

Quantifying, Projecting and Addressing India's Hidden Hunger

Supplementary Information

Supplementary Table 1: Loss and waste percentages by food chain stage and commodity group for South and Southeast Asia. Due to poor data availability on India-specific food loss figures, regional average figures from the FAO¹⁴ were applied to derive estimates of macronutrient losses at each stage in the Indian commodity chain.

Supplementary Table 2: Indian population gender and age demographics. Percentages of the Indian population within each age and gender grouping⁴². This study excludes infants <1 year old, hence percentages have also been normalised to those >1 year, to give a total percentage of 100%.

Supplementary Table 3: Daily Estimated Average Requirements (EAR) of key dietary vitamins and minerals. Estimated Average Requirements (EAR) of key vitamins and minerals by age and gender demographics⁴³. Weighted EAR values for the population are derived from Indian population distribution figures in Supplementary Table 2.

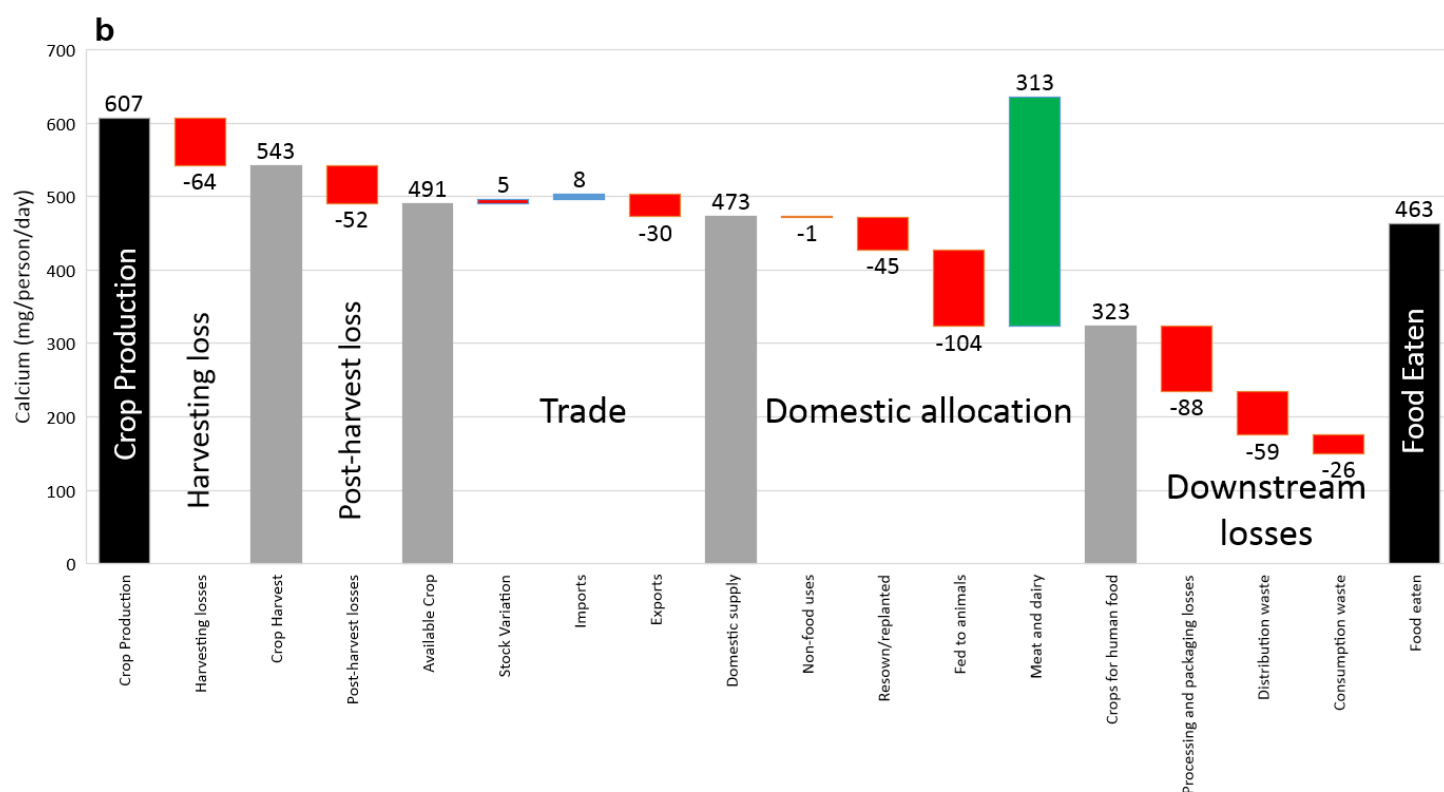
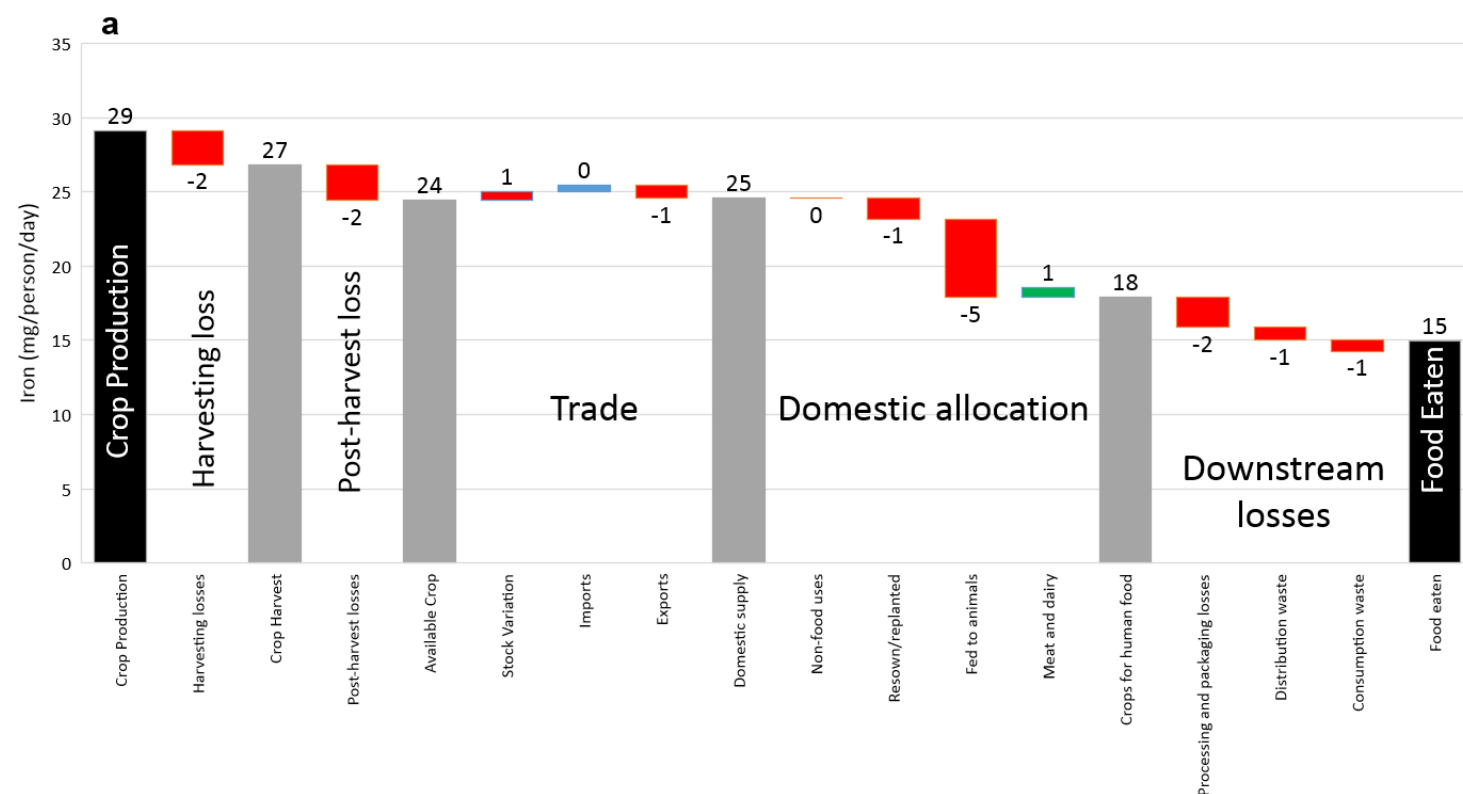
Supplementary Table 4: Daily Estimated Average Requirements (EAR) of essential amino acids. Estimated Average Requirements (EAR) of all essential amino acids (AA) by age and gender demographics⁴⁴. Weighted EAR values for the population are derived from Indian population distribution figures in Supplementary Table 2.

