of variation for both vitamin A and folate, as in previous studies.[23–25] We believe that the assumption of 25% coefficient of variation is conservative because pollinator-related shortages in food and nutrient availability would probably mirror inequalities in food distribution among socioeconomic and demographic groups, potentially widening distributions to a greater extent and disproportionately affecting those with lower intakes.

Because micronutrient deficiencies are rare in higher-income countries, we restricted the micronutrient deficiency analysis to 81 countries in developing regions as defined by the Millennium Development Goals regional groupings, excluding upper-middle-income economies in north Africa, the Middle East, eastern Europe, and western Asia (appendix pp 9).

Change in non-communicable disease and micronutrient-related diseases

We estimated the burden of non-communicable diseases and diseases related to micronutrient deficiency caused by pollinator losses using the comparative risk assessment framework, described by Murray and colleagues[26] and prevalences from the Global Burden of Disease 2010 study.[27] Appendix pp 17 shows a summary of data inputs and sources. To isolate the effect of pollinator-related dietary losses, all other contributing causes of non-communicable diseases and deficiency-related diseases (eg, tobacco and alcohol use, obesity, or childhood underweight) remain unchanged.

See Online for appendix

Analysis of uncertainty

To incorporate various sources of uncertainty and capture the full breadth of possible dietary and health outcomes, we ran Monte Carlo simulations (n=1000) and drew randomly from the distributions of crop pollinator dependence and nutritional composition of each food, as well as existing prevalence data and relative risks for associated diseases. For each analysis, our central estimate was the median of the simulations, with 95% uncertainty intervals (UIs). This step can result in broad uncertainties because of the lack of specificity in the range of pollinator dependence of crops and the delineation of food types from food balance sheets.

Role of the funding source

The funders had no role in study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding author had full access to all of the data in the study. MRS and SSM had the final responsibility to submit for publication.

	Newly vitamin A deficient (%)	Presently vitamin A deficient (%)	Newly folate deficient (%)	Presently folate deficient (%)
Africa	2·6 (1·0–8·6)	51·2 (29·7–62·9)	2·2 (1·3–3·2)	16·4 (16·4–16·4)
Central and South America	2·0 (0·0–18·7)	9·6 (0·2–67·6)	1·5 (0·8–2·7)	18·3 (18·3–18·3)
North America	0·3 (0·0–16·2)	0·8 (0·0–20·0)	4·0 (2·9–5·2)	11·2 (11·2–11·2)
Eastern Mediterranean	2·4 (0·2–13·4)	6·9 (1·0–37·0)	3·4 (2·1–4·7)	42·5 (42·5–42·5)
Southeast Asia	0·2 (0·0–12·5)	96·0 (20·4–100·0)	5·9 (3·6–8·4)	40·2 (34·4–46·1)
Western Pacific	0·1 (0·0–1·9)	12·1 (0·7–14·4)	2·0 (1·3–2·5)	10·7 (10·7–10·7)

