Nutritional and environmental benefits of increasing insect consumption in Africa and Asia

Matthew R Smith, Valerie J Stull, Jonathan A Patz and Samuel S Myers

1 Department of Environmental Health, Harvard T.H. Chan School of Public Health, Boston, MA, United States of America
2 Global Health Institute, University of Wisconsin-Madison, Madison, WI, United States of America
3 Nelson Institute and Department of Population Health Sciences, University of Wisconsin-Madison, Madison, WI, United States of America
4 Harvard University Center for the Environment, Cambridge, MA, United States of America

* Author to whom any correspondence should be addressed.
E-mail: msmith@hsph.harvard.edu

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Abstract

Most global dietary forecasts predict a reduction in nutritional deficiencies over the next several decades driven by significant increases in environmentally unsustainable livestock and animal source food consumption. Here, we explore a more environmentally sensitive alternative to improve global nutrition, consuming insects. Our study focuses on Africa and Asia, two continents with a history of eating insects and high rates of nutritional deficiency. We model the impact of adding modest amounts (2.5, 5 and 10 g per day, dry weight) of regionally appropriate and farmable species on total nutrient intake and population-wide risk of deficiency for specific nutrients of concern: protein, zinc, folate, and vitamin B12. We also estimate the total potential change in dietary iron. Five grams per day of insect consumption could alleviate a considerable amount of risk of nutritional deficiency: 67 million (95% uncertainty interval: 49–84 million) fewer people at risk of protein deficiency, 166 million (120–220 million) fewer people at risk of zinc deficiency, 237 million (120–439 million) fewer people at risk of folate deficiency, and 251 million (28–2271) fewer people at risk for vitamin B12 deficiency. For iron, per capita supplies could increase by 3% (0.8%–6.0%) with insects, and even more so for vulnerable groups in countries currently suffering severe rates of anemia: 4.2% (0.5%–8.8%) for women of childbearing age and 4.1% (0.4%–10.0%) for children under 5. Doubling or halving insect intake per capita causes the benefits for nutritional deficiency risk to roughly double or halve accordingly. Effects are most pronounced in South and Central Asia, though sub-Saharan Africa, East Asia, and Southeast Asia also see considerable reduction in nutritional risk. These results demonstrate the potential for insects to fill a crucial role in providing nutrition for these populous and rapidly developing regions while safeguarding the global environment.

1. Introduction

Despite considerable progress over the last several decades [1, 2], global nutrient deficiencies, or so-called 'hidden hunger,' remain a stubbornly persistent threat to human health. In 2019, 1.7 billion people worldwide, including 40% of children under age 5, were estimated to be anemic, mainly due to insufficient dietary iron and disproportionately located in South Asia and sub-Saharan Africa [3]. Likewise, 17% of the world is assumed to be consuming inadequate dietary zinc [4] and 10% are consuming inadequate protein [5, 6], also focused in populations in sub-Saharan Africa and South Asia. For other nutrients of concern—folate and vitamin B12—there have not yet been assessments of global-level deficiency, but meta-analyses examining national-level deficiency patterns show similar concentrations among developing regions of South and Southeast Asia and sub-Saharan Africa, as well as...
in Central and South America for vitamin B12 deficiency [7, 8]. Deficiencies in vitamin A and iodine are also quite pervasive [9, 10]. Collectively, nutrient deficiencies directly cause a large global burden of disease, accounting for 2% of all life-years lost globally in 2019 [11].

Though we are currently unable to provide sufficiently nutritious food to large swaths of the world, global food demand is predicted to increase steeply over the next several decades, particularly in developing countries where rapid population growth and dietary changes may significantly affect the demand for different types of foods. In particular, rising incomes in developing countries are expected to drive even greater demand for animal source foods compared with staple foods; meat and dairy demand are projected to grow by 1.8% per year in developing countries between 2005/2007 and 2050, compared with 0.3%–0.4% per year for developed countries [12]. The regions expected to see the largest growth in demand for animal source foods are sub-Saharan Africa, South Asia, and Near East/North Africa [12].

While these trends may be beneficial for the nutritional adequacy of those currently undernourished, they would be devastating to the global environment if they are achieved by scaling up current approaches to producing animal source food. Currently the global food system accounts for 21%–37% of all greenhouse gas emissions [13], of which livestock production accounts for roughly half (14.5% of total emissions) [14], generating more emissions per kilocalorie than nearly any other food [15]. As meat consumption is predicted to increase, diet-related greenhouse gas emissions are projected to rise 50%–80% between 2010 and 2050 [16]. This trend runs counter to recent recommendations by the IPCC for 45% GHG reduction by 2030 with net zero by 2050 to avoid ‘dangerous’ climate disruption once global average temperatures exceed 1.5 °C above pre-industrial levels [17].

In addition to exacerbating climate change, animal source food production consumes vast amounts of natural resources, including the consumption of ~1/3 of agricultural water [15, 18], with beef production requiring 20 times more water per kilocalorie than staple crops like cereals or starchy roots [18]. Furthermore, livestock production requires an immense amount of land primarily for grazing and feed production—30% of the Earth's ice-free land surface [19]—and the conversion of forested or natural grassland to grazing pastures, along with the accompanying natural habitat loss, are the major drivers of alarming losses in global biodiversity [20, 21].