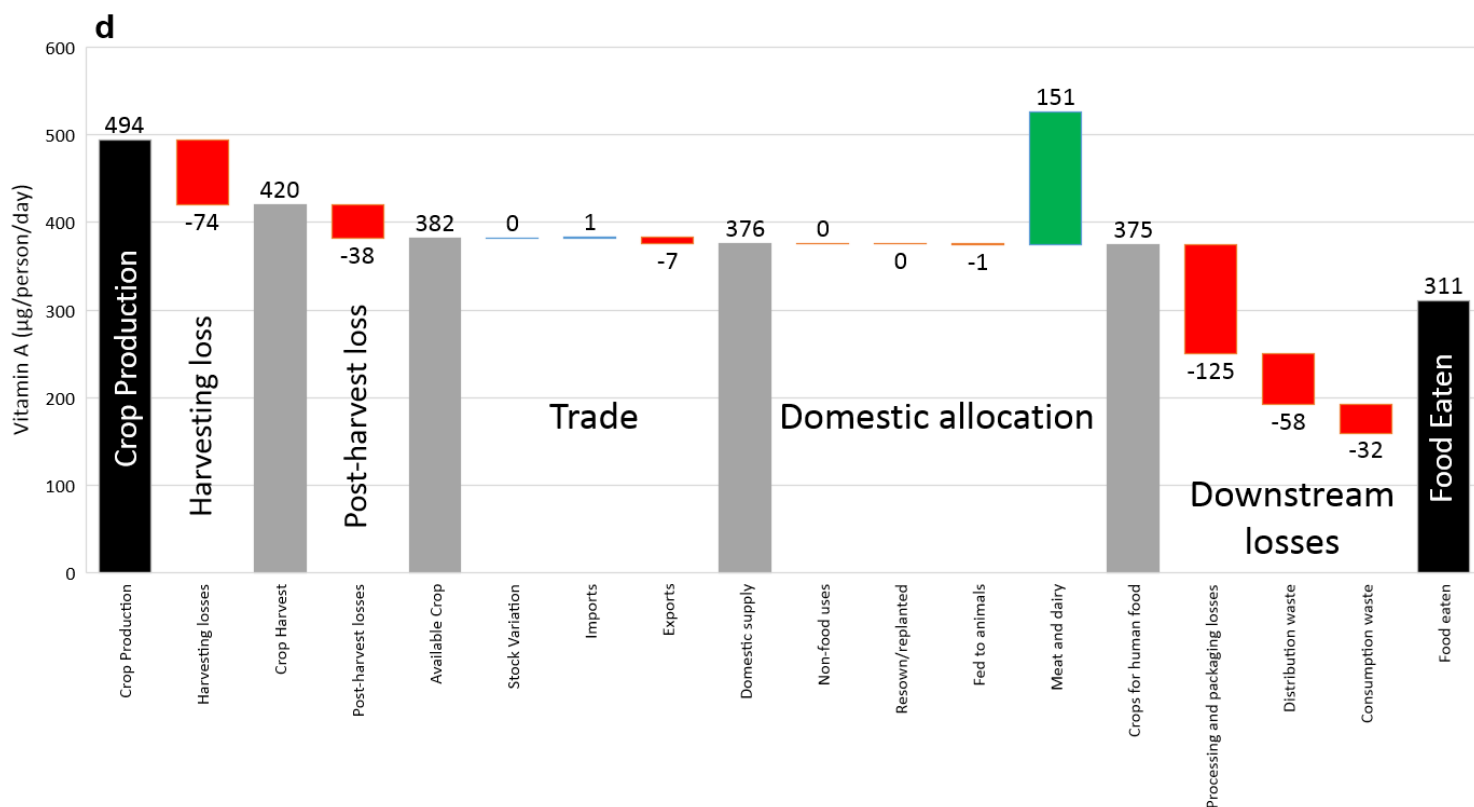
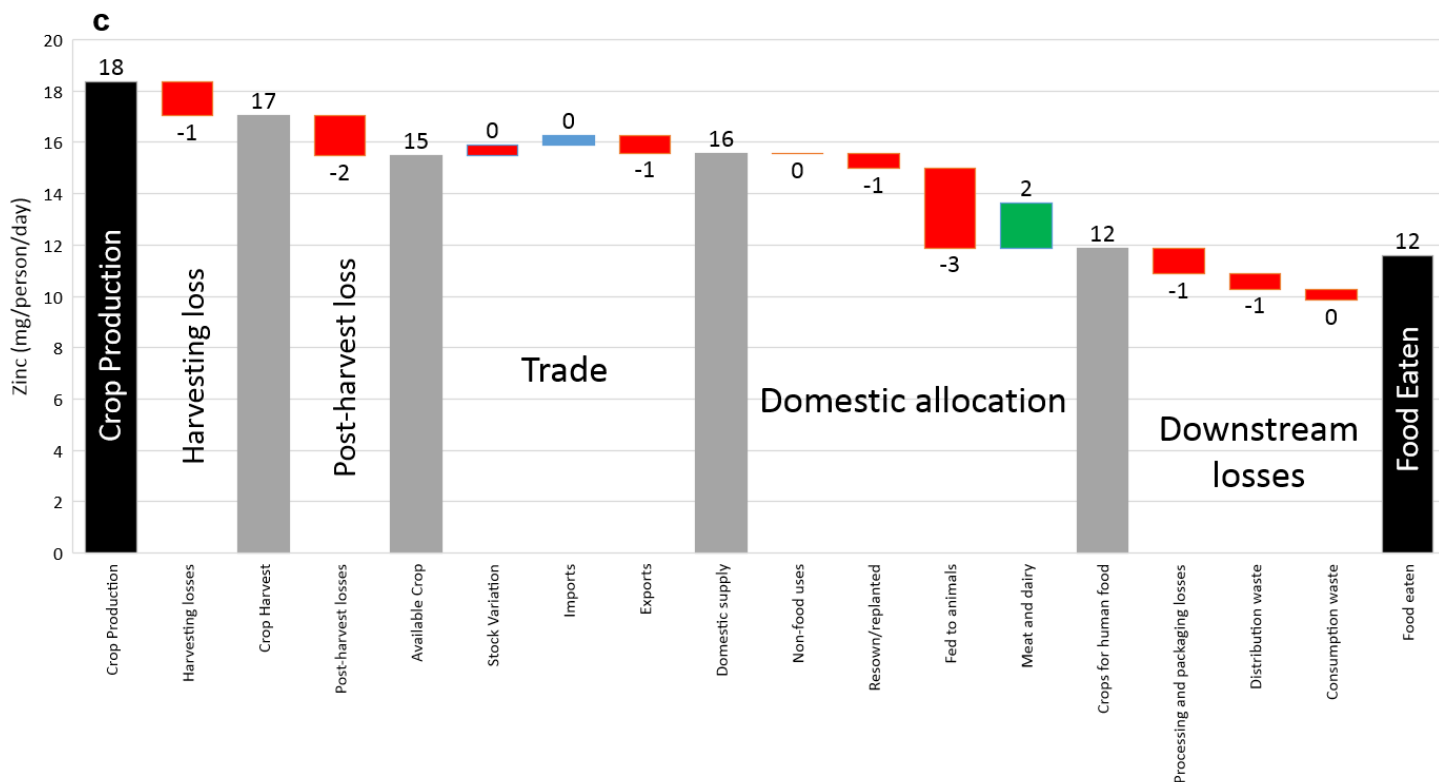
Supplementary Table 5: Indian baseline and 90% attainable yield (AY) values for key crop types. Year 2000 and 90% attainable yield⁴⁵, and 2011 yield data derived from the FAOstats database (<http://faostat.fao.org/beta/en/#home>). The necessary percentage increase in yield from 2011 levels to reach the 90% AY value has also been shown.