Table 1: Increase in vitamin A and folate deficiencies by region

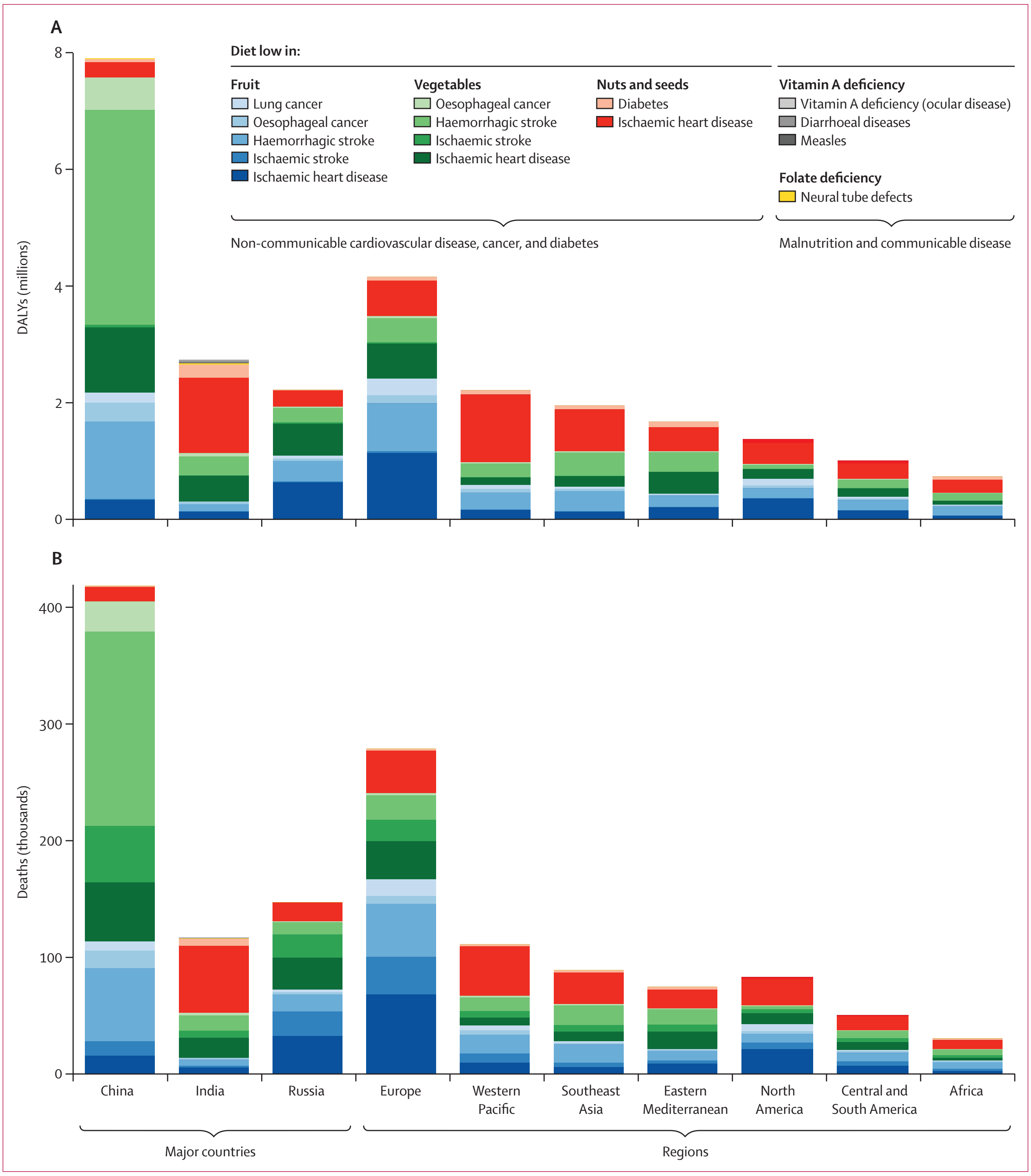

Figure 1: **Burden of disease caused by pollinator removal, by cause and risk factor**
Additional yearly (A) DALYs lost and (B) deaths attributable to declines in pollinator-dependence foods and nutrients in countries with a significant health burden (China, India, and Russia) and elsewhere globally by region. DALY=disability-adjusted life-year.

Results

We estimated that complete loss of animal pollinators globally would place an additional 71 million (95% UI 41–262) people at risk for vitamin A deficiency. The same losses of animal pollinators would place an additional 173 million (134–225) people at risk for folate deficiency (table 1).

In addition, many people in low-income countries already consume inadequate amounts of each nutrient from their diet, and would be subject to further declines in supply. For vitamin A, this population is estimated at 2·2 billion (1·2–2·5), comprising 42% (22–48) of people in at-risk regions, and generally focused in central Africa and southern and southeast Asia. For folate, 1·23 billion