The environmental cost of meeting growing demand for animal-source protein through livestock production, therefore, would be large, and alternatives will be needed in order to protect the global environment. We explore one such alternative, the production and consumption of edible insects. The environmental advantages of insect cultivation are numerous and have been reviewed extensively [22–28]. Insects typically have a greater feed conversion efficiency compared with livestock [28] and, because feed rather than the rearing facility itself is the main contributor to the environmental footprint of industrial insect production, cultivating insects requires significantly less water [29], land [30], and energy than conventional livestock systems [24, 31–34]. Additionally, insects extract water from their food at a higher rate and can be reared in smaller spaces, lowering their resource needs even further [34]. Also, a greater percentage of an insect is edible compared with livestock—80% versus 55% for pigs and poultry, and 40% for cattle—which increases their edible yield per unit of resources required [28]. Finally, several lifecycle analyses have shown that insect production also tends to generate fewer greenhouse gases compared with livestock systems [29, 31–33], ranging from ~45% fewer CO2-equivalents for mealworms [31] or crickets [32] compared with chicken production, up to 88% fewer CO2-equivalents for mealworm production compared with beef [33]. These comparisons become even more favorable if we assume that we can feed some insects non-conventional feedstocks, such as otherwise unused crop residues or food waste [23]. The reduced footprint of insect versus livestock production with respect to land and water requirements, along with GHG emissions would yield large benefits with respect to some of our most pressing global environmental challenges: climate change, biodiversity loss, and resource scarcity. Although beyond the scope of this paper, insects also present opportunities to improve the efficiency of poultry, livestock, and aquaculture systems when used as feed in circular or closed loop rearing models.

Edible insects are capable of supplying high-quality nutrition while moderating the environmental harm compared to traditional livestock rearing. In this study, we will explore the potential of modest insect consumption by humans to improve nutrition in regions with high prevalence of deficiencies for key nutrients of global concern, while alleviating the potential environmental harm inflicted by increased industrial livestock rearing practices.

1.1. Insect consumption
Although rarely considered in Western cuisine, edible insects are common ingredients in traditional dishes across cultures. Entomophagy—the practice of eating insects—is a global phenomenon, and numerous species have served important roles in the human diet throughout history [35, 36]. More than 2100 known edible insects have been identified to date [37] with beetles (Coleoptera) making up the most widely consumed order in terms of number of species eaten [37]. Across the African continent, at least 500 species
are consumed [38]. Insects are frequently consumed whole (raw, cooked, or dried in a variety of ways) and in other contexts they are ground into powders or flours and integrated into other foods. Insects are a versatile ingredient, and simple processing allows them to be integrated into other foods including baked goods, pastas, complementary cereals for children, snacks, and sauces, to name a few.

The vast majority (~92%) of insects eaten today are harvested from the wild [23, 38, 39], serving in many cases as a valuable free and nutritious food resource. Many species are only available seasonally, however, limiting their impact on year-round food security [40]. Given growing food demand and rising prices, the future of large-scale wild-collection is tenuous; insect overexploitation and some habitat destruction have already been observed [41–43]. Not surprisingly, recent efforts to farm insects at various scales have emerged, building off our longstanding success with sericulture (silk production) [44] and apiculture (beekeeping) [45]. Contemporary insect farming offers an avenue to boost access to and consumption of insects globally [32, 46]. Insect agriculture could also yield added-value products from the component parts of processed insects (e.g. oils, fibers, proteins, fertilizer from frass) and has the potential to generate household income while improving nutrition [34].

In Thailand, around 20,000 independent cricket farmers generate the majority of the household income from rearing edible crickets. Women are successfully farming mealworms for food at the household level in Guatemala thanks to training from the Mealflour project [47], and other small-scale insect farming projects have recently emerged in Zambia, the Democratic Republic of Congo, Ghana, Kenya, Madagascar, and elsewhere. The commercial insect company Aspire Food Group is automating edible cricket production in the US, and Ynsect in France acquired more than $372 million in Series C investments to produce mealworms for feed in 2020. Although thousands of edible species have been identified [37], cultivation for food has not been attempted for the vast majority. Reasons for this are multifaceted, likely stemming in part from Western bias against insects as food [48] (which has limited research and industry investment), the prevalence of important and forageable insects in geographic contexts where they are traditionally consumed [49] and a historical emphasis on pest management over edible insect growth optimization in the field of entomology. There is ample room for further investigation to identify reparable species with favorable properties for health and the environment.

1.2. Nutritional value of insects

It is very difficult to generalize the nutrient content of insects across species and growth conditions. Nutrient content can even vary within species throughout the lifespan, and subtle changes to an insect’s diet can significantly shift its macro- and micronutrient composition. In broad terms, insects have nutrient profiles akin to meat—high in protein and fat, with minimal carbohydrates. Perhaps most well-known for their high protein content, insects offer crude levels comparable to and in some cases higher than conventional animal foods [50–52]. Crickets, grasshoppers, and locusts, for example, often have protein values averaging around 60% but sometimes reaching closer to 80% on a dry weight basis [39, 53]. Insect proteins are generally considered to be of good quality—bioavailable and relatively digestible [50, 54, 55]. Many contain essential amino acids for human nutrition, with some species providing all nine [39, 56, 57]. Insect-sourced essential amino acids may be particularly valuable in contexts where malnutrition remains problematic. Fortuitously, insects frequently contain complementary essential amino acids that are deficient in staple-based diets composed primarily of cereals (ex. maize), tubers, or legumes [40, 58, 59]. In some regions, insects are a cheaper protein source than meat [40, 60], and wider adoption of large-scale farming could drive prices down further.

Insects are also often a reliable source of micronutrients, including minerals and some vitamins. Specifically, they represent an animal source of iron and zinc, which are both crucial for human growth and development [39, 51, 61, 62], as well as potassium, calcium, copper, magnesium, manganese, phosphorus, and selenium. Some insects outperform conventional meats in their content of these micronutrients [51, 63, 64]. Entomophagy is sometimes touted as one means to increase consumption of dietary iron [64], which is particularly relevant to the large numbers of children and women of child-bearing age at high risk of iron deficiency. In terms of vitamin content, insects tend to contain high levels of B vitamins, such as niacin, folate, biotin, riboflavin, pantothenic acid, pyridoxine, and vitamin B12 [39, 61, 65]. Insects, therefore, represent a potentially powerful and regionally adaptable source of nutrition to help ameliorate food insecurity.

