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India has natural resource capacity to achieve nutrition security, reduce health risks and improve environmental sustainability

Kerstin Damerau[1]✉, Kyle Frankel Davis[2,3,4], Cécile Godde[5], Mario Herrero[5], Marco Springmann[6], Shilpa N. Bhupathiraju[1], Samuel S. Myers[1] and Walter Willett[1]

Sustainable development of India's food system must ensure a growing population is fed while minimizing both widespread malnutrition and the environmental impacts of food production. After assessing current adequacy of nutrient supplies at the national level, associated natural resource use (land, fresh water) and greenhouse gas (GHG) emissions, we apply an integrated subnational environmental and nutritional optimization approach to explore resource constraints that might limit the achievement of national food self-sufficiency goals. We find that India currently has the capacity to produce sufficient amounts of nutritious foods, supplying vitamins and minerals that would mostly exceed requirements. Regional cropland use could be reduced by up to 50%, water demand by up to 65% and combined resource inputs by up to 40% while still supporting adequate nutrition. Associated GHG emissions would decline by 26–34% and could possibly be sequestered in agroforestry systems. Such dietary shifts could lower the number of diet-related premature deaths by 14–30%. Achieving these potential gains, however, would require a major transition from current production and consumption patterns, particularly of refined cereals, to free-up resources for more traditional and nutritious foods.

Since the Green Revolution in the 1960s, India has been steadily increasing its domestic food supply. Producing about 2,000 kcal cap^{-1} d^{-1} (where cap is per capita) in 1961 for about 440 million people, the country now supplies about 2,450 kcal cap^{-1} d^{-1} for approximately 1.3 billion people[1]. This increase has primarily been achieved through a series of policy measures and technological advances, including land reforms and increased crop yields (particularly rice and wheat). The National Food Security Act[2] extended policy measures and incentives to further improve food supply and availability. The country has also been increasing its imports of legumes, fruit, vegetables, nuts and palm oil in recent decades, accounting for 4.6% of India's current total caloric food supply, while becoming a net exporter of rice, wheat and maize[1]. Today, India's agricultural sector uses 57% of the country's land area for food production—primarily cropped by smallholders—and is responsible for 87% of total freshwater consumption and 16% of national greenhouse gas (GHG) emissions (Supplementary Tables 1–3).

As a result of these developments, India now faces substantial negative consequences both environmentally and for the health of its growing population. Soil degradation and erosion, and the overuse of groundwater resources and fertilizers, make it increasingly difficult to produce sufficient amounts of food[3–5], while domestic per capita supply of some nutrient-rich foods such as legumes and coarse grains (millet and sorghum, so-called 'nutri-cereals') has declined[1]. Although today's average supply of dietary calories appears adequate, unequal access and poor food quality (refined grains (53%), sugar (6%) and added fats (11%) supply the majority of calories[1]), together with enteric infection, leaves large parts of the population undernourished and susceptible to communicable and non-communicable diseases[6–10]. For example, over 50% of Indian children and women suffer from anaemia[11], while vitamin A deficiency affects over 60% of preschool children and 30% of women[12]. At the same time, increasing rates of overconsumption can be observed in some parts of the Indian population along with growing rates of chronic diseases[13]. Climate change, unsustainable natural resource use and an expected population peak of 1.7 billion people (estimates range from 1.5 to 2.1 billion) around the year 2060[14] could further diminish the country's ability to produce sufficient food in the future.

An emerging body of work has explored the effects of different diet patterns on both natural resource use and nutritional outcomes for the Indian population[5,15–25]. While these studies highlight the enormous challenge of simultaneously increasing the production of nutritious foods while limiting natural resource use, they have not quantified the environmental constraints that could limit future domestic food production (see Supplementary Information for detailed information). Here we determine the limits of India's natural resource capacities to produce sufficient nutritious foods domestically. We calculate current average nutrient supplies and associated environmental footprints, and employ a regionalized linear optimization approach to assess the potential to meet or exceed nutrient requirements on a population level by allocating increasingly limited cropland and freshwater resources as efficiently as possible. We adhere to India's national target of reaching (caloric) food security as self-sufficiently as possible[2], but do not aim at matching food supplies with a specific, predefined diet for the Indian population. While ensuring minimum nutritional requirements, this approach allows the exploration of the environmental boundaries for a wide

[1]Harvard T.H. Chan School of Public Health, Boston, MA, USA. [2]Department of Geography and Spatial Sciences, University of Delaware, Newark, DE, USA. [3]Department of Plant and Soil Sciences, University of Delaware, Newark, DE, USA. [4]Data Science Institute, Columbia University, New York, NY, USA. [5]Commonwealth Scientific and Industrial Research Organisation, St Lucia, Queensland, Australia. [6]Oxford Martin School, University of Oxford, Oxford, UK. ✉e-mail: kerstin.damerau@gmail.com

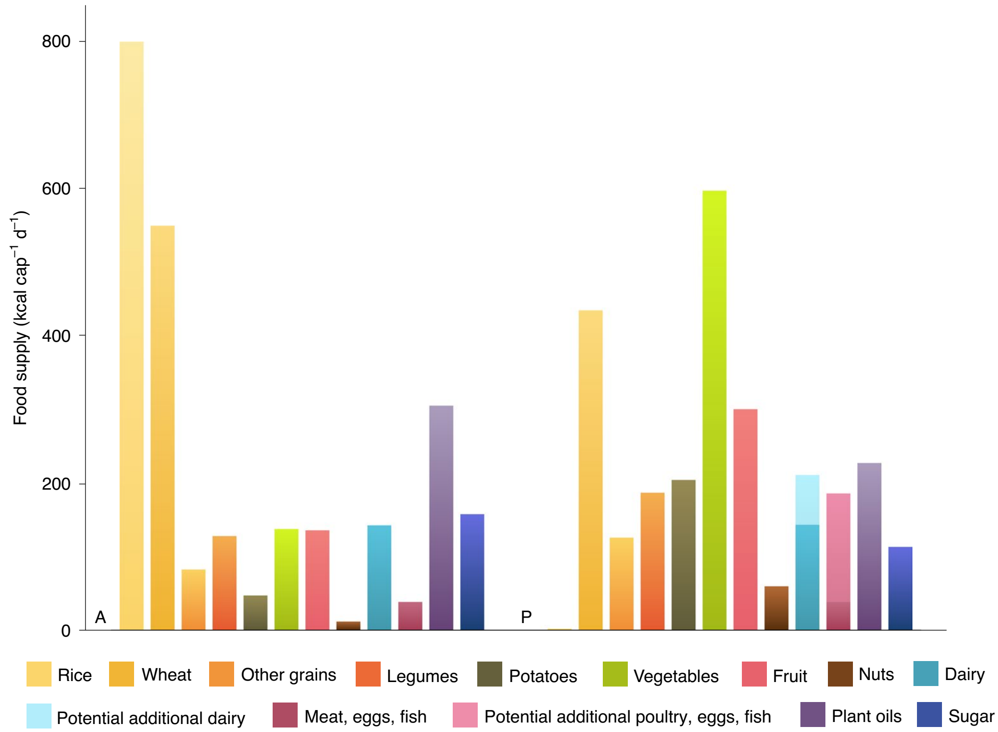

Fig. 1 | Current average food supply (A) versus potential optimized food supply (P). Using regionally equal or less amounts of land and freshwater resources, the optimized food supply provides the maximum total amount of 20 micronutrients. Average dietary share of plant foods is held stable at the current level of 2,275 kcal cap^{-1} d^{-1}. Animal-source foods may potentially increase by using surplus crop residues as feed source. Compared to the current food supply there is a shift towards more nutrient-rich plant foods such as vegetables, legumes, nuts and fruit. Better nutritional quality and higher total amounts of crop residues could lead to a potential increase in animal-source foods of ~215 kcal cap^{-1} d^{-1}. All micronutrient gaps in the current diet could be closed by the maximized food supply with the potential exception of vitamin B_{12} whose sufficient supply depends on the amount of animal-food sources that could be provided additionally (source data, Supplementary Table 9a,b).

set of culturally acceptable and nutritionally adequate diet compositions according to current dietary recommendations. Finally, we estimate potential positive effects on population health as a result of associated changes to dietary patterns. By linking sustainable food production with nutrition, we identify a feasible option-space within which India can achieve environmental and human health co-benefits in the years to come.