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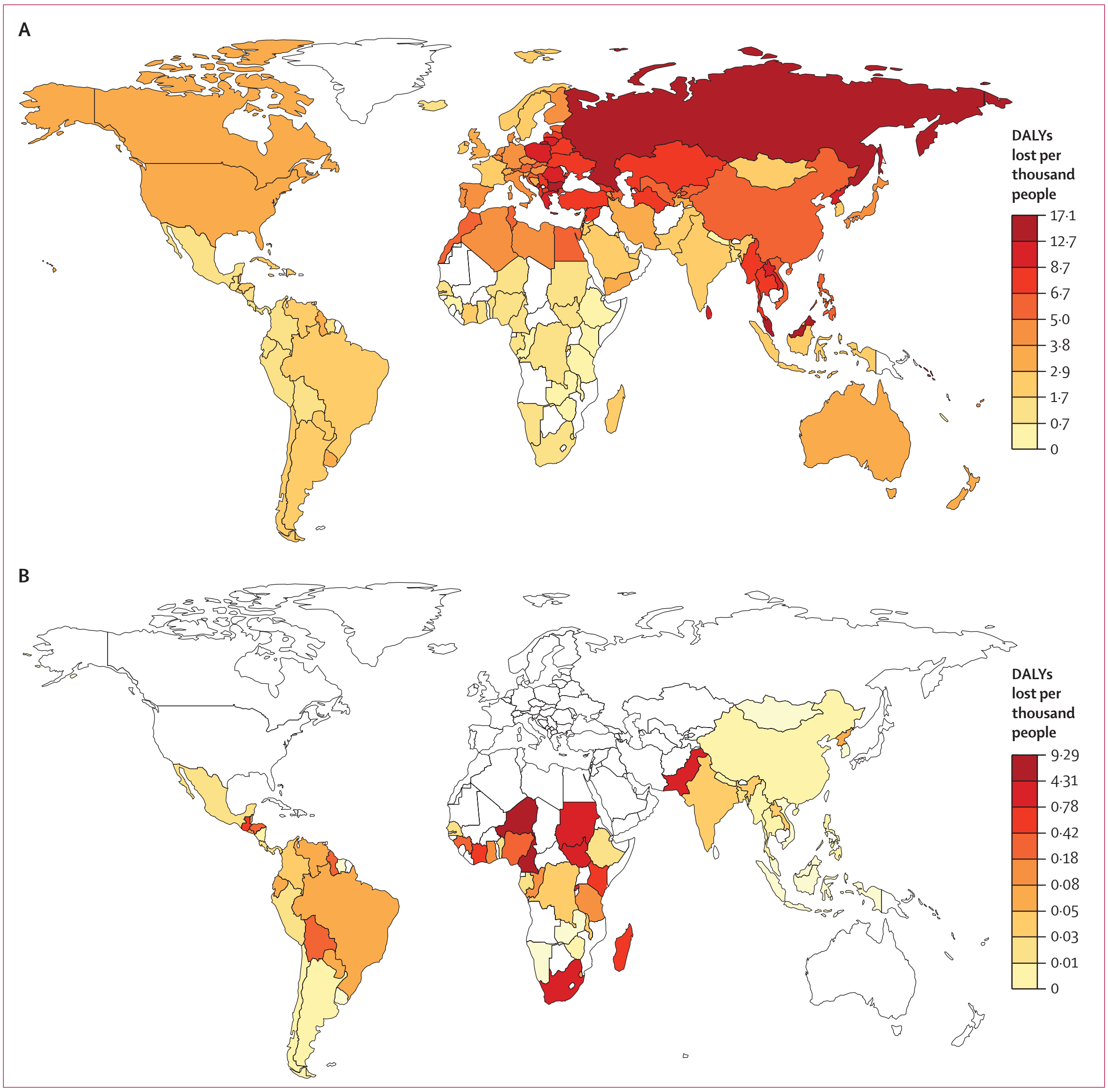

Figure 2: **Additional health burden from pollinator removal**
For (A) non-communicable cardiovascular disease, cancer, and diabetes, and for (B) malnutrition and communicable disease. DALY=disability-adjusted life-year.

(1·12–1·33) people are already consuming below their required amount, mainly in south Asia, and could experience more severe deficiency.

Full pollinator service loss would lead to an estimated 1·42 million (1·38–1·48) additional deaths per year from non-communicable and malnutrition-related diseases, and 27·0 million (25·8–29·1) lost disability-adjusted life-years (DALYs) per year, equivalent to a 2·7% increase in total yearly deaths and 1·1% of DALYs yearly. Figure 1 shows results by cause and risk factor. Nearly the entire health burden is attributable to increases in non-communicable diseases associated with low fruit, vegetable, and nut and seed intake (ischaemic heart disease, stroke, lung cancer, oesophageal cancer, and diabetes). Under full pollinator service loss, average global fruit supplies could decline by 22·9% (19·5–26·1), vegetables by 16·3% (15·1–17·7), and nuts and seeds by 22·1% (17·7–26·4).