The impressive nutritional profile of insects, paired with their manifold environmental benefits, present an opportunity to help solve the challenge of meeting our global nutrient needs in a more environmentally advantageous way. Here we model the impact of consuming low (2.5 g d−1), medium (5 g) and high (10 g) amounts of regionally appropriate insects on total nutrient intake and the risk of nutritional deficiencies. We focus specifically on regions currently suffering from high rates of deficiency across Africa and Asia. To increase the relevance of the study, we look specifically at nutrients that are crucial for global health and where insect consumption could make a meaningful difference: protein, zinc, folate, vitamin B12, and iron.
2.Methods

2.1.Consumable insects by region

We focus on four United Nations (UN) Sustainable Development Goal (SDG) regions where nutritional deficiencies are prevalent and insect consumption is relatively common, suggesting a greater likelihood of acceptance (figure 1): sub-Saharan Africa, Northern Africa & Western Asia, Central & South Asia, East & Southeast Asia. For each region, we identified 3–6 insect species with available, reliable nutrient data that are currently farmed, semi-cultivated, or have a realistic potential to be cultivated or semi-cultivated in the near future (table 1). It should be noted that extensive nutrient composition data have been published, but these data are of inconstant quality, use variable methodologies, and capture only a handful of the thousands of known edible species. Here, we chose insect species that have cultural and culinary relevance as human food in the regions where they are listed. To reach the scale of population-level consumption modeled in this study, insects need to be produced in bulk continuously, not just wild-harvested when seasonally available. In one case, a pest species (Lepidiota mansueta; a scarab beetle) that is not farmed was included due to its prevalence in the environment, dietary significance, and potential to be collected in bulk while simultaneously protecting crops. We aimed to include as wide an array of edible insects as possible, combining potentially farmable species with available data from various orders to represent the existing diversity in consumption trends.

2.2. Nutritional value of insect species

To estimate the impact of insect consumption on nutrition, we collected and aggregated nutrient data from numerous published sources for the insect species listed in table 1. Data sources were carefully vetted, including only original analyses and excluding meta-analyses that reported an aggregate value or range of values from unverifiable sources. For two analyses of the nutritional content of Bombyx mori [66], the protein density values were less than half of even the lowest of the other 18 protein values collected from 14 different sources, so we deemed these to be extreme outliers and none of the nutrient composition information from that reference was included.

In particular, we searched for five nutrients of global health importance for which insects are often a good source: protein, iron, zinc, folate, and vitamin B12. In addition, we also collected data on phytate content to enable an estimation of zinc bioavailability due to phytate’s role in inhibiting zinc absorption [67]. Two other nutrients of concern for global health—vitamin A and iodine—were not included in this study because insects do not tend to be good sources of vitamin A [39], and very little is known of the iodine content of insects or other foods due to insufficient nutrient density data. However, the little
| UN SDG region       | Species                        | Common name                      | Current status                                                                                     |
|---------------------|--------------------------------|----------------------------------|--------------------------------------------------------------------------------------------------|
| Sub-Saharan Africa  | *Rhynchophorus phoenicis*      | African Palm Weevil              | Eaten across sub-Saharan Africa [37]. Currently farmed and semi-cultivated by several small-scale projects in Ghana, DRC, and elsewhere (ex. [https://farmsfororphans.org/](https://farmsfororphans.org/), [https://aspirefg.com/](https://aspirefg.com/)). |
|                     | *Ruspolia differens*           | Green Cone-Headed Cricket        | Consumption reported across sub-Saharan Africa [37]. Current attempts to develop methods to mass-rear this species in process ([68], [www.unipid.fi/infobank/project/244/](http://www.unipid.fi/infobank/project/244/)). Also, mass harvested from the wild currently. |
|                     | *Gonimbrasia belina*           | Mopane Worm                      | Commercially traded food insect across central and southern Africa. Predominately wild-harvested but efforts to semi-cultivate and manage forest habitats have begun [69, 70]. |
|                     | *Locusta migratoria*           | Migratory Locust                 | Widespread consumption across African continent [37]. Commercially produced by Hargol Food Tech in Israel ([https://hargol.com/](https://hargol.com/)), long history of being reared in laboratories. Can also be wild-harvested at scale during pest infestations. |
|                     | *Gryllus bimaculatus*          | Two-Spotted Cricket/African Field Cricket | Widely farmed globally. Consumed by some populations across sub-Saharan Africa [37]. Eaten and farmed in Zambia ([71]; [nutripeopleproject.org](http://nutripeopleproject.org)). Reared in laboratories under various conditions [72]. |
|                     | *Cirina forda*                 | Emperor Shea Moth                | Consumed across sub-Saharan Africa [37]. Included in national food composition database for Nigeria and researched [73]. Plausible to raise on *Vittelaria paradoxa* tree leaves [74]. Not much evidence that it is currently farmed, but semi-cultivation as ancillary harvest from shea likely possible. |
| East and Southeast Asia | *Bombyx mori*                 | Domesticated Silkworm            | Extensive history of human cultivation and use for silk and food. Native to China, but now fully domesticated in many contexts. Consumed and farmed widely. For example: Japan [75] and Thailand [46]. Pupa often consumed, and insects sometimes used for medicinal purposes. |
|                     | *Tenebrio molitor*             | Yellow Mealworm                  | Farmed and consumed in China, Laos, and elsewhere [37]. Commercially produced by numerous large-scale insectaries across the globe including in China, North America, and Europe. One of the most widely produced edible insects to-date. |
|                     | *Rhynchophorus ferrugineus*    | Asian Palm Weevil/Sago Larvae    | Farmed and consumed in Thailand [46]. Consumed across Malaysia, Vietnam, Borneo and elsewhere. Farming may depend on natural availability of specific trees (ex. lan phrue and sago palm). |