Results

Nutritional adequacy and environmental footprints of the current Indian diet. Primarily based on data from the national household survey[26], we estimated that average per capita food consumption amounts to ~2,450 kcal d^{-1} (Supplementary Table 4) with total food intakes ranging between 1,440 and 3,050 kcal cap^{-1} d^{-1} depending on age and sex. About 15% of calories are consumed outside of the house (mainly cereals, fats, some dairy, legumes, fruit and vegetables). About 11% of energy is derived from protein, 22% from fat and the remainder from carbohydrates. Together, wheat and rice provide about 50% of total food energy, and about 50% of total protein. Overall protein intakes appear relatively low yet (on average) potentially adequate. Based on total food intake, we further assessed adequacy of average intakes for 20 vitamins and minerals. For 12 nutrients (calcium, iron, potassium, zinc, vitamin A, thiamin, riboflavin, niacin, vitamin B_6, folate, vitamin B_{12} and choline), the current average Indian adult diet appears to provide less than the estimated average requirement (EAR) (Supplementary Tables 5 and 6). With 70% of food energy stemming from refined cereals, added fat and sugar, variations in regional micronutrient supplies are limited. Estimates of state-level nutrient intakes can be found in Supplementary Table 7a–ai.

Eighty-seven per cent of India's cropland (including land under permanent crops) is currently used for national food production. Overall freshwater consumption for all crop production amounts to 253 km^3 yr^{-1}, of which 12% is used for crops intended for export. Thirty-six per cent of the arable land and 71% of freshwater used for domestic food production is used for cereal production. On average, the current share of fresh water that is sourced at unsustainable rates for national food production amounts to 36% of total freshwater consumption (this value is comparable to those reported in refs. [5] and [27]) (Supplementary Table 8). Total GHG emissions from domestic and exported food production amount to 0.77 and 0.04 bn t CO_2-eq yr^{-1}, respectively (Supplementary Tables 2 and 3). Regarding losses occurring between farms and markets, we adopted loss rates from the Food and Agriculture Organization of 10% for crops and 15% for livestock products[1].

Current natural resource capacities for nutritious food production. Based on the land and freshwater footprints of the current diet in India, we explored the maximum potential of India's agricultural sector to produce nutritious foods, focusing primarily on closing current micronutrient gaps in the most efficient way. Figure 1 compares the current per capita average food supply with maximized food supplies. Holding the energy supply of plant foods stable, the final output of between 2,440 and 2,650 kcal d^{-1} depends on both potential increases in milk yields due to feed quality improvements and additional poultry (including eggs and organ meat) and fish that could be fed with excess crop residues. Meat supply from ruminants and pigs was held constant as domestic demand has remained low over the last decades[1]. Protein supply would reach 81–112 g cap^{-1} d^{-1} (minimum recommended intake ranges between

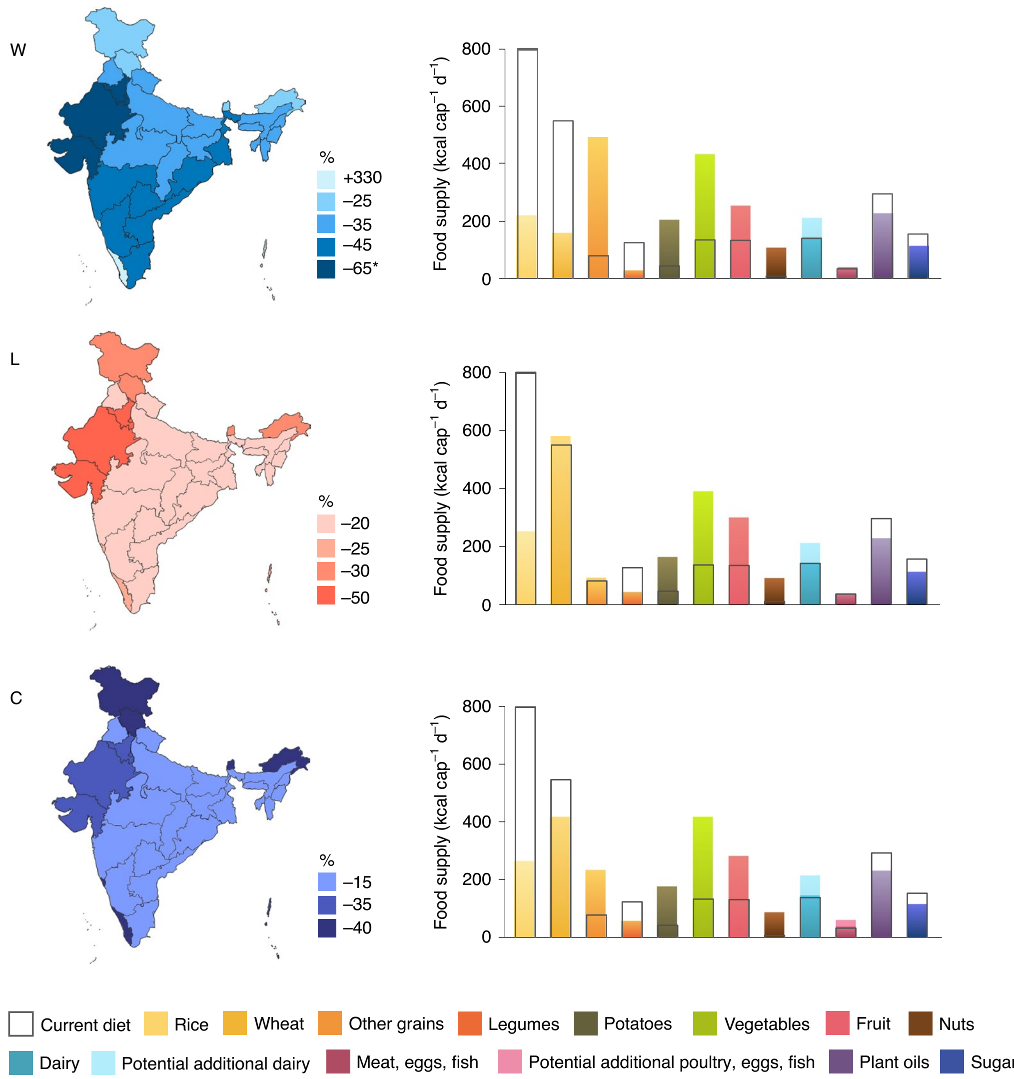

Fig. 2 | Relative potential regional reductions of irrigation water (W), cropland (L) and combined resource use (C). Average national irrigation water demand could be reduced by up to 40%, cropland use by 27% (15% total land), or 16% and 20% (11% total land), respectively, under combined resource restrictions. Potential reductions in dietary GHG emissions range between 31% and 34% (Supplementary Table 2). Total resulting caloric supply from plant foods is held stable at 2,275 kcal $cap^{-1} d^{-1}$. Compared with the current Indian food supply there is a shift towards more nutrient-rich plant foods such as vegetables, nuts and fruit, yet lower vegetable and legume production than in the potential maximized food supply (Fig. 1). These differences consequently reduce associated crop residue output that could be used as livestock feed, and hence the amount of potential additional animal-source foods (source data, Supplementary Table 9a). *Includes 65% cropland reduction.