Although the absolute health burden trends are proportional to population size, concentrating in high population countries such as China and India, on a per-person basis, the additional DALYs lost are spread more uniformly across countries, with the averages of the bottom and top quintiles of countries differing by an order of magnitude (figure 2). The regions most vulnerable to increased non-communicable disease burden are in eastern Europe, and central, eastern, and southeast Asia (figure 2A). These countries tend to have

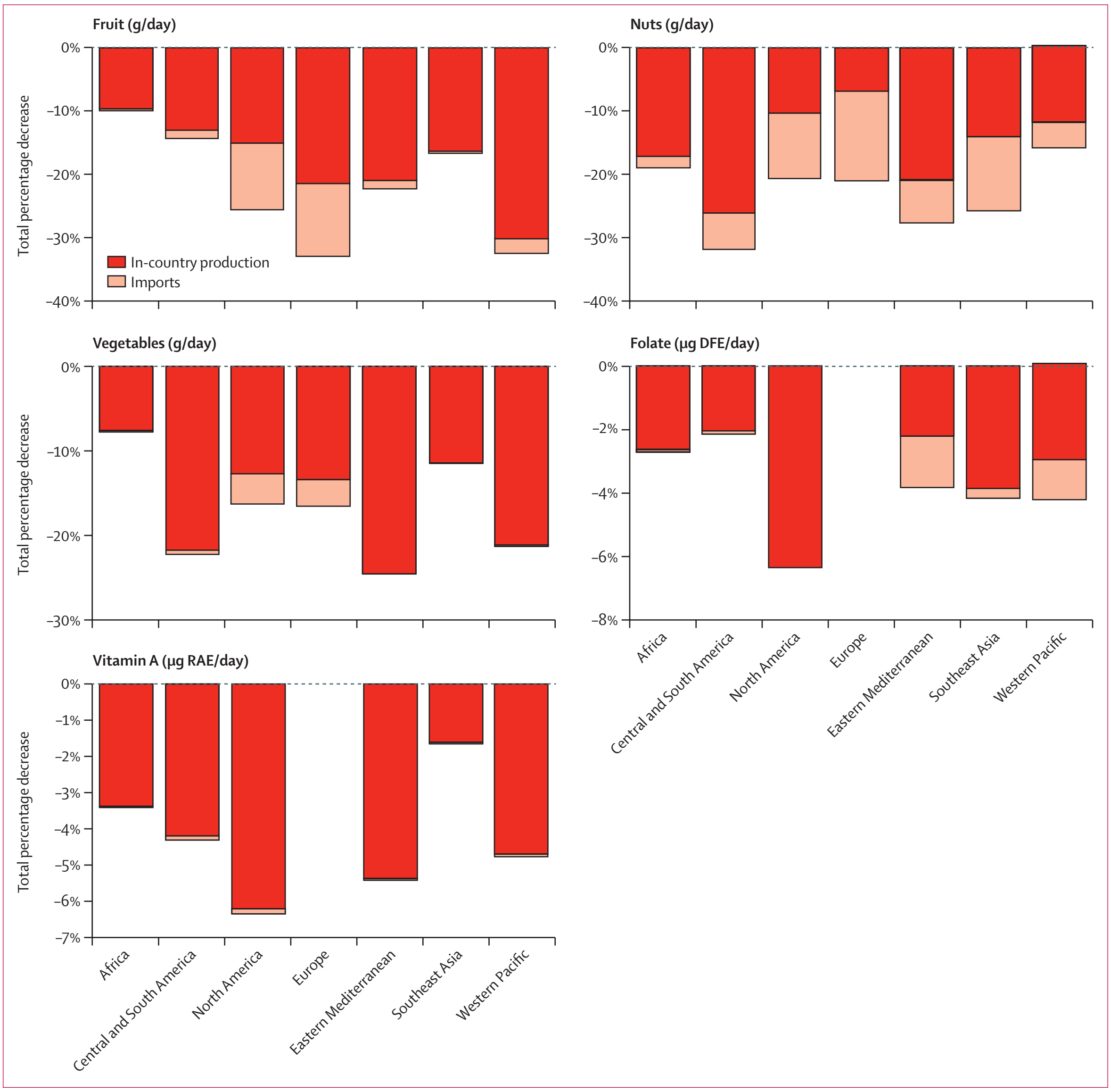

Figure 3: **Decreases in food and nutritional intake with full pollinator removal**
RAE=retinol activity equivalent. DFE=dietary folate equivalent.

high prevalences of chronic and metabolic disease and depend more heavily on pollinator-related fruits, vegetables, nuts, and seeds. Conversely, the largest increases per person in communicable and malnutrition-related disease burdens related to pollinator loss disproportionately occur in low-income countries in sub-Saharan Africa, south Asia, and parts of South America (figure 2B). These countries have the highest rates of communicable diseases and their associated symptoms, and would be most affected by further increases in malnutrition.

To identify the specific sources of pollinator-dependent foods to guide potential management strategies by country, we also assessed whether imported or indigenous (in-country) sources were larger by food and country (figure 3). Indigenous production was a much larger contributor to nearly all foods and nutrients, with nuts and seeds in Europe being the only exception. We also calculated the relative size of the health effects that could be attributed to indigenous and exogenous (imported) sources (table 2, appendix pp 18–20), assuming their proportional consumptions are constant throughout the population (ie, healthier people are not eating more or less imported foods than unhealthy people). 82% of all pollinator-related DALYs that are lost were associated with indigenous production, and most health burden comes from the loss of in-country production in 85% of all countries.

Assuming a 50% loss of pollinator services, total attributable deaths fell to 0·70 million (95% UI 0·66–0·74), half of the deaths estimated with full pollinator removal. Similarly, DALYs are also reduced by nearly half: 13·2 million (12·3–14·2) with 50% pollinator loss. With a 75% loss of pollination, attributable deaths increased to 1·05 million (0·99–1·11), equal to roughly three-quarters of the deaths with 100% removal. DALYs decreased to 19·5 million (18·3–20·8) from 27·0 million.

Discussion

Human activity is altering the structure and function of most of the Earth's natural systems in profound, pervasive, and accelerating ways. These changes are driving species extinctions at roughly 1000 times the baseline rate[28] and, since 1970, have reduced the populations of mammals, reptiles, amphibians, birds, and fish by an estimated 50%.[29] The global health community is increasingly recognising that the human health consequences of this transformation might comprise a significant share of the global burden of disease over the next century.[30] We have quantified one example of such a consequence in an attempt to appropriately value the health benefits of an ecosystem service—in this case pollination.

This study provides the first global analysis of the contribution of pollination to human health through diet, specifically examining our reliance on pollinator-dependent foods for controlling chronic and malnutrition-related disease. Use of food balance sheet data paired with regional nutrient compositions provides a novel and more granular global dataset on diets and nutrition. However, a weakness of our analysis, as with many global studies of this type, is the paucity of global dietary data. Food balance sheets, the most comprehensive global dataset of diets, measures food supplies rather than intake and only on a mean per-person basis.

Furthermore, food balance sheets can be unreliable because they rely on government ministries for information and inconsistent reporting of foods grown or hunted for subsistence. For our study of the losses of whole food groups (eg, fruits, vegetables), we tried to ameliorate this issue by applying percentage losses derived from food balance sheets to measured intakes of food groups by age and sex. However, similar age–sex-specific datasets do not exist globally for nutrients, and intra-individual distributions need to be estimated as normal distributions with empirically derived shapes.

Future work should incorporate information on dietary intake, via 24-h recall or household expenditure data, to obtain more accurate estimates of global diets. These more detailed datasets will also provide greater information on sex, age, or socioeconomic disparities in access to food, thereby giving greater insight into intracountry vulnerability to malnutrition and food shortage.

	DALYs from indigenous food and nutrient sources (thousands)	Percentage of total	DALYs from imported sources (thousands)	Percentage of total
Africa	1183 (832–2278)	77 (71–80)	77 (5–371)	22 (20–29)
North America	781 (673–857)	60 (52–63)	553 (483–688)	40 (37–48)
Central and South America, Caribbean	891 (668–1045)	83 (77–88)	113 (44–380)	17 (12–23)
Europe	4209 (3812–4621)	62 (61–63)	2171 (1944–2445)	38 (37–39)
Eastern Mediterranean	1621 (1394–1984)	87 (79–89)	198 (130–425)	13 (11–21)
Southeast Asia	3825 (3283–5689)	79 (76–85)	904 (665–1204)	21 (15–24)
Western Pacific	9369 (8216–10 608)	92 (91–92)	736 (596–909)	8 (8–9)

DALYs=disability-adjusted life-years.