(Continued.)
| UN SDG region | Species                     | Common name                                      | Current status                                                                                                                                 |
|---------------|-----------------------------|--------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|
| Central and South Asia | **Gryllus bimaculatus** | Two-Spotted Cricket/African Field Cricket         | Widely farmed across the globe. Farmed in Thailand [46]. Reared in laboratories under various conditions [72].                               |
|                | **Acheta domesticus**      | House cricket                                    | Widely farmed across the globe for human food and animal feed. Farmed in Thailand for food and sales [46].                                     |
|                | **Samia ricini**           | Eri Silkworm                                      | Currently farmed in India for silk and human food [76]. Also farmed, though not widely consumed, in Nepal [77].                              |
|                | **Oecophylla smaragdina**  | Weaver Ant                                       | Consumed in India [78] with other reports of consumption across Thailand, Myanmar, China [79, 80], and Australia [81]. Potential for semi-domestication established [82]. |
|                | **Lepidiota mansueta**     | Scarab Beetle                                     | Predominately collected/wild harvested and consumed in northeastern Indian states when insect infests crop fields [83]. Offers good nutrient value [84]. No evidence of farming to-date, but collection could improve food security by supplying edible insects and preserving crop yields. |
| North Africa and Western Asia | **Schistocerca gregaria** | Desert Locust                                    | Consumed in North Africa and Morocco [81]. Laboratory rearing and other farming efforts underway, but not yet optimized [85, 86].          |
|                | **Locusta migratoria**     | Migratory Locust                                 | Widespread consumption across African continent [37]. Commercially produced by Hargol Food Tech in Israel ([https://hargol.com/](https://hargol.com/)), reared in laboratories. Can be wild-harvested at scale during pest infestations. |
|                | **Gryllus bimaculatus**    | Two-Spotted Cricket/African Field Cricket         | Consumed in South Sudan [87, 88]. Widely farmed across the globe. Farmed in Thailand [46]. Farmed in Zambia ([nutripeopleproject.org](https://nutripeopleproject.org)). Reared in laboratories under various conditions [132]. |
data that exist suggest that insects are poor sources of iodine [89].

Insect nutrient data were generally reported as either dry weight or as-is/fresh weight, and in our analyses the latter were converted to dry weight using the moisture content when supplied. If no moisture content was reported, those values were omitted from analysis. The full list of insects, nutrient densities, and their published sources is found in supplemental table S1 (available online at stacks.iop.org/ERL/16/065001/mmedia).

2.3. Nutritional intakes and possible additional contributions from insects

We then compared the nutritional contribution from various amounts of insect consumption against the baseline supply of each nutrient from the rest of the diet. To estimate the baseline dietary nutrition for all nutrients except vitamin B12, we used the Global Expanded Nutrient Supply (GENuS) dataset [90]. GENuS estimates nutrient supplies for 34 age–sex groups in each country, and is described in more detail in the Supplementary Methods. For vitamin B12, GENuS data is not available, so vitamin B12 contents from the United States Department of Agriculture food composition table [91] were matched to GENuS food supply estimates [92] to estimate vitamin B12 supplies by age and sex.

We used three amounts of human insect consumption to represent the range of feasible national-average values (in dry weight): 2.5, 5 and 10 g per person per day. Five grams per day was chosen as our baseline value. To account for insect intakes varying among demographic groups in each country, we apportioned the national average values among each age–sex group based on the ratio of their individual caloric supply relative to the national-average caloric supply from GENuS [90].

Next, we multiplied insect intakes for each age–sex group by their nutrient densities to estimate their nutritional contribution. Protein supplies were also converted to digestible protein to account for their varying availability by food source, and zinc was converted to absorbable zinc because of the interactions of dietary phytate on zinc bioavailability. Data sources and justifications for assumptions are included in the supplementary methods.

We used Monte Carlo simulations to estimate the range of possible nutrient contributions by iteratively selecting a single randomly chosen insect (N = 1000) from among the possible candidate insects in each region from supplemental table S1. Estimates of the nutrients provided by all other foods in GENuS were calculated using a similar randomized method, choosing from among the candidate foods on each of a thousand iterations, so the 1000 individual insect estimates were added to the baseline model runs from GENuS data to determine medians and uncertainty intervals.

2.4. Inter-individual distributions of nutrient intake

Next, we estimated the inter-individual distribution of intakes in each age–sex group and country. To do so, we derived the distribution shape parameters for each nutrient as follows.

Distributions of protein intake were estimated as in Medek et al [5] which found that the shape of the distribution of protein intakes was generally lognormal with its dimensions determined according to the following equations:

\[ \mu = \ln(x) - \frac{\sigma^2}{2} \]

\[ \sigma = \sqrt{\ln \left(1 + CV^2\right)} \]

where \( \mu \) is the mean of the distribution, \( \sigma \) is the standard deviation, \( x \) is the average protein intake for each age–sex group, and CV is the coefficient of variation for each country. Furthermore, the CV for each country was shown to be correlated with its Gini index of income inequality using the relationship derived in [5]. We adopted the same approach here, and our input Gini indices were collected from the World Bank (2009–2013 average) [93] and supplemented with data from Milanovic [94] where World Bank data did not exist.

For absorbable zinc and folate, intakes are assumed to be distributed normally with means equal to the average nutrient supply in each age–sex–country group and coefficients of variation—25% and 30%—established as in previous studies [1, 4, 6, 95, 96].

For vitamin B12, average values were estimated as described above, but existing estimates of the CV of population-level distributions did not exist. Therefore, we undertook a new literature search to quantify it. Within-individual intake distributions for vitamin B12 are commonly quite large, so we took special care to only include studies that had sufficient duration and sample size to control for and remove the effect of within-person intake variance. The resulting median coefficient of variation for between-individual B12 intakes was 55% (supplemental table S3). Because this CV is large, we assumed the shape of the distribution of B12 intakes was lognormal, concordant with previous studies [96, 97].