42 and 106 g $cap^{-1} d^{-1}$) and total fat supply would range between 72 and 116 g $cap^{-1} d^{-1}$ (27–39% of energy). To maximize potential micronutrient output, a large share of cropland (77%) and irrigation (blue) water resources (85%) currently used for cereals, sugar cane and oil crops was instead allocated to produce more legumes (lentils), potatoes, vegetables, fruit and nuts (peanuts) (Fig. 2). Figure 3 compares the associated relative supply of 20 micronutrients. The maximized food supply would meet or exceed per capita energy and all specific macro- and micronutrient requirements. Total freshwater consumption would increase by 0.8% (sourced from sustainable resources); total land requirements would shrink by 9%, and associated GHG emissions would decrease by 26%, mostly due to notable reductions in rice production. Notably, potential vegetable supply could exceed realistic demand patterns (compare ref. [28]). Consequently, the current national capacity to provide minerals and vitamins greatly exceeds estimated average requirements. This opens up possibilities for a wide range of various diet compositions that lie between today's diet and our calculated maximum nutrient supply, which would meet both nutritional needs and specific regional and cultural preferences. This includes, for example, higher amounts of cooking oils, but also foods such as rice or mangoes that are not part of the potential maximized food supply but play an important role in many Indian cuisines. Thus, such foods could be included in a national food supply that is not fully optimized for micronutrient output but which moves towards achieving multiple food sustainability goals.

Minimizing natural resource inputs. By decreasing regional resource inputs gradually and in proportion to their respective availability within each Indian agroclimatic region (subtropical highland, humid subtropical, (semi-)arid, tropical wet and dry, tropical wet (Supplementary Fig. 1)), we identified maximum possible restrictions for natural resource use while still meeting basic national food security and diversity goals (Fig. 2). Focusing solely on irrigation water inputs, average per capita requirements could be reduced by up to 40%. This breaks down to a reduction of 65% in the

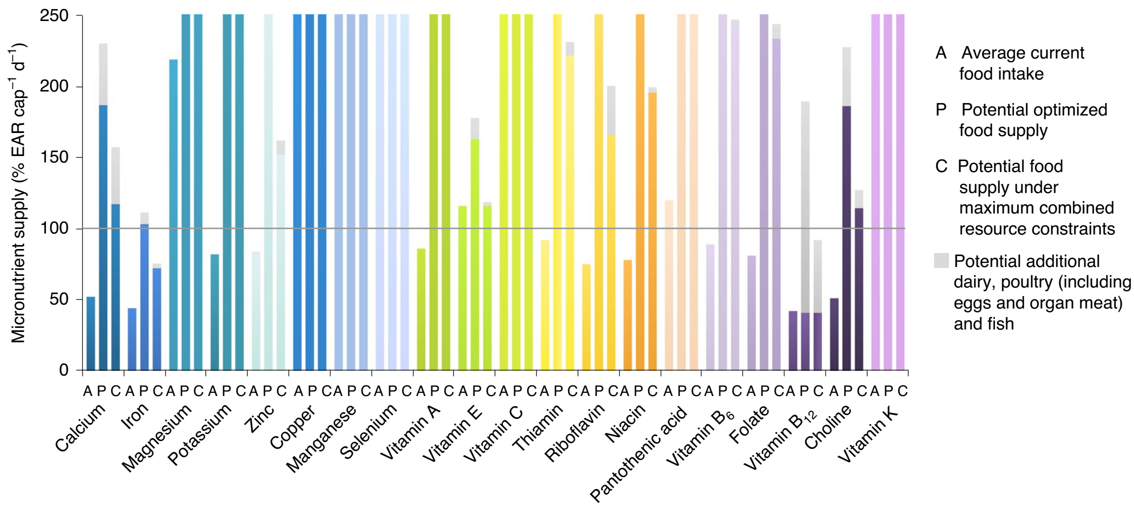

Fig. 3 | Micronutrient supply of average, potential maximized and potential under resource-constrained diets. Micronutrient supply as a percentage of the EAR for 20 essential minerals and vitamins, comparing current average Indian intakes (A) with potential maximized nutrient supplies (P) and nutrient supplies under maximum combined resource constraints (C) (capped at 250%). Grey portions of each column represent nutrients stemming from potential additional dairy yields, poultry (including eggs and organ meat) and fish fed with surplus crop residues. The current average diet meets the EAR for 8 out of 20 nutrients. Modelled food supplies could generally meet or exceed all included nutrient requirements with the exception of iron and vitamin B_{12} under maximum combined resource constraints (source data, Supplementary Table 10).

(semi)-arid region, 45% in the tropical wet and dry region, 35% in the humid subtropical region and 25% in the subtropical highland region. Thus, regional irrigation water use for domestic food production could be reduced to at least sustainable levels in one region ((semi-)arid, including associated cropland reduction by 65%) and below available sustainable freshwater supplies in two other currently highly water-stressed regions (tropical wet and dry, humid subtropical). An additional reduction in the highlands as well as the total increase in freshwater consumption in the tropical wet region does not substantially affect regional and national sustainable freshwater supplies. National use of sustainable water resources decreases from the current level of 88% to 62%. When not aiming at reducing current freshwater consumption, total cropland use could be reduced by 27% (total land reduction amounts to 15%; associated green water consumption declines by 18%) while still meeting basic dietary goals. This average results from a 50% reduction in the (semi-)arid region, 30% reduction in the highlands, 25% in the tropical wet region and 20% each in the tropical wet and dry and humid subtropical regions. When restricting both resources simultaneously, total national water and cropland footprints could be reduced by 16% and 20%, respectively (total land reduction amounts to 11%, associated green water consumption declines by 14%). The availability of sufficient land and associated rainwater resources, therefore, has a large impact on potential reductions in freshwater use in the Indian agricultural sector. Associated total dietary GHG emissions decline by 31–34%.

The resulting caloric output ranges between 2,420 and 2,520 kcal cap^{-1} d^{-1}, and the total protein supply amounts to 70–85 g cap^{-1} d^{-1}. Compared with the maximum potential nutrient output using currently available per capita resources, we see a shift towards more cereals (in particular wheat, maize and millet, but also rice) and nuts (peanuts) but lower amounts of vegetables and legumes (lentils). Consequently, these differences lead to a lower availability of crop residues as livestock feed, reducing the potential for producing additional animal-source foods. Figure 3 displays associated relative micronutrient supplies under maximum combined resource constraints, with iron and vitamin B_{12} supplies failing to meet their respective EARs. Using food grain such as maize as feed crop instead would lower the respective caloric output by ~81% and protein supply by ~20% (but would increase critical micronutrient supply).

While it is possible to reduce per capita cropland and freshwater inputs substantially, a total combined reduction in water and land resources by less than 20% might not suffice to compensate for future population growth alone. Exploring the maximum nutrient output under specific environmental constraints means that many other potential food supply scenarios, which lie somewhere between the current average diet and our maximum values, would therefore be feasible. This allows further regional adaptation of diets to cultural preferences and to (changing) environmental conditions that go beyond our restrictions. We only find actual limitations for the production of two major foods groups: legumes (excluding lentils) and nuts (excluding peanuts). Both food groups currently show relatively low average yields and relatively high water demands. Including substantial amounts in the national food supply currently appears feasible only when lowering total national caloric output or increasing multicropping approaches. In addition, our assumptions on increases in animal-source food production (dairy, poultry, fish) rely on the more efficient use of crop residues. With increasing shares of cereals in the food supply, the amount (and often nutritional value) of crop residues available for feed decreases directly. We find that a caloric share of about 20% or less of animal-source foods in the diet would require the inclusion of organ meat (or shellfish) to meet current vitamin B_{12} recommendations without the need for supplementation.