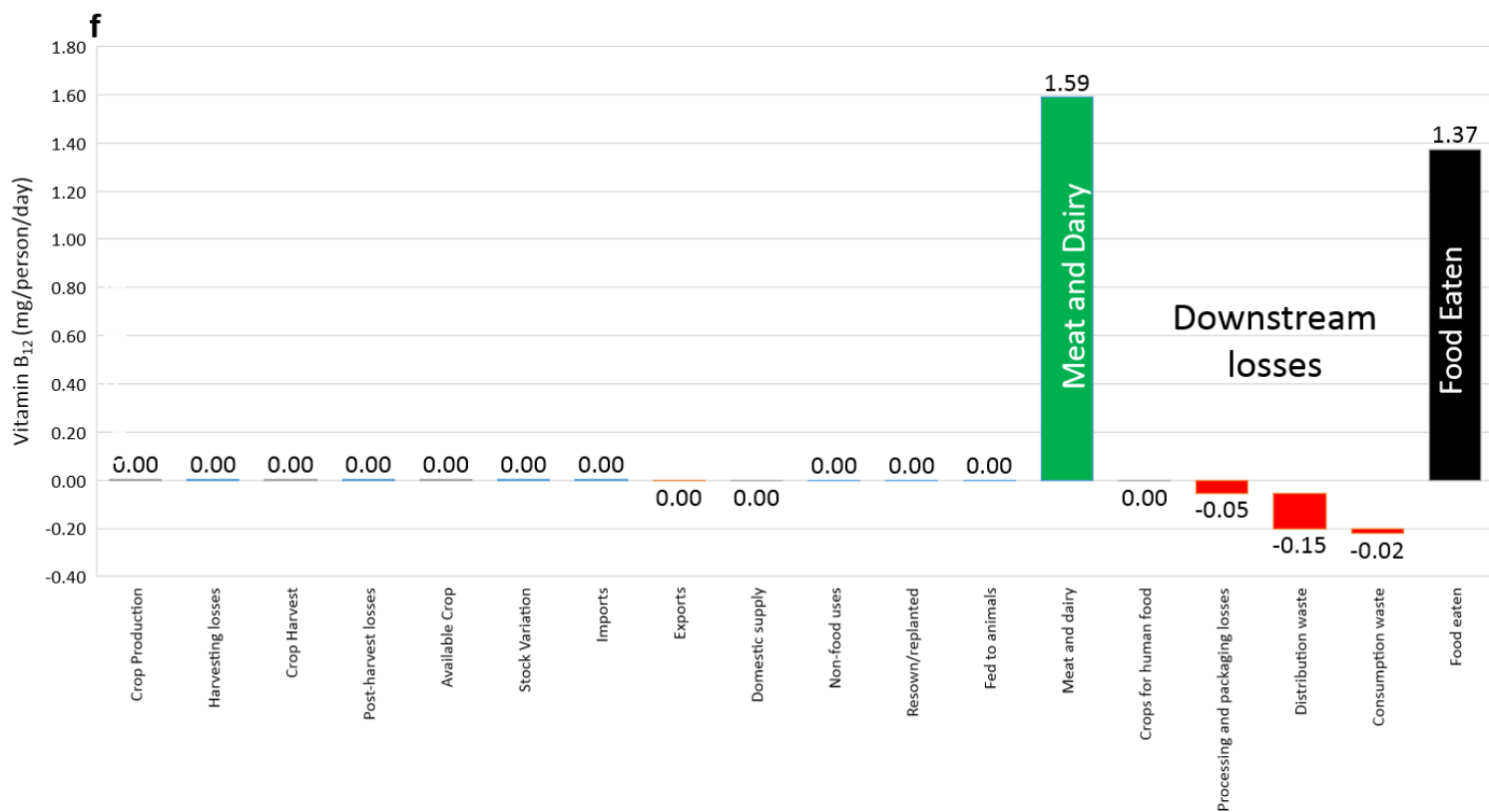
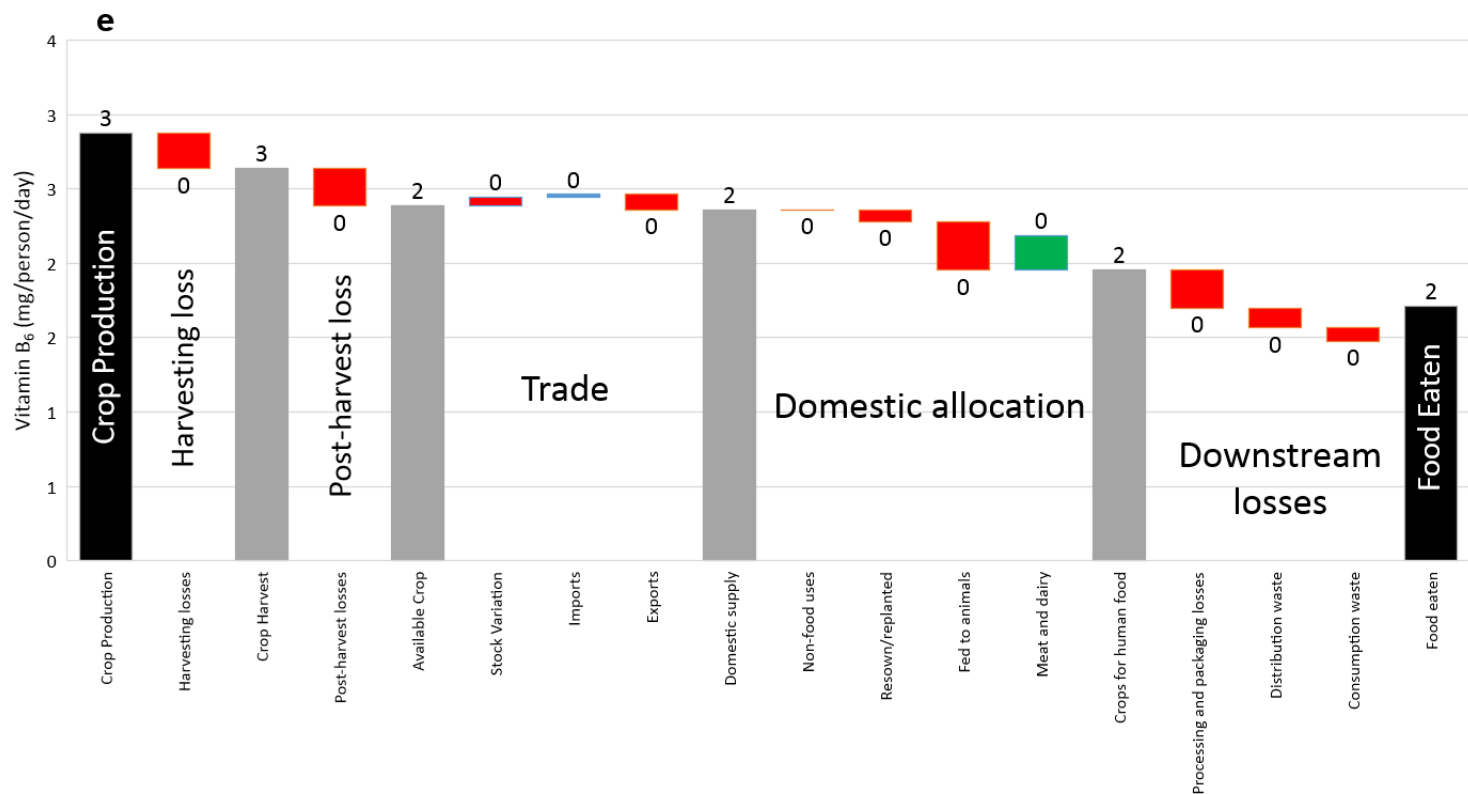
Supplementary Table 6: Average estimated climatic impacts on Indian crop yields in 2050. Average values have been assumed based on the range of historic studies on yield sensitivities and climatic models within literature review⁴⁶. These models are projected on the basis of a doubling of CO₂ from pre-industrial (which is approximately equivalent to a business-as-usual scenario).

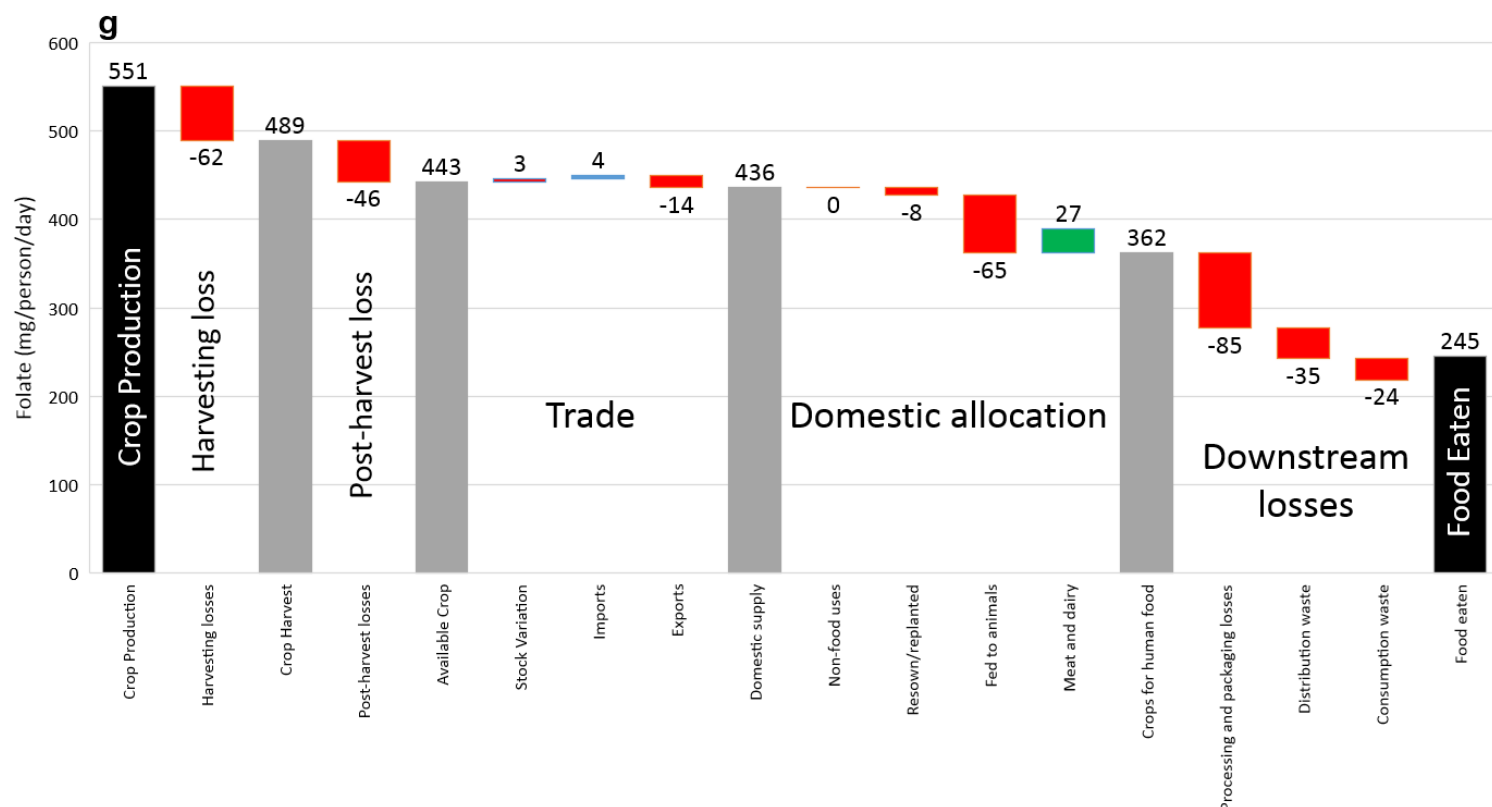
Supplementary Table 7: Dietary sources of micronutrients by commodity group. Key dietary sources of key vitamins, minerals, and limiting amino acid, lysine have been highlighted in grey.