2.5. Human nutritional requirements

To assess how adding insects in the diet might improve nutritional adequacy, we also estimated the human nutritional requirements in each age–sex group and country to compare with nutrient supplies before and after adding insects. Methods for estimating physiologic requirements varied by nutrient, but are explained in full in the supplemental materials.

2.6. Risks of nutritional deficiencies

To calculate the baseline percentage of the population at risk of nutritional deficiency, as well as its...
change when insects are added to the diet, we used the nutrient intake distributions and EARs as inputs into the EAR cut-point method [98]. Paired nutritional intake distributions with and without insects for each of the 1000 model iterations were used to calculate the median and 95% uncertainty intervals for baseline and change in the prevalence of those at risk of nutrient deficiency. These were then multiplied by the 2020 population of each age–sex group using data from the UN World Population Prospects [99], the most recent year with sufficiently detailed data, to calculate the size of the current population that would be removed from risk of deficiency after the addition of insects.

3. Results

Globally, we find that the addition of our medium value of 5 g of insects per person per day to the diet would lower those at risk of protein deficiency across our study regions by 1.2% (95% UI: 0.9%–1.5%), equal to 67 (49–84) million people in 2020 (table 2). For zinc, the reduction in the population at risk of deficiency would be 3.0% (2.1%–4.0%), corresponding to 166 (120–220) million people. For folate, 4.3% (2.2%–8.0%), or 237 (120–439) million people, would be removed from deficiency risk, and for vitamin B12 the values are 4.4% (0.5%–41.3%) reduction or 251 (28–2271) million people.

Our sensitivity tests, which estimate the impact of halving (2.5 g day$^{-1}$) or doubling (10 g day$^{-1}$) insect intake, show that the corresponding effects for risk of nutrient deficiency would scale roughly linearly (table 3). Taking zinc as an example, 3 g per day of insect intake would reduce those at risk of deficiency by a median value of 3.0%, while 2.5 g per day would reduce those at risk by 1.6% and 10 g per day would reduce the risk by 5.3%.

When looking at the regional level, we see that the benefit to deficiency risk prevalence of adding 5 g of insect consumption per day to the diet would be significant across most of Asia and sub-Saharan Africa, with a lesser effect in North Africa and Western Asia (table 4). In Central and South Asia, we see that multiple factors—very high baseline levels of risk, significant contributions from farmable insects, and a large population—combine to produce the largest effect sizes among all regions and nutrients, both in percentage and absolute measures of deficiency risk. In contrast, North Africa and Western Asia show somewhat low baseline risks of deficiency and somewhat lesser nutritional value from added insects, leading to the lowest impact from added insects among regions across all measures. Both North Africa and Western Asia have a relatively high intake of meat and dairy products, reducing the baseline risk of insufficient nutrient intake and limiting the benefit of greater insect consumption.

Sub-Saharan Africa, as well as East and South-east Asia, both show large populations removed from deficiency risk from modest additions of insect consumption, ranging from 13 to 74 million people depending on the nutrient. However, sub-Saharan Africa has a larger percentage decrease (1.6%–3.9%) compared with East and Southeast Asia (0.6%–3.5%) across all nutrients except folate, though with large uncertainty intervals. Consumption of animal source food is low in sub-Saharan Africa, with a stronger reliance on starchy staple foods—wheat, maize, cassava—which increases the baseline risk of nutrient deficiency and allows for larger benefits from additional insect nutrition. In East and Southeast Asia, baseline nutritional deficiency risk is lower due to diets higher in meat and fish, making the percentage benefit smaller, though the absolute number of people removed from deficiency remains high due to the region's very large population. On average, we find that the average nutritional contribution from insects is similar across regions, despite the diversity in farmable species. Expanded versions of table 2 for each individual region are available in supplemental tables S4–7.

An example of a country that could be significantly helped by adding insects to the diet is Madagascar, a low-income country of 24 million people with a heavy reliance on dietary staples; nearly 80% of calories are derived from cereals and starchy roots, predominantly rice and cassava [100]. Depending on the measure, the nutritional status in Madagascar is also stagnating or declining, with the number of people undernourished and anemic on the rise contrary to the trend across sub-Saharan Africa [2]. Because of these impoverished diets, we estimate that baseline rates of nutritional deficiency risk are among the highest in the world: risk of protein deficiency is 33% (29%–38%), 31% (29%–32%) for zinc, 59% (37%–65%) for folate, and 48% (16%–91%) for vitamin B12. We estimate that adding 5 g per person per day of insects at a national level would make a considerable difference to alleviating those at risk of deficiency, lowering risk of protein deficiency by 3.2% (0.7%–4.3%) or 910,000 people (202,000–1.9 million), risk of zinc deficiency by 5.5% (3.9%–7.4%) or 1.5 million people (1.1–2.1 million), risk of folate deficiency by 6.8% (2.9%–17.5%) or 1.9 million people (0.8–4.8 million), and risk of B12 deficiency by 4.8% (0.6%–80.8%) or 1.3 million people (0.2–22.4 million). This illustrates the potential for countries to make a considerable difference to their nutritional status through insect production and consumption.

For iron, we find that insects could provide an additional 0.5 g (0–3.2 g) per person per day, equivalent to an additional 3% (0.8%–6.0%) of dietary iron compared with baseline supply. However, this effect is even more pronounced in age–sex groups that are most vulnerable to the health effects of insufficient iron, and in countries that are already suffering from
### Table 2. Summary results across all regions: nutrient intakes and risk of deficiency before and after adding nutrients.