Carbon sequestration through agroforestry approaches. We estimated that current total diet-related GHG emissions amount to 0.77 bn t CO_2-eq yr^{-1} (including emissions from food losses) (compared with other recent estimates of 0.48–0.58 bn t CO_2-eq yr^{-1} (refs. [25,29])). Producing a nutritionally optimized food supply for 1.28 billion people under no additional resource constraints would decrease GHG emissions to 0.51 bn t CO_2-eq yr^{-1}, mainly due to reductions in rice production. Reaching maximum natural resource constraints lowers these estimates further to 0.47 bn t CO_2-eq yr^{-1}. The EAT Lancet report defined a global boundary for GHG emissions

Table 1 | AHEI scores of current and potential optimized food supplies

	Current food supply		Potential food supply		Potential food supply under maximum combined natural resource constraints	
Food	Amount	AHEI score	Amount	AHEI score	Amount	AHEI score
Vegetables ($g\,d^{-1}$)	230	3.8	1,669	10	984	10
Fruit ($g\,d^{-1}$)	125	2.6	286	6.1	272	5.7
Whole grains ($g\,d^{-1}$)	6	0.7	127	10	148	10
Sugar-sweetened beverages ($g\,d^{-1}$)	17	4.1	0	10	0	10
Nuts and legumes ($g\,d^{-1}$)	41	10	57	10	29	10
Red/processed meats ($g\,d^{-1}$)	3.3	9.8	3.3	9.8	3.3	9.8
Trans fat (% of energy)	1.3	0	1.3 (0)	0 (10)	1.3 (0)	0 (10)
Long-chain n–3 PUFAs ($mg\,d^{-1}$)	74	3.9	104 (332)	4.2 (10)	87 (133)	3.5 (5.3)
PUFAs (% of energy)	5.2	4.0	4.5 (5.1)	3.1 (3.8)	4.6 (4.7)	3.3 (3.4)
Sodium ($mg\,d^{-1}$)	4,255	0.2	4,255 (<1,362)	0.2 (10)	4,255 (<1,362)	0.2 (10)
Total AHEI score		38.2		63.2 (89.7)		62.5 (84.3)

Values in parentheses reflect potential diet scores when reducing diet components, which are either the result of potential additional animal-source foods (polyunsaturated fatty acid (PUFA) supply) or not directly associated with food production (sodium, *trans* fat).

stemming from food production of an average of 5 bn t CO_2-eq yr^{-1} (ref. [30]). This breaks down to 0.65 t CO_2-eq $cap^{-1}\,yr^{-1}$ today and shrinks to 0.59–0.51 t CO_2-eq $cap^{-1}\,yr^{-1}$ for a population between 8.5 and 9.9 billion people in 2050. Current Indian per capita emissions exceed these limits. Potential emissions from optimized food supplies, however, fall below current and future emission boundaries. In addition to reducing GHG emissions through optimized production and consumption, other interventions offer potential to sequester the carbon still emitted. Applying the full range of sequestration potentials from tropical agroforestry systems, between 0.1 and 3.4 Mha, or 0.05–1.8% of Indian cropland, would need to be converted permanently to agroforestry systems for every 0.1 bn t CO_2-eq emitted to sequester and offset diet-related GHG emissions. With an estimated total national land potential for agroforestry systems of 330 Mha[31], dietary GHG emissions could potentially be sequestered and offset for 97–149 (median, current emissions) to 159–245 years (median, maximum combined resource constraints). Crops grown in agroforestry systems might yield at least as much as under current land management practices, and hence do not impair total food output[32,33].

Health impacts of changing diets. If Indian food consumption patterns were to follow changes in national food supply closely, the resulting healthier eating patterns (that is, a reduced intake of highly processed foods and an increase in foods such as (minimally processed) fruit, vegetables, nuts and legumes) could also have a major positive impact on morbidity and mortality rates from both infectious and chronic diseases[34]. Focusing on potential positive effects on non-communicable disease patterns in the population, we used the Alternate Healthy Eating Index (AHEI) to score (0–100) and rank the overall nutritional quality of the current and potential optimized food supplies, including foods and nutrients that have been shown to be predictive of chronic disease risk in previous studies. We calculated an AHEI score of 38.2 for the current average Indian food supply, compared with a global mean of 50.0 and a global maximum reference score of 94.0 (ref. [35]). A low consumption of fruit, vegetables, whole grains and ω–3 fatty acids (national data on the long-chain n–3 contents of dairy were not available) as well as high *trans* fat intakes were major contributors to the current low score. A maximized potential food supply would raise the AHEI score from its current level to 63.3 (69.8 when including potential additional animal-source foods) (Table 1). An additional lowering/elimination of sodium and *trans* fats would raise the score further to 83.1 (89.7). Similarly, for the potential food supply under maximum combined resource constraints, the respective AHEI score increases to between 62.5 (64.5) and 82.3 (84.3) when also including reduced sodium and *trans* fat consumption. These scores are based on the entire potential food supply, which might exceed actual caloric requirements. A particular choice of foods from this supply (for instance, due to regional preference or cultural acceptability) could impact the AHEI score. A higher intake of fruit and both ω–3 and ω–6 fatty acids from plant- and animal-source foods would raise these scores further towards their maximum of 100.

An increase in the AHEI scores of potential Indian diets due to both improved food production patterns and higher-quality food choices could have profound effects on a number of non-communicable disease risks, which subsequently would translate to a reduced number of associated premature deaths. Figure 4 presents the preventable numbers of sex-specific total premature deaths and associated population-attributable fraction (PAF) for total deaths from chronic disease as well as for cause-specific premature deaths from six major causes. Increased average AHEIs from modelled maximized food supplies are associated with a potential reduction in total premature deaths by 14.6–30.0% (2.1–4.3 million people per year); food supplies under maximum combined resource constraints could result in a potential reduction by 14.2–26.9% (2.0–3.8 million people per year).

Discussion

Our study estimates India's capacity to provide its growing population with sufficient nutritious foods that are sustainable and healthy, primarily defined by micronutrient adequacy. Environmental challenges are large, and many political and socioeconomic barriers for both farmers and consumers need to be overcome to achieve national nutrition security. There are numerous trade-offs between natural resource use and food production for different dietary patterns. Focusing solely on one single resource or allowing for a small number of crops might lead to an over- or underestimation of saving potentials in the agricultural sector. Nevertheless, our study shows that depending on future environmental constraints, India has the land and freshwater capacities to potentially increase the production of nutrient-rich foods by allocating natural resources more efficiently. Tapping into this potential requires a gradual shift