Supplementary Figures 1a-g









Supplementary Figures 1a-g: Production and losses in the Indian food system from ‘field to fork’ in 2011. Food pathways in (a) iron; (b) calcium; (c) zinc; (d) vitamin A; (e) vitamin B₆; (f) vitamin B₁₂; and (g) folate, from crop production to food eaten, normalised to average per capita levels assuming equal distribution. Red bars (negative numbers) indicate food system losses; blue bars indicate system inputs; green bars indicate meat and dairy production; and grey bars indicate micronutrient availability at intermediate stages of the chain.

Supplementary Discussion

Analysis of business-as-usual pathways to 2050, and accelerated intervention strategies to 2030, highlight that, while increased meat and dairy intake, increased crop production and a reduction in supply chain losses have the potential to reduce the prevalence of MiND, they will be insufficient alone—even in the most optimistic scenarios—to meet the target of SDG2 by the target date of 2030, or even 2050.

It's important to note the scale of the challenge India would face in accelerating these three broad-based strategies to 2030 as envisaged here. The contribution and challenges of each of these options are described below.

Increased meat and dairy intake: Animal-based products are described as 'complete proteins', having adequate proportions of all essential amino acids (meaning none are considered to be 'limiting'). In addition to being a key source of high-quality protein, meat is rich in iron, zinc and B-vitamins; dairy products form a key source of calcium, B₁₂, vitamin A and folate³. Animal products are the only natural source of vitamin B₁₂. Their consumption has shown additional nutritional benefits beyond those expected from increased micronutrient provision alone; studies have linked their consumption to increased bioavailability and absorption of iron and zinc from other food groups when consumed together⁴.

There is significant agreement that moderate consumption of animal-based produce is particularly important for children, leading to improved growth outcomes, including improved cognition and motor performance⁵. Studies across a number of low-income countries in Africa and South Asia have suggested a strong link between meat consumption in young children and lower stunting rates⁶. As India has strong lactovegetarian preferences⁷ and one of the highest rates of childhood stunting globally⁸ this is an important consideration.

Increased meat consumption has historically been a direct reflection of economic growth⁹, and therefore tends to grow in line with economic trends. This makes it challenging to deliberately accelerate uptake, unless through economic mechanisms such as meat subsidisation. We suggest that, while increased meat consumption should continue to be a focus, the promotion of sustainable and nutritionally-similar alternatives such as pulses, legumes and meat-free substitutes¹⁰ should also be closely considered.

Pulses and legumes may offer a significantly more sustainable alternative protein and micronutrient source (with the exception of vitamin B₁₂)¹¹. The development and increasing popularity of meat-free substitute products, such as mycoprotein and in-vitro meat, may also offer sustainable proteins with a comparable nutritional profile^{12,13}. The lack of market access, and current economic barriers in India mean that widespread uptake of these products is unlikely to be feasible in the short-term. However, significant progress in the biotechnology sector to reduce consumer cost and widen market penetration for such meat-free products could be a viable target; this could provide lower-cost, micronutrient-rich proteins, allowing India to 'leapfrog' the traditional development pathway of increasing meat consumption.

Reduction of supply chain losses: Supply chain inefficiencies and losses have received significant attention in their contribution to malnutrition¹⁴ and environmental impacts¹⁵. It's important to distinguish between food 'losses' and 'wastage': the former describes edible food lost at the harvesting, post-harvest, production and processing stages of the chain, whereas the latter describes wastage as a result of behavioural factors at the retail and

consumer level¹⁶. Food system analyses in this study highlight that the majority of India's losses occur within the post-harvest, processing and distribution stages of the food chain - likely as a result of poor management, refrigeration, and preservation practices during storage and transportation. This loss is even more significant for micronutrient-rich commodities such as fruits, vegetables and animal products¹⁷.

The majority of developed countries have planned food processing infrastructure, which has effectively reduced the amount of upstream food loss (although this has transitioned to higher wastage at the consumer level)¹⁴. Food processing in the form of packaging and preservation can significantly reduce food losses and enhance nutritional value¹⁷. It not only prevents overall spoilage, but also helps retain micronutrients that might otherwise be lost over time. Processing is also a pre-requisite for food fortification (discussed below), hence the two strategies go hand-in-hand.

Investment in improved management systems to prevent losses can reap multiple benefits: it improves the nutritional value of foods and subsequently contributes to reducing micronutrient deficiencies; it can allow farmers a higher income through a larger sellable harvest; and it reduces the resource inputs (water, energy, fertiliser, and resultant greenhouse gas (GHG) emissions) for a given utilisable output. The benefits of investment in food supply chain management can therefore be very significant, and reaped by a range of beneficiaries.

Our results indicate that the micronutrients with the greatest supply chain losses—vitamin A, folate, and calcium—are associated with widespread risk of deficiency (across the majority of the population in India). This signals the need for a mass intervention strategy with nation-wide coverage. India's demographic distribution currently poses important challenges to developing a country-wide food network. Such infrastructure is most effective through centralised distribution centres—thereby most-suited to urban populations, and rural regions with sufficient connectivity¹⁷. We suggest that the development of such networks in expanding urban centres should form a near-term (next 5 years) priority. Connectivity with rural populations is likely to be limited during this period, however work towards rural integration over longer timescales (>10 years) should be an ongoing and progressive priority.

Increased crop yields and production: this study modelled the impact of closure of current yield gaps to 90% of attainable yields (AY) by 2030 (scenarios 3 and 4). To achieve this high level of production, India would have to significantly improve on its historical trend of staple crop yield enhancement through to 2030. For example, wheat yields in India are growing at approximately 0.9% per annum (non-compounding) from 2009 levels and have shown roughly linear growth at this rate over the last decade¹⁸. To attain the 90% AY figures used in this study, yields would have to increase by 36% from 2011 levels, equating to a consistent annual growth rate of 1.9% to 2030. This is double India's historical growth rate—a highly ambitious target which would require significant investment in terms of agricultural practice, irrigation and fertilisation practices.

Resource constraints in terms of soil fertility¹⁹, declining water tables²⁰ and recent concerns over yield stagnation globally—in wheat, rice and maize in particular²¹—suggests that such progress may be technically unfeasible even with significant investment.

India's challenge of maintaining balance between macro- (calories, total protein, and fat) and micronutrient (mal)nutrition is difficult to address. India's agricultural policies are currently still oriented towards achieving self-sufficiency in calories and protein²², predominantly through favourable subsidies for rice, wheat, and sugarcane production²³. Despite this drive for self-sufficiency, the prevalence of MaND (calories, protein and fat deficiency) remains high;

domestic food production faces a serious challenge in addressing current malnutrition, in addition to keeping pace with projected population growth²⁴.

Our analysis suggests that agricultural policy orientation and land allocation towards production of staple crops may have resulted in a domestic crop composition which is insufficient to also address micronutrient needs. Crop and dietary diversification may offer one option. However, the re-allocation of land used for staple crop production towards more micronutrient-dense commodities will, in most cases, result in reduced total caloric production. This suggests an important conclusion, supported by the results from the scenarios we have considered: India's domestic agriculture will be insufficient to address both macro- and micronutrient deficiencies simultaneously.

As such, food imports could play an important role in bridging this gap. However, food imports can have a significant impact on domestic prices²⁵, and with the dominance of agriculture as a primary source of employment in India, a negative influence on farmer income²⁶. Further research is therefore needed on how to best optimise global food trade and import strategies for India, without significant adverse impacts on domestic prices and livelihoods. In an optimal scenario, such trade agreements would benefit poorer rural households through increased agricultural income, thereby making dietary diversification more affordable for all demographics.

The types of commodities essential in reducing MiND vary by micronutrient (key dietary sources of each micronutrient are detailed in Supplementary Table 7). Vegetables—leafy greens in particular—are typically micronutrient-dense, with high levels of calcium, iron, zinc, vitamin-A and folate²⁷. Pulses and legumes hold multiple benefits for overall nutrition in India: they possess high levels of iron, zinc, and folate, and are one of the few commodities with calcium levels comparable to dairy produce (ibid). They also offer a key source of high-quality protein (thereby contributing to overall protein malnutrition alleviation), being the few plant-based commodities rich in lysine. From a sustainability perspective, pulses and legumes have been highlighted as a core solution on transitioning towards a more sustainable food system; nitrogen-fixation in leguminous crops aid soil fertility and reduces fertiliser demands²⁸; they also constitute one of the lowest-intensity, high-protein food groups in terms of GHG emissions²⁹, and have low water requirements relative to alternatives³⁰. Whether imported or produced domestically, pulses and legumes could form an integral part of Indian dietary diversification, with a unique ability to simultaneously address MiND and protein malnutrition sustainably.

While the broad-based strategies discussed here will be integral to addressing MiND in India, to adequately address 'hidden hunger', India will have to combine these strategies with additional targeted interventions. The three key targeted interventions discussed here are food fortification, biofortification, and dietary supplementation.

Food processing and fortification

Food processing not only allows for a reduction of supply chain losses, but also provides the infrastructure necessary to facilitate food fortification. Food fortification is implemented at the processing stage, and involves the addition or enhancement of one or more nutrients to a food product. Several types of fortification programmes exist, covering mass, targeted, voluntary and mandatory fortification³¹. Multiple programme types are relevant in the Indian context.

Mandatory fortification applies in the case where the government makes it a regulatory requirement to fortify a given food product³¹. The most common case of mandatory fortification is the Universal Salt Iodisation (USI) programme—which India also implements—

which requires salt to be fortified with an adequate amount of iodine (≥ 15 ppm). The USI programme has achieved significant global success, with an estimated eradication of iodine deficiency in 34 countries, and delivery of iodised salt to more than 70% of households across the world³². India has also celebrated significant success in decreasing levels of iodine deficiency³³, however progress in addressing this MiND appears to be slowing¹⁷. Iodised salt only reaches an estimated 71% of Indian households³³, falling well short of the 90% coverage required to achieve USI status. The 30% of households which are currently not receiving iodised salt are likely to be those in the most remote areas—meaning there are significant distribution and access barriers—and of low socioeconomic status. Overcoming these infrastructural challenges for full coverage should be an urgent priority, with USI being a practice which is sustained in the long-term. USI is a sustainable, cost-effective means of eradicating iodine deficiency, with an annual cost of only US\$0.05 per person, and a benefit:cost ratio of 30:1³⁴.

Mass fortification involves the addition of micronutrients to particular food groups or products which are widely consumed across a given population, such as wheat or rice in India. This type of programme is used in addressing nutrient deficiencies which are prevalent across a large proportion of the population. In the case of India, this would include calcium, vitamin A, B₁₂, folate and lysine. However, this coverage could also be extended to a wider range of micronutrients, especially those such as iron and zinc where deficiency is still highly prevalent, albeit within smaller demographics. The major barrier to mass fortification is India's current lack of centralised food processing and distribution networks; these form a fundamental pre-requisite for effective mass fortification programmes. As with biofortification (described below), the financial hurdle to fortification is the capital cost involved in development of appropriate infrastructure and networks¹⁷. Once in place, the running costs can be very low, with a high payback ratio; wheat and flour fortification can cost just US\$0.12 per person per year³⁴.

We suggest that food fortification strategies should be coupled with processing developments for reduction of supply chain losses—it is recommended that this forms a near-term (next 5 years) priority, with acknowledgement that coverage is likely to be initially limited to urban populations. Connectivity and wider infrastructure networks for broader coverage should continue to be a focus over longer timescales.

Biofortification

Biofortification occurs at the earliest stage of the food system. It is a comparably newer strategy, involving the innovative use of plant breeding to increase micronutrient concentrations in staple crops³⁵. Despite biofortification sometimes being considered a competing strategy, it can be a well-suited complement to commercial fortification¹⁷. Since the two approaches are most effective in targeting different beneficiaries, they can be used simultaneously to reach a larger subset of the total population. Commercial fortification is more easily suited to urban, well-connected populations, whereas biofortification can be more effective in rural areas where food production is localised, often subsistence-driven, and poorly-connected to distribution centres.

Following the development and distribution of biofortified crop varieties, the farmer should ideally be able to sow and harvest the crop using traditional approaches (i.e. the farmer's only change would be in adopting the new seed varieties) and incur no change in relative costs. Biofortification research and development is still in its relative infancy, with efforts focused across countries in the Global South³⁶.

Crops targeted for biofortification should be staple crops commonly produced and consumed by the local population—in India, this is likely to be wheat, rice, pearl millet and sweet potato. To date, effective biofortification of crops with iron, zinc and vitamin-A has been proven, with

distribution via the HarvestPlus programme (<http://www.harvestplus.org/>). In India, this includes zinc wheat, iron pearl millet, and 'golden rice' (vitamin-A enriched rice). Such biofortification could address the targeted deficiencies of iron and zinc—most likely to be prominent in rural pregnant women and children—and widespread vitamin-A deficiency.