| Nutrient         | Unit | Average per capita daily supply | Estimated average requirement (EAR) | Current rate of risk of deficiency (%) | Amount supplied by 5 g of insects | Absolute change in risk of deficiency with 5 g insects (%) | 2020 population removed from risk of deficiency with 5 g insects (millions) |
|------------------|------|---------------------------------|-------------------------------------|----------------------------------------|----------------------------------|----------------------------------------------------------|--------------------------------------------------------------------------|
| Protein          | g    | 62.2 (60.7–64.6)                | 28.0                                | 10.8 (9.7–11.7)                        | 2.6 (1–3.8)                       | −1.2 (−1.5–−0.9)                                         | 67 (49–84)                                                               |
| Zinc (absorbable)| mg   | 2.64 (2.60–2.70)                | 1.96                                | 24.2 (22.9–25.3)                       | 0.1 (0.07–0.13)                   | −3.0 (−4.0–−2.1)                                         | 166 (120–220)                                                           |
| Folate           | mcg  | 374 (347–461)                   | 2.95                                | 35.3 (31.2–39.9)                       | 18 (9–45)                         | −4.3 (−8.0–−2.2)                                         | 237 (120–439)                                                           |
| Vitamin B12      | mcg  | 2.90 (2.16–3.69)                | 1.82                                | 45.2 (37.0–55.2)                       | 0.14 (0–3.51)                     | −4.4 (−41.3–−0.5)                                        | 251 (28–2271)                                                          |
| Iron             | mg   | 24.4 (21.4–32.1)                | a                                   | a                                      | 0.48 (0.01–3.2)                   | a                                                        | a                                                                       |

*Due to weak link between dietary iron intake and deficiency, we are only capable of estimating the amount of additional iron supplied by the diet.*
| Nutrient                  | Per capita daily insect intake: 5 g | 2.5 g | 10 g |
|--------------------------|------------------------------------|-------|------|
|                          | Absolute change in risk of deficiency with insects (%) | 2020 population removed from risk of deficiency with insects (millions) | Absolute change in risk of deficiency with insects (%) | 2020 population removed from risk of deficiency with insects (millions) | Absolute change in risk of deficiency with insects (%) | 2020 population removed from risk of deficiency with insects (millions) |
| Protein                  | −1.2 (−1.5−−0.9)                  | 67 (49–84) | −0.6 (−0.8−−0.5) | 34 (25–44) | −2.3 (−2.8−−1.7) | 124 (91–154) |
| Zinc (absorbable)        | −3.0 (−4.0−−2.1)                  | 166 (120–220) | −1.6 (−2.1−−1.1) | 87 (62–115) | −5.3 (−6.7−−3.9) | 292 (216–375) |
| Folate                   | −4.3 (−8.0−−2.2)                  | 237 (120–439) | −2.2 (−4.2−−1.1) | 121 (60–231) | −8.3 (−14.3−−4.3) | 453 (234–786) |
| Vitamin B12              | −4.4 (−41.3−−0.5)                 | 251 (28–2271) | −2.6 (−31.2−−0.2) | 143 (14–1694) | −6.9 (−45.6−−1.0) | 378 (55–2496) |
Table 4. Changes in risks of deficiency with 5 g of insects, by individual region.

| Nutrient       | Sub-Saharan Africa | Central and South Asia | East and Southeast Asia | North Africa and Western Asia |
|----------------|--------------------|------------------------|-------------------------|-------------------------------|
|                | Current rate of risk of deficiency (%) | Absolute change in risk of deficiency with 5 g insects (%) | 2020 population removed from risk of deficiency with 5 g insects (millions) | Current rate of risk of deficiency (%) | Absolute change in risk of deficiency with 5 g insects (%) | 2020 population removed from risk of deficiency with 5 g insects (millions) | Current rate of risk of deficiency (%) | Absolute change in risk of deficiency with 5 g insects (%) | 2020 population removed from risk of deficiency with 5 g insects (millions) | Current rate of risk of deficiency (%) | Absolute change in risk of deficiency with 5 g insects (%) | 2020 population removed from risk of deficiency with 5 g insects (millions) |
| Protein        | 17.5 (16.5–18.5)  | −1.6 (−2.1—−0.4)       | 15 (3–19)               | 9.3 (8.1–10.6)                | −1.4 (−2.0—−0.9)              | 28 (18–40)                     | 10.8 (8.7–12.2)               | −1.1 (−1.5—−0.5)              | 23 (10–31)                     | 4.6 (4.1–5.2)                | −0.6 (−0.8—−0.3)              | 2 (1–3)                       |
| Zinc (absorbable) | 27.2 (26.2–28.0) | −3.6 (−4.9—−2.6)       | 33 (23–44)              | 27.9 (26.4–29.1)              | −3.3 (−4.5—−2.4)              | 67 (48–90)                    | 19.3 (17.7–21.1)              | −2.5 (−3.3—−1.8)              | 54 (39–71)                    | 25.1 (24.3–25.9)             | −2.4 (−3.2—−1.7)              | 10 (7–14)                     |
| Folate         | 25.8 (18.8–30.7)  | −3.0 (−7.9—−1.4)       | 27 (12–70)              | 48.6 (43.1–54.3)              | −5.9 (−13.6—−2.9)             | 118 (58–269)                  | 29.9 (22.2–38.9)              | −3.5 (−6.5—−1.3)              | 74 (27–138)                   | 22.9 (20.4–25.4)             | −3.1 (−6.8—−1.5)              | 13 (7–30)                     |
| Vitamin B12    | 45.2 (24.4–76.1)  | −3.9 (−58.2—−0.8)      | 35 (7–52.3)             | 76.6 (66.5–84.3)              | −4.4 (−74.8—0)                | 85 (0–1461)                   | 17.4 (5.2–37.7)               | −0.6 (−23—0)                  | 13 (0–492)                    | 36.1 (16.9–60.6)             | −2.4 (−46.9–0)                | 10 (0–203)                    |


high rates of anemia. For countries whose prevalence of anemia is classified as severe (>40%) as determined by the WHO [2, 101], we find that women of childbearing age would see their iron supplies increase by 4.2% (0.5%–8.8%) with 5 g of insects per person per day, and by 4.1% (0.4%–10.0%) for children under 5. Though we are unable to quantify the health benefit this additional iron could provide, increasing iron supplies by >4% would undoubtedly alleviate the prevalence of anemia among the nearly 800 million women and children living in these severe-risk countries.