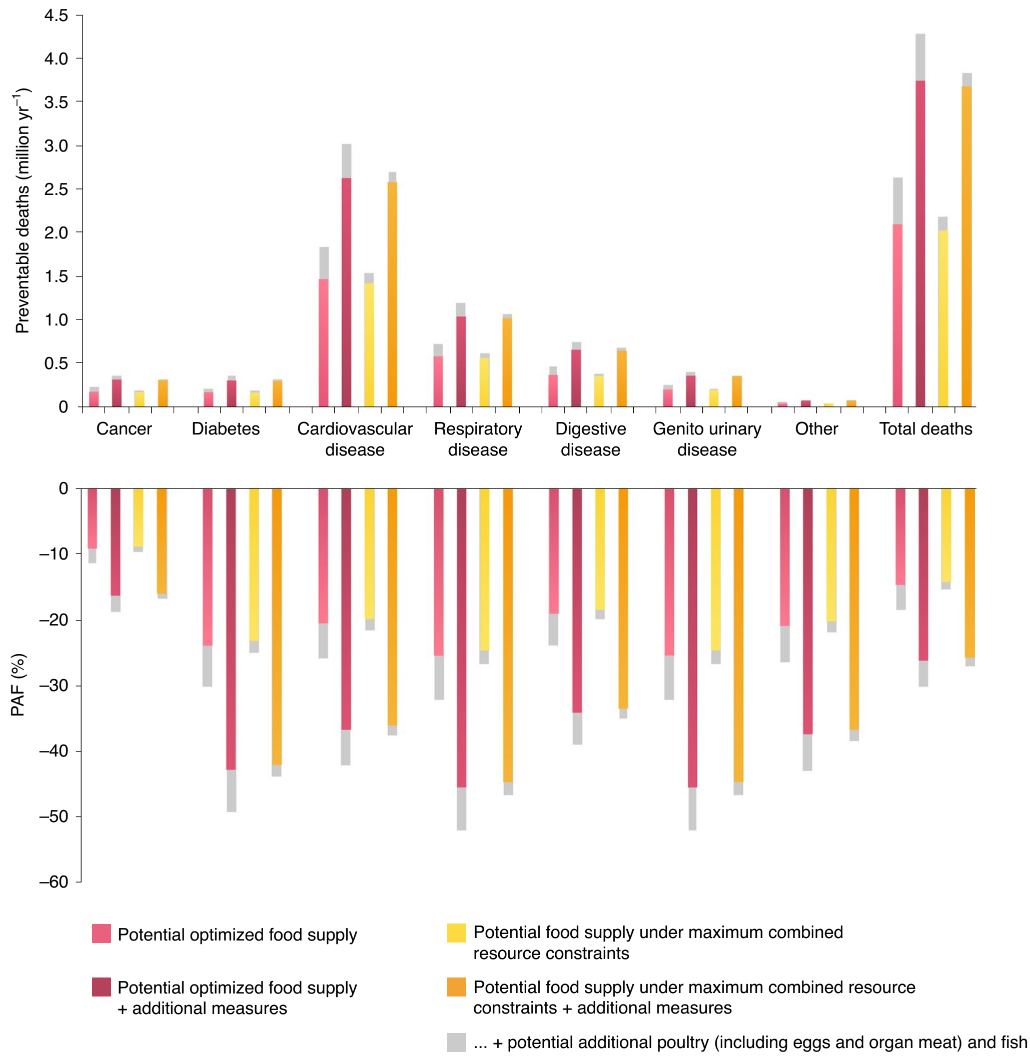

Fig. 4 | Reduction in deaths as a result of improved food supply. Total and percentage reductions in deaths as a result of improvements in AHEI score from current average Indian food supplies to potential optimized food supplies. Total average premature death rates from chronic disease could potentially be reduced by 14.2–30.0%. Total preventable deaths were calculated by summing all preventable-cause-specific deaths. PAFs were calculated as the percentage of preventable total deaths in total deaths, excluding those due to infection and injury. PAFs for total mortality were calculated based on the biological effects (risk ratios) for total deaths (deaths due to injury and infection excluded) from the Nurses' Health Study and the Health Professionals' Follow-Up Study (source data, Supplementary Table 11).

away from current production and consumption patterns, particularly of refined wheat, rice and sugar, towards higher supplies of fruit, vegetables and nuts. As a result, both quantity and quality of crop residues might increase. Using those residues as feed could become an important resource for livestock production, and consequently support additional supplies of animal-source foods.

There are a number of limitations that could have led to either an over- or underestimation of our final estimates. These include quantity and quality of natural resource use data, agricultural GHG emissions, livestock diets and food waste rates. From a nutrition perspective, there are several uncertainties regarding current food and nutrient intakes, their bioavailability as well as our dietary model constraints, that is the quantity and quality of minimum versus optimal macro- and micronutrient requirements. While testing the sensitivity of our input data revealed that detected overall trends consistently persisted through all modelled scenarios, more research is required to be able to include regional and seasonal food production limitations in more detail, to assess the effects of changing crop residue compositions as direct and indirect feed source on livestock production, and to generate more precise data on national food intakes and nutritional recommendations (see Supplementary discussion). Facilitating initial steps towards changed food production and consumption patterns could, in turn, have profound effects on population health in regard to non-communicable disease risk.

From an economic perspective such shifts could also lead to an increase in farm incomes, both directly through higher net profits from crops, and indirectly through a potentially increased production of animal-source foods. Compared with today's average food supply, current investment cost (cost of cultivation for crops) would rise by 37% for a potential maximized food supply, and 5% for a food supply under maximum combined resource constraints. Net profits at this time, however, would increase by 97 or 45%, respectively, as a result of a growing demand for fruit and vegetables over the last decades (Supplementary Table 12). Currently there are several political hurdles that hinder a development towards more efficient natural resource use in the agricultural sector as well as the economic viability of more sustainable and healthy food supply patterns for both farmers and consumers. More cohesive policy measures on the national to state level could target a diversification of currently subsidized foods, supporting primarily wheat, rice and sugar as part of the Public Distribution System[9], as well as adapting other indirect food-related subsidy schemes such as energy subsidies and national bioenergy targets. Additional policy measures include investments in storage and transport infrastructure; providing farmers with insurance schemes for vulnerable horticulture crops and crop redistribution; expanding the support for agroforestry projects; creating incentives for the food industry to increase the choice of convenient, affordable, nutritious foods and reduce the amount of nutrient-poor, highly processed foods (although some of these foods are currently being fortified with micronutrients); adding environmental sustainability goals to the national dietary guidelines; supporting research to improve animal diets, methane capture and improved manure management, increasing yields of various legumes, nuts and drought-resistant crops; and continuing to support a reduction in injudicious fertilizer use. In addition, opening markets to more international food trade might lower environmental pressures domestically—but might shift them to other regions—as well as increase food diversity. Such steps, however, might reduce national food and nutrition security through increased dependence on international food imports.

While all of these measures and incentives would support a transition of the food system in the medium to long term[36], there are also a variety of regional and local policy options that could address current environmental and health issues more immediately. These include regulating the market on select produce to ensure access to fresh nutritious foods for all citizens; investing in small-scale water infrastructure such as rainwater ponds to decrease the pressure on groundwater resources; offering guaranteed government purchases of fruit and vegetables, for example, to complement the Mid-day Meal Scheme and provide more nutritious foods at hospitals and other charitable institutions, while supporting diversified local food production; increasing the number of food banks to reduce the amount of food waste; supporting urban agriculture projects such as school gardens or fruit tree plantings in low-income areas; and educating people locally on healthy nutrition.

Methods

Nutritional status of the Indian population. To estimate current diet quality in regard to caloric intake, nutrient composition and nutritional adequacy, we based our analysis on the national household survey, which assesses per capita food supplies within households[26]. We then averaged data from Bowen et al.[37] and Singh et al.[38] to integrate the amounts and composition of foods that are consumed outside of the house (Supplementary Tables 4 and 9a,b) (compare Rawal et al.[39]). While India's regional cuisines vary substantially with respect to food preparation and flavour profiles, average diet composition (supply and share of major food groups), and hence average nutrient supplies, show strong similarities across the country (Supplementary Table 7a-ai).

To assess current macro- and micronutrient intakes in relation to their respective intake recommendations, food intakes were then adjusted for sex and age by applying (5 year) age group distribution patterns that were adopted from the Global Dietary Database[40]. Weighted national average food intakes were calculated by setting the average age to 25–29 years[41]. As we determine per capita protein intakes as a population average, we might underestimate the sufficiency of current protein supplies. The minimum recommended intake is set at 0.8–2.0 $g\,kg^{-1}$ depending on age, activity level and health status[42]. It has been estimated that the protein intakes of about 35% of the Indian population amount to less than 0.8 $g\,kg^{-1}$ (ref. [16]).

To determine the micronutrient contents of these foods we integrated data from two food composition databases. The Indian Food Composition Tables[43] offer information on several hundred foods in their raw/uncooked state. To estimate compositions of prepared Indian foods, we matched Indian data with their equivalent in the United States Department of Agriculture Food Composition Database[44]. After calculating relative deviations in nutrient contents between the two, we then adjusted nutrient values of raw Indian foods if applicable. In our analysis we included all macronutrients (protein, fat, carbohydrates), total fibre, vitamins A (RAE), C, E, B_1–B_6, folate, B_{12}, K, choline, and minerals calcium, iron, magnesium, potassium, zinc, copper, manganese and selenium.