Table 2: **Health burden attributed to losses of indigenously grown versus imported foods and nutrients**

The relatively low numbers of deaths related to micronutrient deficiency can be explained by the small decreases in pollinator-related micronutrient intake overall (roughly 3–6% average nutrient loss per person) and globally diminishing incidences of measles and diarrhoeal diseases that would be exacerbated by low vitamin A intake. However, the estimates include increased risk of nutrient-deficiency-related death and disability only from people who become newly deficient and only because of a few select causes (eg, measles, diarrhoea) and do not include the billions of people who are already deficient in these nutrients but whose conditions would be made more severe. In this sense, the estimates are very conservative and probably underestimate the true effect. We were also conservative in assuming that all calories lost from pollinator declines will be replaced by consuming increased quantities of staple foods.

32 countries, including the USA and many European nations, derive 5–10% of dietary calorific intake directly from the action of pollinators. Human food demand is expected to roughly double by 2050, while increasing water scarcity, land degradation, and climate change are substantial challenges to global food production; therefore, we suspect that extensive pollinator declines could easily constrain capacity to meet future calorific needs at least in some regions of the world. We did not attempt to account for any such effect on calorific undernutrition in this analysis because of the vast uncertainties related to the future of global food production, but undoubtedly, these effects will be another dimension of health effects of pollinator declines.

We modelled losses in pollinator services. However, many governmental pollinator management agencies measure population sizes of pollinators and do not measure the services they provide directly. Despite the complicated relationship between the abundance of pollinators and their services, many have found a linear relationship, even at near-zero and very high pollinator densities.[31–34] Therefore, for the purposes of this discussion, we assume that a percentage loss of pollinators is directly proportional to a loss of pollination services.

We report that indigenous production has a disproportionate effect on the share of the pollinator-related health burden. This finding suggests that local resource management decisions that help maintain robust populations of pollinator species would be likely to produce local health benefits. This possibility might further incentivise active stewardship of pollinator populations because of their multifaceted role in local economics, agriculture, conservation, and human health.

Of course, international trade will also affect which populations experience the greatest health effects of pollinator declines. We made the simplest assumptions that yield declines related to pollinator losses will translate directly to reduced intake of those food commodities and that these reductions will be evenly distributed across national populations and around the world. The reality is far more complex. Changes in yield will alter pricing of those commodities and reduced yields are likely to lead to increases in price. The result will be that wealthy populations will be relatively insulated from food losses while poor communities will probably have disproportionately impoverished diets. Because of the complexity of modelling the economics of these trade scenarios, we assumed a direct, proportionate, relationship between yield reductions and intake, recognising that this is probably a conservative assumption.

In conclusion, pollinator-related losses of foods and micronutrients have the potential to substantially increase the burden of disease from non-communicable disease and micronutrient deficiencies around the world. As a result of these findings, policy makers in countries at risk of pollinator declines might address this vulnerability by implementing management strategies to ease the burden. This year, the US Government has proposed to help pollinators through expansion of protected habitat for wild pollinators and increased study of environmental and anthropogenic stressors.[35] The European Union has instead focused on restricting use of pollinator-harming neonicotinoid pesticides and promoting national apiculture programmes. As more countries begin to monitor trends in wild and managed pollinators, a range of intervention strategies might become necessary. By knowing a country's vulnerability to pollinator declines, leaders can make better decisions about strategies needed to address these potential threats and optimise health outcomes.

Contributors
SSM and MRS designed the study. MRS analysed the data with assistance from SSM, GMS, and DM. All authors interpreted data and wrote the Article.

Declaration of interests
DM has received personal fees from Nutrition Impact, Amarin, AstraZeneca, Haas Avocado, Bunge, Life Sciences Research Organization, and Unilever North America outside of the submitted work. All other authors declare no competing interests.

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