This analysis suggests that consistent insect consumption could play a significant role in reducing nutrient deficiencies in lower income countries and identifies certain regions where this approach would be particularly effective based on regionally appropriate insect species.

4. Discussion

These results show that even adding minor amounts of insects—as little as 2.5 g—to the diet has the potential to alleviate a considerable amount of nutritional deficiency for many important nutrients across much of Africa and Asia. Furthermore, based on the data available we find that there are similar average insect nutrient densities across regions (supplementary tables S4–7), despite the diversity of species modeled. Notably, several insect species that are very popular and commonly consumed, but less studied or less likely to be farmed, could not be included in our model. However, these nutritional averages cloak large within-species and between-species variability, suggesting there is considerable opportunity to optimize the nutritional profile of cultivated insects through the selection of more nutritious species or growth stages, or in identifying and adopting sophisticated rearing practices to boost their nutritional profile, such as improved feeding. However, large research gaps remain in linking these practices with greater nutrition quality [102, 103]. On the other hand, due to our inability to fully assess the quality of these many studies, this high nutritional variability could simply reflect methodological error in laboratory analyses, and more research and methodological rigor may be needed.

One question raised by this study is whether the per capita insect consumption amounts studied here represent reasonable targets. This remains unresolved for two reasons. First, adequate or even average serving sizes for insects are not well established. Second, the capability of insect farming to expand to provide sufficient insects at the population-wide scale imagined in this study has yet to be quantified. For serving sizes, we used three values to measure the impact of eating insects on nutrition: 2.5, 5, and 10 g of dried insects. Very little has been published about common serving sizes for traditionally consumed edible insects [104]. Insects are often consumed as side dishes, as a protein accompanying a carbohydrate-rich staple (e.g. maize, sorghum, rice), or incorporated as ingredients into main dishes (soups, sauces). They are also commonly eaten as a complementary food for infants to increase the nutritional value of porridges [105]. Rarely do they make up an entire meal. Insects are frequently eaten as snacks in-between meals [40, 88, 106]; however, consumption patterns undoubtedly vary by species, availability, and cuisine. Newly established North American and European companies selling insects as food have specified serving sizes. EXO, for example, suggests a serving size of 10 g for their dry cricket flour [107]. Entomo Farms recommends 20 g as a serving size of cricket protein powder or 20 g (1/3 cup) of dry roasted whole crickets [108]. Powdered or processed insects can be easily integrated as ingredients in other foods.

We estimated serving sizes based on utilizing insects as a snack or side dish. We used dry weight to match how the majority of papers report nutrient values for insects. The moisture content of insects varies across species. Finke [109] reported moisture levels between roughly 58% and 83% for several common edible insects (e.g. 62% for Tenebrio molitor larvae, 69% for Acheta domesticus crickets). As such, for a large cricket (such as Gryllus bimaculatus) with approximately 70% moisture, 5 g of dry crickets (weighing about 225 mg each) would total close to 22 crickets. This is a reasonable serving size for a side dish or snack (about an adult handful). Moreover, ground insect products could be integrated into porridges, sauces, or baked goods in even larger quantities.

As to whether commercial insect production can meet the demand based on widespread consumption of a few grams per person each day, there remains very little research into the ability of the industry to produce such large quantities. As a rough calculation, if the 5 billion people living in our study regions consumed 5 g per day, 25 000 tonnes of insects per day (dry weight) would be required to meet demand. That amount is generally equivalent to total regional production by weight of lemons and limes combined, or of pineapples. Because the capacity of the insect industry to produce that amount hinges largely on dedicated investment, it is quite difficult to say whether this value is feasible. Nevertheless, we can look to other large-scale production regions as benchmarks for our modeled future production goals. Thailand, for instance, currently produces roughly 2000 tonnes of crickets per year in dry weight equivalent [46], which, if extrapolated to the entire population of our study region, would equate to roughly 400 tonnes per day of cricket production, still short of our necessary production, but a substantial quantity. Meanwhile, the International Platform of Insects for Food and Feed, the organization representing the
European Union’s edible insect industry, is targeting a total production of 5 million tonnes of fresh-weight insects per year by 2030, about 14,000 tonnes per day [109] or 2000–6000 tonnes per day in dry weight equivalent, depending on moisture content. With these values as a reference, it seems possible that insects are capable of being produced at the order of magnitude prescribed by our study, but not without considerable economic investment and regulatory reorientation that will be required to achieve these levels at such a broad scale. Presumably, local or at-home insect rearing could also provide this necessary supply, but because there is no equivalent yet for year-round steady continental-scale local production of any food, this path would be mainly theoretical.

Though data remains sparse and mainly focused on individual production systems, the existing comparisons find that insect rearing is more environmentally friendly than conventional livestock systems. Using an example of a Dutch mealworm facility [33], beef requires 8–14 times more land, uses 5 times as much water, and emits 6–13 times as much greenhouse gases compared to mealworms for an equivalent amount of edible protein, while requiring equivalent or slightly more fossil-fuel energy than mealworms. Another study comparing cricket and broiler chicken production in Thailand found that crickets impart fewer environmental harms on an equivalent protein basis, including 24% less freshwater depletion and 55% fewer greenhouse gas emissions, among many other measures [32]. Despite these likely benefits of current insect production techniques, the environmental impact of scaling up production by the magnitude required to supply all of Africa and Asia remains unclear, but continues to appear promising. Because the industrial insect rearing production sector is still in its infancy, there is considerable unrealized potential to increase the environmental efficiency of production over current methods. For example, many industrial insect production facilities feed insects high-quality corn or soy-based meals [31, 32], which are land-, water-, and energy-intensive to produce. Meanwhile, there is great potential to rear insects on alternative underused or unused organic substrates, such as agricultural byproducts, food waste, and even manure [40], thus ‘valorizing’ otherwise unused waste products [22, 28]. Producers will need to carefully calibrate costs and benefits across feed substrates, as feed quality will impact the feed conversion efficiency and growth performance of the insects as well [110]. This same optimization can extend to other rearing practices such as housing, water delivery, and geographic location of production, which remain largely understudied or proprietary [25, 111]. Furthermore, the number of commercially produced insect species represents a tiny fraction of the total number of consumed insects worldwide [112], and greater opportunities for efficiency may be found in identifying species with properties that are more innately suitable for industrial-scale production [59].