We used average EARs to assess adequate mineral and vitamin intakes on the population level. The World Health Organization offers data on required nutrient intakes as well as on nutrient-specific conversion factors to derive EARs[45]. For magnesium, vitamin B_5 and vitamin K no conversion factors were available. We calculated these data using average mineral and vitamin conversion factors. There were no World Health Organization values available for manganese, choline, potassium and copper. We therefore used adequate intake estimates from the United States and converted them accordingly to EAR values[46] (Supplementary Tables 5 and 6, and Supplementary discussion). Besides adequate amounts of minerals and vitamins in the diet, the supply and composition of specific fatty acids, fibre and highly processed foods also play an important role in the overall healthfulness of diets. However, we did not include those diet components into our optimization approach as quantitative average requirements or upper limits have not yet been defined.

Environmental footprint of the current Indian diet. We calculated total land and cropland requirements, consumptive freshwater use in the form of green (rain) and blue (irrigation) water, and associated GHG emissions to estimate three main environmental footprints of the Indian food supply. To determine land and freshwater requirements, we divided India into five main agroclimatic regions: subtropical highland, humid subtropical, (semi-)arid, tropical wet and dry, and tropical wet (Supplementary Fig. 1). We calculated regional yields as weighted averages based on available state-level data[47]. Grazing land productivity for ruminant diets were averaged from Suresh et al.[48]. Consumptive water use was calculated using regional weighted averages based on available state-level data from the Water Footprint Network Database[49], which were derived from calculations by the CropWat model (Supplementary Table 13). The total annual blue water demand for the national food supply currently amounts to 219 $km^3\,yr^{-1}$ (assuming a 10% loss rate between farms and markets[1]). Today, most parts of India are experiencing water stress (that is, unsustainable water demand), where human water demand exceeds annual renewable water availability). Based on data reported by Davis et al.[5], we estimated regional water stress by calculating the weighted average of annual irrigation water use for domestic food production in relation to available sustainable water resources (accounting for environmental flows[50]). The (semi-)arid region currently draws 67% of its total water requirements for national food production from unsustainable sources, followed by the tropical wet and dry region at 42% and the humid subtropical region at 19%. The subtropical highland and tropical wet region currently use less than 10% of their respective sustainable water resources. On average, this amounts to 36% of the current national irrigation water demand for domestic food production being sourced unsustainably (Supplementary Table 8). Competing industrial and domestic water needs together with expected changes in precipitation patterns and melting glaciers are likely to aggravate the situation in the future[51].

GHG emission intensities for Indian plant foods were adopted as national averages from Sapkota et al.[29] and Vetter et al.[17,52]. Regarding animal-source foods, we adopted country-specific livestock data from Herrero et al.[53]. Total livestock-related GHG emissions amount to 0.32 bn t CO_2-eq yr^{-1}. Animal numbers, average feed intakes and associated total GHG emissions were matched with average water-use and land-use data for providing feed (grass and concentrates, including cereal grains) as well as drinking water needs. Natural resource use and GHG emissions were allocated according to the same allocation method, distributing resources and emissions evenly across total livestock weight (live weight plus, if applicable, milk/eggs) (Supplementary Table 13). These data were then applied to the average Indian diet by multiplying respective resource intensities by daily per capita food supply, and extrapolated to yearly footprints.

Cropland and freshwater capacity for nutritious diets. To determine India's natural resource capacities to produce nutritious foods most efficiently, we used a linear optimization approach to maximize the micronutrient output of the national food supply under current and potential future regional land and freshwater constraints. Modelled potential food supplies have to meet or exceed today's national average caloric intakes. We did not include food trade (and associated natural resource use) in our model as only small amounts of imported foods, mainly peas and soybean oil, play a role in the current Indian diet. The model balances national nutrient supplies across five major agroclimatic regions and their specific crop yields and water footprints, including up to 36 regionally suitable crops (173 variables in total), their macronutrient composition, fibre content, nutrient content (based on 20 minerals and vitamins) and their associated crop residues[54,55]. As crop residues could be used to feed livestock, the model further determines potential additional animal-source foods (poultry (including eggs and organ meat) and fish). Our objective function is the total sum of all included minerals and vitamins from plant and potential animal-source foods as percentages of their respective EAR (see Supplementary methods for detailed overview of the optimization approach, using R version 3.43[56]). To ensure diversity (both crop diversity within each region to increase the ecological resilience of the agricultural sector and conform with currently predominant smallholder farming patterns, and diet diversity to align potential national food supplies with basic dietary requirements), we applied a number of environmental and dietary constraints to our model approach. Modelled food supplies are based on limited regional land availability for each crop (land limitations for rice and wheat were equally split for whole and refined grains but remain interchangeable from an environmental perspective). These modelled supplies ensure minimum overall caloric, protein and fat supplies, and have to include regional production of fruit and vegetables; however, they limit the total amount of fruit and vegetables by constraining nutrient and caloric supplies of high and low calorically dense crops (Supplementary Table 14).

Urbanization and industrial development, increasing exports of agricultural products, national reforestation goals and ongoing land degradation do not allow for a substantial expansion of cropland in the future. We constrained regional land use for domestic food production to a maximum of its current level. Regional rainwater availability correlates directly with respective cropland availability. Total irrigation water use was restricted for the three major agroclimatic regions currently experiencing water stress, but not for the two remaining, subtropical highland and tropical wet, which possess abundant sustainable freshwater resources. However, we did not restrict overall GHG emissions because additional livestock resulting from changes in crop residue, and hence feed availability, remain speculative but could potentially impact overall dietary GHG emissions.

As the model does not include food (and other agricultural) exports, the associated land (26 Mha), irrigation water needs (35 $km^3 yr^{-1}$) and GHG emissions (0.04 bn t CO_2-eq yr^{-1}) (Supplementary Table 3) are not part of our optimization approach. Further, we assume that crop losses, seed use and waste rates remain stable. Food and Agriculture Organization Food Balance Sheets[1] document an aggregated loss rate between production and markets of ~10% for crops and ~15% for animal-source foods. Resulting total food supply estimates align very well with our calculated average food intakes of ~2,450 kcal $cap^{-1} d^{-1}$ (2,550 kcal $cap^{-1} d^{-1}$ average food supply, 15% stemming from foods consumed outside the house).

Due to expected population growth, climate change and ongoing environmental degradation, less land and water will be available per capita for food production in the future. As it is currently not possible to quantify future national natural resource availability on an annual level, we explore the limits of possible reductions in freshwater and cropland use, both separately and in combination, by decreasing regional resource inputs gradually and in proportion to their respective availability in 5% steps until a regional maximum reduction is reached. Potential reductions on the national level result from summing up regional maxima. We start from today's footprints, until resource constraints become too limiting to produce a given national output (≥2,450 kcal $cap^{-1} d^{-1}$). Increasing water constraints do not include changing drinking water needs for lactating and non-lactating livestock; adding these increases our calculated final freshwater needs only slightly.