The HarvestPlus programme predicts that it could take more than a decade before biofortified crops are widely distributed and utilised in target countries¹⁷. This suggests that increasing uptake should be a near-term intervention focus for India, but wide adoption is only likely to be achievable over the longer-term. In the meantime, we suggest that development work should focus on addressing the qualities of biofortified varieties which will increase their social acceptability: they should be equally (if not more) profitable for a farmer than current harvested varieties; harvested crops must be attractive and accepted by consumers in target markets; and the nutritional benefits must be clearly demonstrable through evidence-based results. Increasing the coverage of micronutrients which can be biofortified, to include those such as folate, lysine and calcium, should also be a longer-term focus.

As with food fortification, investment is largely focused at the capital stage. Limited evidence makes it challenging to complete a total cost-benefit analysis. However, it is estimated that adaptive breeding (capital) costs for biofortification of total rice production in India would be approximately US\$1,600,000 per year³⁷. At the national level, this would be a relatively small investment. The largest beneficiaries of biofortification are likely to be low-income households, hence this cost should ideally be absorbed through private or public investment, rather than financed through farmer or consumer price increases. The potential economic benefits of such an investment are expected to be extremely high³⁷, and delivered to demographics of low socioeconomic status.

Supplementation

Food processing and biofortification are complementary strategies to address MiND over near- to long-term timescales (>5-10 years). However, the social, health and economic costs of malnutrition in India are on-going, making urgent interventions – such as provision of dietary supplements - necessary to bridge this period. Dietary supplementation is most commonly delivered in tablet or powder-form.

The irreversibility and permanence of maternal and childhood malnutrition means that the most common target groups for dietary supplements are children, pregnant and lactating women^{38,39}. India has had national programmes delivering vitamin-A to children under the age of five (providing a biannual dosage), and a national anaemia control programme for pregnant women and children (delivering 100 tablets of iron and folic acid), for more than 30 years⁴⁰. Evaluation of these programmes has indicated an extremely low success rate, attributed to economic, social and educational challenges. It's estimated that allocated funding for these programmes is sufficient to cover only 10% of requirements; less than 50% (vitamin-A) and 10% (iron) of necessary supplies are available; distribution is irregular, with <5% of pregnant women receiving more than 90 of the required 100-dosage; and due to poor nutritional education⁴⁰, very poor compliance in intended beneficiaries.

India's large population size and prevalence of MiND makes the investment scale even more challenging. Supplementation can be inexpensive, with annual costs ranging from US\$1-1.20 per person in South Asia and high benefit:cost ratios of (17:1) for vitamin-A supplements alone³⁴. However it is, in relative terms, more expensive than interventions such as commercial food fortification and biofortification (in the order of dollars, rather than cents per person). We suggest that delivering the necessary investment and distribution networks for supplementation programmes in pregnant women and children should be an urgent and near-term priority. Additional key supplements should also be considered for

these groups—lysine supplements for children, in particular. However, a long-term programme providing total coverage of the Indian population would be an unsustainable delivery model for addressing MiND. Total costs would be prohibitively high, and compliance would likely drop with time.

Supplementation should therefore form an urgent and short-term (<5 years) cornerstone in addressing MiND, but should be utilised as a bridge towards more efficient and sustainable delivery mechanisms such as fortification, biofortification, and dietary diversification. Thereafter, supplementation should be reserved for vulnerable demographics with significantly higher daily requirements, such as pregnant women—a practice also implemented in developed countries today.

Supplementary Discussion on FAO Food Balance Sheets (FBS)

The challenge in developing accurate Food Balance Sheets (FBS) at the national and global level are widely acknowledged and discussed by the FAO ⁴¹. The accuracy of FBS is constrained by the completeness and reliability of commodity production and utilization statistics in national records.

The high prevalence of small-holder and subsistence farms in India makes estimates of total production challenging—in this case, completeness of data collection as well as the reliability of farmer reports (farmers often equate production with tax collection) introduce uncertainty to final estimates. Such uncertainty is also present in values of non-food utilizations. Import and export data—which is more meticulously recorded—is likely to be the most accurate of the national statistics recorded in FBS. Issues in agricultural and nutritional data collection in India are described in detail within the FAO's 2030/50 Agricultural Outlook ⁹.

Food loss and waste figures, especially in countries where small-holder farms and local markets are prevalent, has a high level of uncertainty. To our knowledge, national statistics on supply chain losses and waste in India is not available down to the level of commodity and chain stage breakdown. For this reason, published FAO figures on regional losses for South and Southeast Asia were applied in this study (Supplementary Table 1). This introduces further uncertainty to supply chain losses.

Where data within FBS is deemed to be incomplete or inconsistent, judgement from national expert opinion and technical expertise within the FAO is used to provide as reflective coverage as possible. While likely to provide a close approximation, this is rarely 100% accurate.

Nonetheless, the FBS is currently the best available data source for construction and analysis of complete commodity chain analysis. Literature is available based on studies conducted at the household level, however, very few studies attempt to provide coverage of the food chain dynamics from crop production through to human consumption. Without a complete overview of the commodity chain, the impacts of interventions (such as improved food management and storage; trade; reduced allocation of crops to non-food uses; improved crop yields) are almost impossible to assess.

As the FAO notes, food balance sheets “provide an approximate picture of the overall food situation in a country and can be useful for economic and nutritional studies, for preparing development plans and for formulating related projects” ⁴¹. In this study, we have therefore relied on FAO datasets in order to construct a high-level overview of the Indian commodity chain to assess its overall capacity to meet the country's growing nutritional demands at present, in the near-, and long-term. This overview will not be perfect in a statistical sense, however its strong correlation (<5-10% discrepancy) with national household surveys gives confidence that it provides a good approximation of the national food outlook. For its utilisation in this analysis—to inform broad policy focus and assess the potential of supply chain interventions—we therefore deem it to be appropriate.

Improved agricultural, food waste and nutritional reporting would allow for more accurate and reliable estimates to be constructed. Such data collection will provide important in informing future policy and allowing for forward planning in this sector. It should therefore be an important area of focus for India in the coming years.

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