In interpreting our results on nutrition, it is important to bear in mind that a full accounting of the quality and bioavailability of insect nutrients is not yet well established. This may also point to a fruitful direction for future research. For protein, it is unlikely that insects—when consumed whole—are superior to other animal-based proteins, but they may be superior to plant-based proteins. In a study of insect protein supplementation among healthy adult men, researchers determined that postprandial amino acid availability from insect protein isolate was comparable to soy, a high-quality plant protein, but inferior to whey [113]. A previous study demonstrated that insect protein may be less soluble than other animal proteins, such as casein [114] when given to athletes. It is also thought the high content of chitin could modulate protein digestibility [115]. Processing insects to remove chitin and isolate protein may improve digestibility. Other studies examining insect protein digestibility have revealed relatively high levels (76%–96%) with variation across species and processing methods [116, 117]. Compared with soy protein, some insects have demonstrated equivalent or superior quality [118, 119].

For iron, existing data suggests similar uncertainty regarding insect nutrient quality; for the other micronutrients, there have been few studies on their bioavailability to date. While insects contain similar or higher levels of iron than other animal-based foods [64], insect iron retains a unique set of characteristics from other vertebrates [120] making it difficult to judge whether contributions from insects could make an outsized impact in reducing iron deficiency. Insects contain little heme iron [121], which is the form found in flesh meats and most easily absorbable by humans. Presumably this would imply that the potency of insect iron is low. Yet the non-heme iron in insects would seem to be more bioavailable than plant-based non-heme iron. An in vitro study by Latunde-Dada et al [122] assessed iron bioavailability of four common edible insect species—cricket, grasshopper, mealworm and buffalo worm—compared with sirloin beef and whole wheat flour, and found it to be highly variable, ranging from slightly higher than wheat flour (crickets) to modestly higher than beef (buffalo worms). In malnourished rats, consuming both crickets and palm weevil larvae led to an increase in hemoglobin relative to the control, suggesting high bioavailability [123]. Moreover, infants that consumed caterpillar enriched cereal for 12 months had higher iron concentrations and lower rates of anemia than those that did not in a controlled feeding trial [124]. These limited early results suggest that insect iron may vary significantly by species, with bioavailability likely falling somewhere between plant- and animal-based sources on average.
In addition to the nutrients studied here, insects may also confer other nutritional and health impacts, both positive and negative: the presence of prebiotic dietary fibres [125–127] and bioactive compounds [128], factors affecting food safety and nutrient bioavailability [39], innate and adaptive immune responses to insects [129], or even anticancer, antiviral, or antifungal properties [130]. More research is warranted to better understand the nutrient content and health impacts of insect consumption, particularly human studies.

The results of these analyses are also predicated on the assumption that populations will readily adopt regular insect consumption, even at relatively small levels. Insect eating is common in many countries included in this study; however, large percentages of these target populations do not currently participate. Entomophagy is certainly influenced by experience and exposure, personal preference, consumer knowledge, availability, religious and traditional beliefs, as well as cultural practices [106, 131–135]. However, little is known regarding best practices for promoting widespread adoption; some sensorial-, educational-, and design-focused strategies have been proposed [136, 137]. Fortunately, food culture is not static [138], and early food preferences can change with time given repeated exposure and nuanced learning [139]. Given that all eating requires a series of decisions strongly influenced by complex sociocultural relationships [140], there are opportunities to intervene, combat food neophobia, and promote new behaviours, be it through marketing, health messaging, endorsements, food innovation, or simple sensitization [141]. Efforts to promote insect consumption will be rejected if they are proposed or implemented haphazardly without attention to context and culture. Processing insects into flours or powders and incorporating them into other foods (e.g. bars, chips, pastas) may be one way to increase adoption in contexts where whole insects are not readily consumed, particularly if they are packaged and marketed as recognizable foods with added insect ingredients [136].

The last caveat in our results comes from the wide error bars that accompany many of our estimates, particularly vitamin B12. There is a slim body of literature that has measured B12 contents of insects, and many of the estimates span a wide range of nutrient densities. Because of this paucity of data, it was difficult to identify outliers or assess the reliability of many of these measurements. It is also likely that there is a considerable amount of variation in the micronutrient densities across insect species. Without an ability to discern between measurement error and true species variation, we will need to rely on future studies that will continue to improve the accuracy of these measurements and bolster our confidence in estimating their potential to improve human nutrition.

5. Conclusion

Though still nascent, large-scale insect farming and wider consumption, particularly where eating insects is already traditional, provides a potential path toward improving global nutrition while safeguarding our planet’s natural systems. As we witness the increasing pressure from two countervailing forces—rapidly increasing food requirements, and a global environmental system with shrinking natural resources in which to meet them—our ability to identify new, sustainable, and innovative ways to meet future food and nutritional needs is essential. Here we explore the implications of one such solution and find that it has significant potential to alleviate malnutrition. It is through creativity and the pursuit of many solutions of this kind that we may identify our route to food and nutritional security while minimizing environmental harm.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iDs

Matthew R Smith Ⓢ https://orcid.org/0000-0001-5207-2370
Valerie J Stull Ⓢ https://orcid.org/0000-0003-4309-859X
Jonathan A Patz Ⓢ https://orcid.org/0000-0002-7131-9698
Samuel S Myers Ⓢ https://orcid.org/0000-0002-5808-2454

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