Animal-source foods as byproduct of crop production. Compared with growing plant foods, growing crops as feed for livestock is often regarded as an inefficient use of valuable cropland and freshwater resources, while also contributing to globally rising GHG emissions. While plant foods contain a large number of essential minerals and vitamins for human nutrition, they do not adequately supply certain potentially critical nutrients such as preformed vitamin A[57], B_{12} and K_2[58]. In India only small areas of cropland are used for the purpose of feed crop production (~8 Mha, 4% of total cropland area[1]). Most ruminant feed is obtained from pasture and crop residues. Our optimization model includes total crop residues and potential associated animal-source foods under a number of constraints. Total modelled crop residue/animal-source food outputs were corrected by subtracting current total crop residues yields of 320 million tonnes per year (dry matter), which are already used for other purposes, two-thirds of which as livestock feed[48,53]. This amount was set as minimum crop residue output; only surplus residues could potentially be used to produce additional animal-source foods (see Supplementary discussion). Although additional sources of poultry (including eggs and organ meat) and fish (using an equal share of poultry and fish/shellfish from aquaculture) in the Indian diet would affect land and freshwater use only marginally, GHG emissions from livestock production would increase. We do not change total numbers of ruminants or feed quantities and type composition, and hence natural resource use efficiencies, as any assumptions on future herd sizes and potential additional feed sources remain highly speculative at this point. However, by hypothetically increasing the average nutritional value (total digestible nutrients) of current crop residues of 48% (mostly straws, stovers and oilseeds)[48] to 77% (mostly fruit and vegetable waste)[59], we are able to estimate the potential increase in milk yields from cows applying a conversion factor of 0.315 kg of total digestible nutrients per kg cow milk (4% fat)[60]. We held total GHG emissions from ruminants constant, as no available data so far indicate a potential increase in emissions from such changes in feed quality[59]. The increased drinking water needs to achieve higher milk yields were added to total freshwater needs

Offsetting greenhouse gas emissions from food production. Both plant and animal-source food production are sources of GHG emissions. One approach to sequester carbon within the agricultural sector are agroforestry systems. Depending on air temperature, precipitation patterns, soil composition and the specific form of agroforestry and tree species, a wide range of estimates (and uncertainties) for carbon sequestrations rates or carbon stocks can be found in the literature. Focusing specifically on soil carbon stocks in tropical agroforestry systems after at least 10 years of cultivation and 100 cm of soil depth, these estimates range—depending on literature source—from 8 to 228 t ha^{-1} for approaches including agroforests, woodlots and silvopasture. Median values range between 45 and 95 t ha^{-1} (refs. [61,62]). We adopted this range to estimate India's potential to offset GHG emissions from domestic food supply.

Estimating health impacts of changing diets. We calculated the AHEI score to assess current and future dietary quality[34]. For this approach we assumed potential future diet consumption would align closely with modelled food-supply patterns. The AHEI score is based on total intakes of vegetables, fruit, whole grains, sugar-sweetened beverages, nuts and legumes, red and processed meat, *trans* fats, long-chain ω–3 fatty acids, polyunsaturated fatty acids, sodium and alcohol. Greater adherence to the AHEI is associated with a lower risk of several non-communicable diseases. Wang et al.[35] applied this method on a global level by determining country-specific scores based on data from the Global Burden of Disease Study 2017. Adopting this approach for India allowed us to estimate the total number of preventable premature deaths as well as cause-specific deaths from cancer, diabetes, cardiovascular, respiratory, digestive, genito-urinary and other diseases that are associated with dietary quality. There are two complementary approaches affecting the AHEI score. In a first step, we calculated the potential effects on mortality rates based on changes in quantities and qualities (for example, sugar-sweetened beverages, whole versus refined cereals) of supplied food groups in the current food supply versus potential optimized food supplies. In a second step, we assumed potential changes in *trans* fat and sodium intakes to estimate potential additional positive health effects that are not a direct result of changing food production patterns (see Supplementary discussion). Our estimates do not include health risks associated with the potential exposure to pesticides. Thus, changes in the types and quantities used might affect overall health outcomes additionally.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability
The data supporting the findings of this study are available within the article and its Supplementary Information.

Code availability
Code used for this study is included in the Supplementary methods.

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References
1. *FAO Statistical Database* (Food and Agriculture Organization, 2011–2013); http://www.fao.org/faostat/en/#home
2. *National Food Security Bill* Registered Number DL-(N)04/0007/2003-13 (Government of India, Ministry of Law and Justice, 10 September 2013).
3. Bhattacharyya, R. et al. Soil degradation in India: challenges and potential solutions. *Sustainability* **7**, 3528–3570 (2015).
4. Khajuria, A. Impact of nitrate consumption: case study of Punjab, India. *J. Water Resour. Prot.* **8**, 211–216 (2016).
5. Davis, K. F. et al. Alternative cereals can improve water use and nutrient supply in India. *Sci. Adv.* **4**, eaao1108 (2018).
6. Caulfield, L. E. in *Disease Control Priorities in Developing Countries* 2nd edn (eds Jamison, D. T., et al.) Ch. 28 (International Bank for Reconstruction and Development/World Bank, 2006).
7. Green, R. et al. Dietary patterns in India: a systematic review. *Br. J. Nutr.* **116**, 142–148 (2016).
8. Naik, S., Mahalle, N. & Bhide, V. Identification of vitamin B_{12} deficiency in vegetarian Indians. *Br. J. Nutr.* **119**, 1–7 (2018).
9. DeFries, R. et al. Impact of historical changes in coarse cereals consumption in India on micronutrient intake and anemia prevalence. *Food Nutr. Bull.* **39**, 377–392 (2018).
10. Smith, M. R. et al. Inadequate zinc intake in India: past, present, and future. *Food Nutr. Bull.* **40**, 26–40 (2019).
11. *India: National Family Health Survey (NFHS-4), 2015–16* (International Institute for Population Sciences, 2017).
12. Akhtar, S. et al. Prevalence of vitamin A deficiency in South Asia: causes, outcomes, and possible remedies. *J. Health Popul. Nutr.* **31**, 413–423 (2013).
13. *India: Health of the Nation's States—The Indian State-Level Disease Burden Initiative* (Indian Council of Medical Research, Public Health Foundation of India and Institute for Health Metrics and Evaluation, 2017).
14. Riahi, K. et al. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Glob. Environ. Change* **42**, 153–168 (2017).
15. Sengupta, P. & Mukhopadhyay, K. Economic and environmental impact of National Food Security Act of India. *Agric. Food Econ.* **4**, 1–23. (2016).
16. Rao, N. D. et al. Healthy, affordable and climate-friendly diets in India. *Glob. Environ. Change* **49**, 154–165 (2018).

17. Vetter, S. H. et al. Greenhouse gas emissions from agricultural food production to supply Indian diets: Implications for climate change mitigation. *Agric. Ecosyst. Environ.* **237**, 234–241 (2017).
18. Harris, F. et al. The water use of Indian diets and socio-demographic factors related to dietary blue water footprint. *Sci. Total. Environ.* **587–588**, 128–136 (2017).
19. Davis, K. F. et al. Assessing the sustainability of post-Green Revolution cereals in India. *Proc. Natl Acad. Sci. USA* **116**, 25034–25041 (2019).
20. Milner, J. et al. Projected health effects of realistic dietary changes to address freshwater constraints in India: a modelling study. *Lancet Planet. Health* **1**, e26–e32 (2017).
21. Aleksandrowicz, L. et al. A modelling study using nationally-representative data. *Environ. Int.* **126**, 207–215 (2019).
22. Green, R. et al. Greenhouse gas emissions and water footprints of typical dietary patterns in India. *Sci. Total. Environ.* **643**, 1411–1418 (2018).
23. Ritchie, H. et al. Sustainable food security in India—domestic production and macronutrient availability. *PLoS ONE* **13**, e0193766 (2018a).
24. Ritchie, H. et al. Quantifying, projecting, and addressing India's hidden hunger. *Front. Sustain. Food Sys.* **2**, 11 (2018b).
25. Springmann, M. et al. Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. *Lancet Planet. Health* **2**, e451–e461 (2018).
26. *Household Consumption of Various Goods and Service in India 2011–12. NSS 68th Round* (Government of India, 2014).
27. Rosa, L. et al. Closing the yield gap while ensuring water sustainability. *Environ. Res. Lett.* **13**, 104002 (2018).
28. Mason-D'Croz, D. et al. Gaps between fruit and vegetable production, demand, and recommended consumption at global and national levels: an integrated modelling study. *Lancet Planet. Health* **3**, e318–e329 (2019).
29. Sapkota, T. P. et al. Cost-effective opportunities for climate change mitigation in Indian agriculture. *Sci. Total. Environ.* **655**, 1342–1354 (2019).
30. Willett, W. et al. Food in the anthropocene: the EAT–Lancet commission on healthy diets from sustainable food systems. *Lancet Comm.* **393**, P447–P492 (2019).
31. Ahmad, F., Uddin, Md. M., Goparaju, L., Rizvi, J. & Biradar, C. Quantification of the land potential for scaling agroforestry in South Asia. *J. Cartogr. Geogr. Inf.* 70, 81–89 (2020).
32. Sharma, B. et al. Comparative study of mango based agroforestry and mono-cropping system under rainfed condition of West Bengal. *Int. J. Plant. Soil. Sci.* **15**, 1–7 (2017).
33. Chirwa, P. W. et al. Tree and crop productivity in gliricidia/maize/pigeonpea cropping systems in southern Malawi. *Agrofor. Syst.* **59**, 265–277 (2003).
34. Chiuve S. E. et al. Alternative dietary indices both strongly predict risk of chronic disease. *J. Nutr.* **142**, 1009–1018 (2012).
35. Wang, D. D. et al. Global improvement in dietary quality could lead to substantial reduction in premature death. *J. Nutr.* **149**, 1065–1074 (2019).
36. Pingali, P., Aiyar, A., Abraham, M. & Rahman, A. *Transforming Food Systems for a Rising India* (Palgrave-Macmillan, 2019).
37. Bowen, L. et al. Dietary intake and rural–urban migration in India: a cross-sectional study. *PLoS ONE* **6**, e14822 (2010).
38. Singh, A.et al. Quantitative estimates of dietary intake with special emphasis on snacking pattern and nutritional status of free living adults in urban slums of Delhi: impact of nutrition transition. *BMC Nutr*. **1**, (2015)..
39. Rawal, V. et al. Prevalence of undernourishment in Indian states: explorations based on NSS 68th round data. *Econ. Polit. Wkly* **54**, 35–45 (2019).
40. *The Global Dietary Database—Global Dietary Intakes, Diseases, and Policies among Children, Women, and Men* (Bill and Melinda Gates Foundation, 2016); http://www.globaldietarydatabase.org/the-global-dietary-database-measuring-diet-worldwide.html
41. *Demographic Statistics Database* (United Nations Statistics Division, accessed September 2018); http://data.un.org/Data.aspx?d=POP&f=tableCode%3a22
42. Lonnie, M. et al. Protein for life: Review of optimal protein intake, sustainable dietary sources and the effect on appetite in ageing adults. *Nutrients* **10**, 360 (2018).
43. Longvah, T. et al. *Indian Food Composition Tables* (National Institute of Nutrition, 2017).
44. *Food Composition Database* (United States Department of Agriculture, 2016); https://ndb.nal.usda.gov/ndb/
45. *Human Vitamin and Mineral Requirements. Report of a Joint FAO/WHO Expert Consultation, Bangkok, Thailand* (World Health Organization, 2001).
46. *Nutrient Index* (Oregon State University, 2018); https://lpi.oregonstate.edu/mic/nutrient-index
47. *Statistical Year Book India 2018* (Ministry of Statistics and Programme Implementation, Government of India, 2019).
48. Suresh, K. P. et al. Modeling and forecasting livestock feed resources in India using climate variables. *Asian-Aust J. Anim. Sci.* **25**, 462–470 (2012).
49. Mekonnen, M. M. & Hoekstra, A. Y. *National Water Footprint Accounts: The Green, Blue and Grey Water Footprint of Production and Consumption (Value of Water Research Report Series Number 50)* (UNESCO-IHE Institute for Water Education, 2011).
50. Pastor, A. V. et al. Accounting for environmental flow requirements in global water assessments. *Hydrol. Earth Syst. Sci.* **18**, 5041–5059 (2014).
51. Briscoe, J. & Malik, R. P. S. *India's Water Economy: Bracing for a Turbulent Future* (Oxford Univ. Press, 2006).
52. Vetter, S. H. et al. Corrigendum to "Greenhouse gas emissions from agricultural food production to supply Indian diets: implications for climate change mitigation" [Agric. Ecosyst. Environ. 237 (2017) 234–241]. *Agric. Ecosyst. Environ.* **272**, 83–85 (2019).
53. Herrero, M. et al. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proc. Natl Acad. Sci USA* **110**, 20888–20893 (2013).
54. Renard, C. *Crop Residues in Sustainable Mixed Crop/Livestock Farming Systems* (CABI, 1997).
55. Smil, V. Crop residues: agriculture's largest harvest. *BioScience* **49**, 299–308 (1991).
56. *R: A language and environment for statistical computing* (R Foundation for Statistical Computing, 2016).
57. Haskell, M. J. The challenge to reach nutritional adequacy for vitamin A: β-carotene bioavailability and conversion—evidence in humans. *Am. J. Clin. Nutr.* **96**, 1193S–1203S (2012).
58. Schwalfenberg, G. K. Vitamins K_1 and K_2: the emerging group of vitamins required for human health. *J. Nutr. Metab.* **2017**, 6254836 (2017).
59. Bakshi, M. P. S. Waste to worth: vegetable wastes as animal feed. *CAB Rev.* **11**, 1–26 (2016).
60. Dikshit, A. K. & Birthal, P. S. India's livestock feed demand: estimates and projections. *Agric. Econ. Res. Rev.* **23**, 15–28 (2010).
61. Nair, P. K. R. et al. Soil carbon sequestration in tropical agroforestry systems: a feasibility appraisal. *Environ. Sci. Pol.* **12**, 1099–1111 (2009).
62. Murthy, I. K. et al. Carbon sequestration potential of agroforestry systems in India. *Earth Sci. Clim. Change* **4**, 1000131 (2013).

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Author contributions

K.D., S.S.M. and W.W. designed the study. K.D. developed the modelling approach. K.D., K.F.D., C.G. and M.H. collected and managed data. K.D. and K.F.D. analysed water-use data; K.D., C.G. and M.H. processed livestock emission data. K.D., W.W. and S.N.B. evaluated diet-related health risk data. K.D. wrote the draft and designed the graphs and maps. K.D., K.F.D., C.G., M.H., M.S., S.N.B., S.S.M. and W.W. contributed to the writing of the paper.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to K.D.

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☐	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☐	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☐	☐	Estimates of effect sizes (e.g. Cohen's d, Pearson's r), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No software was used to collect data.
Data analysis	Microsoft Excel 14.7.3 was used to prepare and harmonize data. R 3.4.3 and lpSolve 5.6.13 was used for linear optimization.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors/reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

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Ecological, evolutionary & environmental sciences study design

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Study description	The study uses an integrated environmental and nutritional linear optimization approach (natural resource use efficiency in regard to micro-nutrient supply) to determine the level of self-sufficiency India could reach now and with increasingly scarce resources in the future.
Research sample	Existing data were collected from various publicly available datasets on food consumption and composition (various sample sizes) as well as modelled data on natural resource use for food production.
Sampling strategy	No new data that required sampling were created.
Data collection	Data were collected from various publicly available datasets on food consumption and composition as well as natural resource use for food production.
Timing and spatial scale	Time sensitive data were collected from datasets published between 2009 and 2015.
Data exclusions	Some data from the Indian Food Composition Tables were excluded as they deviated unexplainably from the larger US dataset they were compared to. A cutoff of +/- 250% was used as described in the Supplementary Material of the manuscript.
Reproducibility	Several test runs to test sensitivity of all variable as well as reproducibility were done.
Randomization	Not relevant to this study as adopted datasets were already randomized (if applicable).
Blinding	Not relevant to this study as adopted datasets either aggregated data from food frequency questionnaires or modelled plant and livestock data.

Did the study involve field work? ☐ Yes ☒ No

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n/a	Involved in the study	
☒	☐	Antibodies
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☒	☐	Human research participants
☒	☐	Clinical data

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging