ARTICLE

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Global diets link environmental sustainability and human health

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Diets link environmental and human health. Rising incomes and urbanization are driving a global dietary transition in which traditional diets are replaced by diets higher in refined sugars, refined fats, oils and meats. By 2050 these dietary trends, if unchecked, would be a major contributor to an estimated 80 per cent increase in global agricultural greenhouse gas emissions from food production and to global land clearing. Moreover, these dietary shifts are greatly increasing the incidence of type II diabetes, coronary heart disease and other chronic non-communicable diseases that lower global life expectancies. Alternative diets that offer substantial health benefits could, if widely adopted, reduce global agricultural greenhouse gas emissions, reduce land clearing and resultant species extinctions, and help prevent such diet-related chronic non-communicable diseases. The implementation of dietary solutions to the tightly linked diet–environment–health trilemma is a global challenge, and opportunity, of great environmental and public health importance.

Agriculture is having increasingly strong global impacts on both the environment[1–5] and human health, often driven by dietary changes[6–9]. Global agriculture and food production release more than 25% of all greenhouse gases (GHGs)[2–4], pollute fresh and marine waters with agrochemicals[1,5], and use as cropland or pastureland about half of the ice-free land area of Earth[10]. Despite the intensity and impacts of global agriculture, almost a billion people still suffer from inadequate diets and insecure food supplies[11–13]. Moreover, the global transition towards diets high in processed foods, refined sugars, refined fats, oils and meats has contributed to 2.1 billion people becoming overweight or obese[6,14]. These dietary shifts and resulting increases in body mass indices (BMI) are associated with increased global incidences of chronic non-communicable diseases, especially type II diabetes, coronary heart disease and some cancers[7–9,15–22], which are predicted to become two-thirds of the global burden of disease if dietary trends continue[9,16,17]. In China, for instance, as incomes increased and diets changed[20], the incidence of type II diabetes increased from <1% of its population in 1980 to 10% in 2008, partly because type II diabetes occurs at lower BMI levels and earlier in an individual's life in Asian than in western populations[9]. Moreover, diet-driven increases in global food demand[7,8,12,23] and increases in population are leading to clearing of tropical forests, savannas and grasslands[1,5,23], which threatens species with extinction[1,3–5,23–25].

Because it directly links and negatively affects human and environmental health, the global dietary transition is one of the great challenges facing humanity. Meaningful solutions will not be easily achieved. Solutions will require analyses of the quantitative linkages between diets, the environment and human health, on which we focus here, and the efforts of nutritionists, agriculturists, public health professionals, educators, policy makers and food industries.

Here we compile and analyse global-level data to quantify relationships among diet, environmental sustainability and human health, evaluate potential future environmental impacts of the global dietary transition and explore some possible solutions to the diet–environment–health trilemma (Methods and Supplementary Information). To do so, we first expand on earlier food lifecycle analyses[24,25] (LCAs) by searching for all published LCAs of GHG emissions of food crop, livestock, fishery and aquaculture production systems that delimited the full 'cradle to farm gate' portion of the food/crop lifecycle. Next we use about 50 years of data for 100 of the world's more populous nations to analyse global dietary trends and their drivers, then use this information to forecast future diets should past trends continue. To quantify effects of alternative diets on mortality and on type II diabetes, cancer and chronic coronary heart disease, we compile and summarize results of studies encompassing ten million person-years of observations on diet and health. Finally, we combine these relationships with projected increases in global population to forecast global environmental implications of current dietary trajectories and to calculate the environmental benefits of diets associated with lower incidences of chronic non-communicable diseases.

Lifecycle environmental impacts of foods

Dietary composition strongly influences GHG emissions[2,24–27]. The 120 LCA publications that met our criteria report a total of 555 LCA analyses on 82 types of crops and animal products, allowing us to calculate diet-related GHG emissions per gram protein, per kilocalorie and per serving from 'cradle to farm gate' (Fig. 1; Methods, Extended Data Tables 1–3). We express emissions as CO_2 warming equivalents, in grams (g) or gigatonnes (Gt) of CO_2 carbon equivalents (CO_2-C_{eq}).

GHG emissions vary widely among foods (Fig. 1; Extended Data Table 3 lists means, s.e.m. and number of data points). As is well known, relative to animal-based foods, plant-based foods have lower GHG emissions. This difference can be large; the largest we found was that ruminant meats (beef and lamb) have emissions per gram of protein that are about 250 times those of legumes (Extended Data Table 3; Student's *t*-test comparison of means: $P < 0.0001$). Eggs, dairy, non-trawling seafood, traditional (non-recirculating) aquaculture, poultry and pork all have much lower emissions per gram of protein than ruminant meats (Tukey range test comparing ruminant meats with each other item: $P < 0.0001$ for each comparison). However, when sustainably grazed on lands unsuitable for cropping and fed crop residues, ruminant dairy and meat production can increase food security, dietary quality, and provide environmental benefits via nutrient cycling[28,29]. How a given food is produced can also affect emissions. Seafood caught by trawling, in which nets are often dragged across the ocean floor, has emissions per gram of protein about 3 times those of non-trawling seafood (Fig. 1; Extended Data Table 3; *t*-test mean comparison: $P = 0.017$). Items within the same food group can

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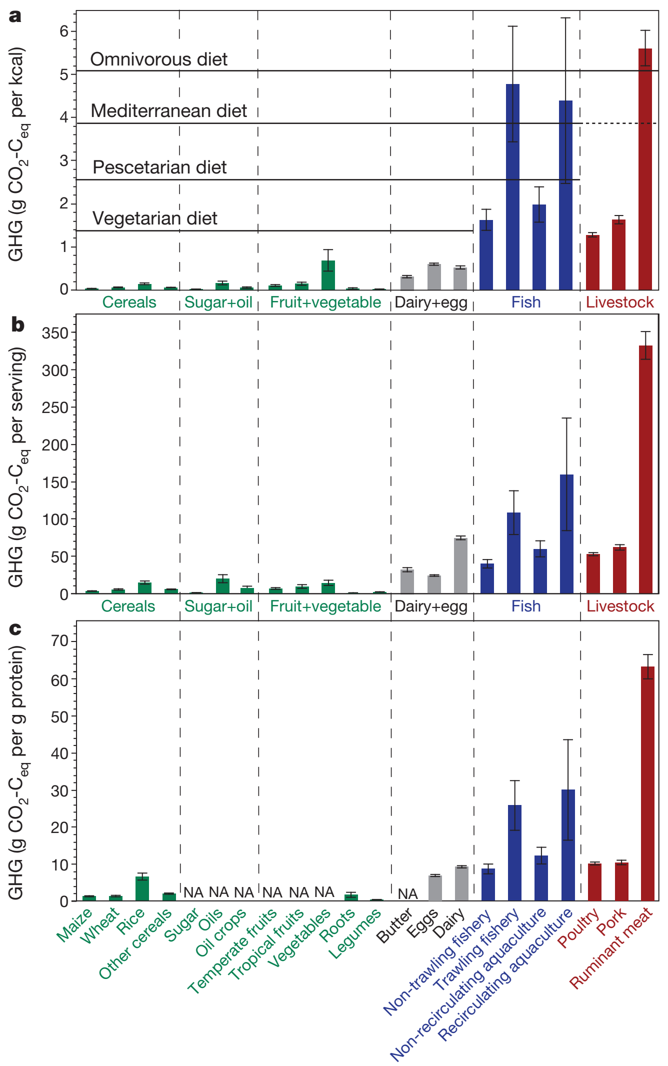

Figure 1 | Lifecycle GHG emissions (CO_2-C_{eq}) for 22 different food types. The data are based on an analysis of 555 food production systems: **a**, per kilocalorie; **b**, per United States Department of Agriculture (USDA)-defined serving; **c**, per gram of protein. The mean and s.e.m. are shown for each case. Extended Data Tables 1–3 list data sources, items included in each of the 22 food types and show the mean, s.e.m. and number of data points for each bar, respectively. NA, not applicable.

also differ. For instance, among cereal grains, wheat has a fifth the GHG emissions per g protein of rice (*t*-test comparison: $P = 0.002$).

Finally, to understand its environmental impacts, it is important to know the nutritional needs that a food meets and how much is consumed to do so. Fruits and vegetables are important sources of micronutrients, antioxidants and fibre. Unlike root crops and legumes, which are calorie-dense or protein-dense, most vegetables are not primarily consumed for calories or protein and should be evaluated by emissions per serving. For instance, 20 servings of vegetables have less GHG emissions than one serving of beef (Fig. 1b). However, fish and meats, which are high in protein, are also nutritionally dense foods that provide essential fatty acids, minerals and vitamins[28,29], and can have relatively low GHG emissions if eaten in moderation. Finally, the nutritional value of some foods can depend on how they are produced. For instance, in comparison to grain-fed cattle, grass-fed beef and dairy have nutritionally superior fatty acid and vitamin content[30].

Global dietary change

Although diets differ within and among nations and regions for a variety of climatic, cultural and historic reasons, diets have been changing in fairly consistent ways as incomes and urbanization have increased globally during the past five decades[6–9]. This dietary transition has many components, but, in broad outline, its magnitude and global nature are illustrated by trends in per capita demand for meat, empty calories and total calories (Fig. 2), where demand is defined as food brought into a household.

As annual incomes (per capita real gross domestic product, GDP) increased from 1961 to 2009, there were concomitant increases in per capita daily demand for meat protein (Fig. 2a) within and among eight economically based groups of nations[23] (Extended Data Table 4). In 2009, the richest 15 nations (Group A; Fig. 2a) had a 750% greater per capita demand for meat protein from ruminants, seafood, poultry and pork than the 24 poorest nations (Group F). Total protein demand also increased with income, but legume protein demand decreased as animal protein demand increased. India, a nation with low rates of meat consumption, is the major exception to an otherwise global trend in the income-dependence of demand for meat protein (Fig. 2a). China initially had meat demand increase more rapidly with income than Groups A–F, but was similar to them by 2009.

A second trend within and among economic groups is the income-dependent increase in demand for 'empty calories', here defined as calories from refined fats, refined sugars, alcohols and oils (Fig. 2b). In 2009, Group A nations had an average per capita empty calorie demand of 1,400 kcal per day, whereas demand was 285 kcal per day for Group F. The exception, China, is on an increasing but lower trajectory (Fig. 2b).

A third trend is that total per capita caloric demand also increased with income (Fig. 2c), with China falling below the fitted trend, and Group A being above it. Because some food brought into homes (demand) is wasted[13], and the proportion wasted tends to increase with per capita GDP[31], actual per capita consumption of meat, empty calories and total calories may be about 20%–25% lower than demand for the Group A nations and about 5% lower in Group F nations. This suggests that, in nations with per capita GDP above approximately \$12,000 per year (in 1990\$), per capita total caloric consumption may be about 500 kcal per day greater than needed nutritionally.

In total, annual data for 1961 to 2009 for China, India and six income-based groups of nations show that global dietary changes are associated with increased income (Fig. 2), which is itself associated with urbanization and industrial food production[20]. When these trends are combined with forecasts of per capita income for the coming decades, we estimate that, relative to the average global diet of 2009, the 2050 global-average per capita income-dependent diet would have 15% more total calories and 11% more total protein, with dietary composition shifting to having 61% more empty calories, 18% fewer servings of fruits and vegetables, 2.7% less plant protein, 23% more pork and poultry, 31% more ruminant meat, 58% more dairy and egg and 82% more fish and seafood.

Diet and human health

Diet is an important determinant of human health. Many of the world's poorest people have inadequate diets, and would have improved health were their diets to include more essential fatty acids, minerals, vitamins and protein from fish and meats and added calories and protein from other nutritionally appropriate sources[12,29]. In contrast, diets of many people with moderate and higher incomes are shifting in ways (Fig. 2) associated with increases in non-communicable diseases[6,7] including type II diabetes[9,19], coronary heart disease[21] and cancer[21], and with higher all-cause mortality rates[18,22].

A point of contrast to the detrimental health impacts of emerging global diets is provided by the benefits reported for three well-studied alternative diets. Here we summarize results from ten million person-years of observations across eight study cohorts[32–39] (Methods; Extended Data Table 5). For each cohort we use reported health outcome effect sizes that had been calculated after statistical control for potentially confounding variables to compare disease incidence rates of individuals who consumed typical omnivorous diets with those who had diets classified as Mediterranean, pescetarian or vegetarian (Fig. 1a). These diets

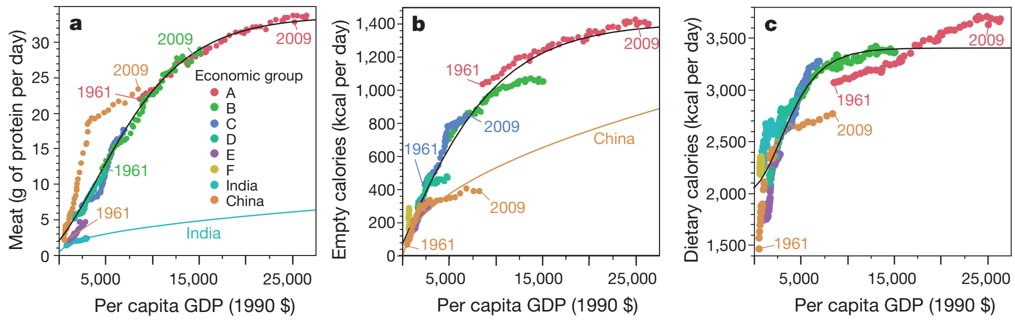

Figure 2 | Dietary trends and income. Dependence of per capita daily dietary demand for: **a**, meat protein; **b**, refined sugars+refined animal fats+oils+alcohol; and **c**, calories on per capita gross domestic product (GDP measured in 1990 International Dollars). Each point is an annual datum for 1961 to 2009 for India, China, and six economic groups containing 98 other nations (Extended Data Table 4). Fitted curves were used to forecast 2050 income-dependent demand.

have different compositions. A vegetarian diet consists of grains, vegetables, fruits, sugars, oils, eggs and dairy, and generally not more than one serving per month of meat or seafood. A pescetarian diet is a vegetarian diet that includes seafood. A Mediterranean diet is rich in vegetables, fruit and seafood and includes grains, sugars, oils, eggs, dairy and moderate amounts of poultry, pork, lamb and beef. Omnivorous diets, such as the 2009 global-average diet and the income-dependent 2050 diet, include all food groups.

Relative to conventional omnivorous diets, across the three alternative diets incidence rates of type II diabetes were reduced by 16%–41% and of cancer by 7%–13%, while relative mortality rates from coronary heart disease were 20%–26% lower and overall mortality rates for all causes combined were 0%–18% lower (Fig. 3). This summary illustrates the magnitudes of the health benefits associated with some widely adopted alternative diets. The alternative diets tend to have higher consumption of fruits, vegetables, nuts and pulses and lower empty calorie and meat consumption than the 2009 average global diet and the 2050 income-dependent diet (Extended Data Fig. 1). Our analyses are not designed to compare the health impacts of the three alternative diets with each other, nor to imply that other diets might not provide health benefits superior to these three diets. Indeed, the reported impacts of individual foods, such as deleterious impacts from sugars[40] and processed meats[19,22], and benefits from nuts and olive oil[41], suggest that variants of these three diets may offer added health benefits, as may other diets.

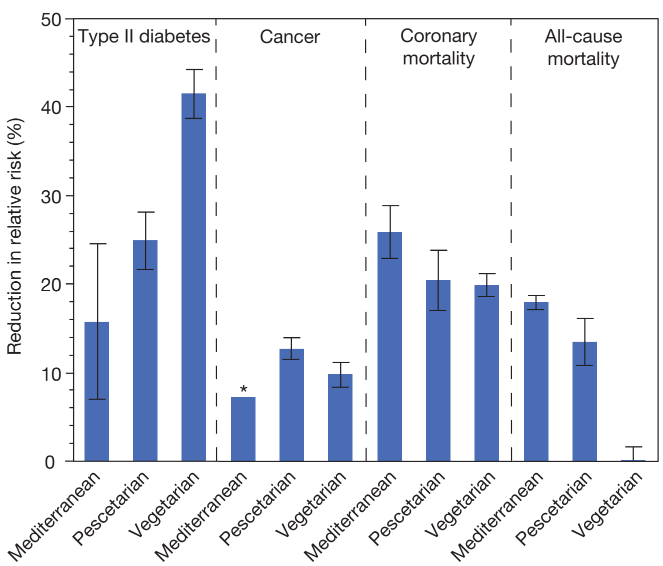

Figure 3 | Diet and health. Diet-dependent percentage reductions in relative risk of type II diabetes, cancer, coronary heart disease mortality and of all-cause mortality when comparing each alternative diet (Mediterranean, pescetarian and vegetarian) to its region's conventional omnivorous diet (Methods). Results are based on cohort studies[32–39]. The mean and s.e.m. values shown are weighted by person-years of data for each study. Number of studies for each bar are, from left to right, 3, 2, 2, 1, 2, 2, 4, 2, 5, 13, 2 and 4. *Cancer in Mediterranean diets is from a single study so no s.e.m. is shown.

Environmental impacts of diets

GHG emissions are highly dependent on diet[24–27,42–44]. Even foods that provide similar nutrition and have similar impacts on health can have markedly different lifecycle environmental impacts. Using LCA emission data, we calculated annual per capita GHG emissions from food production ('cradle to farm gate') for the 2009 global-average diet, for the global-average income-dependent diet projected for 2050, and for Mediterranean, pescetarian and vegetarian diets (Fig. 4a). Global-average per capita dietary GHG emissions from crop and livestock production would increase 32% from 2009 to 2050 if global diets changed in the income-dependent ways illustrated in Fig. 2. All three alternative diets could reduce emissions from food production below those of the projected 2050 income-dependent diet (Fig. 4a), with per capita reductions being 30%, 45% and 55% for the Mediterranean, pescetarian and vegetarian diets, respectively. However, minimizing environmental impacts does not necessarily maximize human health. Prepared items high in sugars, fats or carbohydrates can have low GHG emissions (Fig. 1) but be less healthy than foods they displace[20]. Solutions to the diet–environment–health trilemma should seek healthier diets that have low GHG emissions rather than diets that might minimize GHG emissions.

Changes towards healthier diets can have globally significant GHG benefits (Fig. 4b). From 2009 to 2050 global population is projected to increase by 36% (ref. 10). When combined with the projected 32% increase in per capita emissions from income-dependent global dietary shifts, the net effect is an estimated 80% increase in global GHG emissions from food production (from 2.27 to 4.1 Gt yr^{-1} of CO_2-C_{eq}).This increase of 1.8 Gt yr^{-1} is equivalent to total 2010 global transportation emissions[3]. In contrast, there would be no net increase in food production emissions if by 2050 the global diet had become the average of the Mediterranean, pescetarian and vegetarian diets (Fig. 4b).

Future global land clearing for agriculture could threaten species with extinction[1,5] and release GHG beyond that from food production. However, the extent of such land clearing is uncertain, variously projected to total from 0 to 10^9 hectares[5,23,45,46] by 2050, perhaps because of uncertainties about the future values of five factors: crop yields, agricultural and food waste, livestock yields from pastures, animal feed use efficiency and agricultural trade. Here we focus not on forecasting the absolute amount of cropland needed in 2050, but on estimating across many scenarios (243 combinations of three values for each of the five factors; Methods) the differential impacts of diets on global cropland. The alternative scenarios forecast a range of changes in cropland from 2009 to 2050 for each diet (Fig. 4c). For each scenario we calculated the difference between projected 2050 land demands of the income-dependent diet

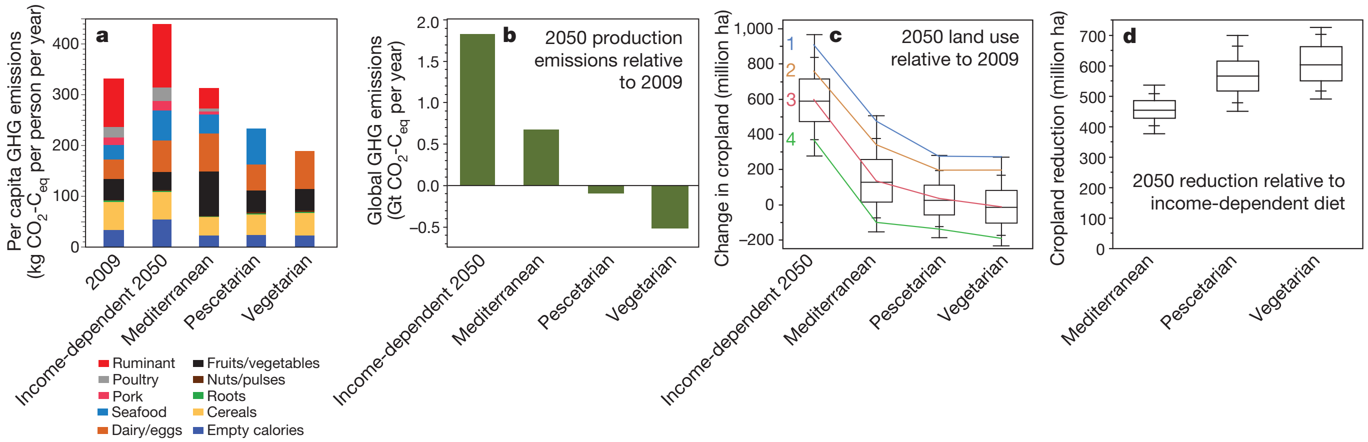

Figure 4 | Effect of diets on GHG emissions and cropland. **a**, Per capita food production GHG emissions for five diets (2009 global-average, 2050 global income-dependent, Mediterranean, pescetarian and vegetarian). **b**, **c**, Forecasted 2009 to 2050 changes (2009 value set to 0) in global food emissions (**b**), and cropland for each diet (Methods; alternative scenarios, such as lines 1-4, have fairly parallel trends) (**c**). **d**, 2050 global cropland reductions from alternative diets relative to income-dependent diet. The box and whisker plots (**c**, **d**) show mean (centre line) and percentiles below (2.5th, 10th, 25th) and above it (75th, 90th, and 97.5th) based on 243 scenarios.

and of each alternative diet (Fig. 4d). Across these scenarios, the income-dependent diet requires from 370 to 740 million hectares more cropland than the alternative diets, and averages 540 million hectares more (Fig. 4d). These results suggest that shifts towards healthier diets could substantially decrease future agricultural land demand and clearing, as could improvements in the five factors (Extended Data Table 6). Land clearing also leads to GHG emissions. Clearing 540 million hectares from 2010 to 2050 would release about 0.6 Gt yr^{-1} of CO_2-C_{eq}.

In addition to dietary shifts, other changes will be needed for agriculture to become environmentally sustainable[13,23,28–31,47–49]. If, by 2050, all forms of crop and food wastage[13,31] were globally reduced by 50%, food production emissions could be reduced by about 0.5 Gt yr^{-1} of CO_2-C_{eq} relative to the 2050 income-dependent diet. Increases in use efficiencies of animal feeds (from those of Extended Data Table 7), fertilizer and irrigation, and improvements in pasture management and aquaculture would increase food production, decrease GHG emissions and improve water quality[28,29,47–49]. Increases in yields of under-yielding nations could also reduce emissions[23]. Climate change, though, can affect yields[50], which could in turn have an impact on agricultural GHG emissions and land clearing.

Discussion

Dietary choices link environmental sustainability and human health. Current dietary trajectories (Fig. 2) are greatly increasing global incidences of type II diabetes, cancer and coronary heart disease. These dietary changes are causing globally significant increases in GHG emissions and contributing to land clearing. Although this pattern does not mean that healthier diets are necessarily more environmentally beneficial, nor that more environmentally beneficial diets are necessarily healthier, there are many alternative dietary options that should substantially improve both human and environmental health.

Our analyses demonstrate that there are plausible solutions to the diet–environment–health trilemma, diets already chosen by many people that, if widely adopted, would offer global environmental and public health benefits. Clearly, to appeal to specific segments of the global population, other such diets should also be developed. The health benefits of adopting such diets could be substantial. Chronic diet-related non-communicable diseases are affecting an increasing number of children and adults in all but the poorest nations. Nations ranging from China and India to Mexico, Nigeria and Tunisia are in the midst of this increasing disease incidence[17]. Unless the nutrition transition that is under way is changed, diabetes, chronic heart disease and other diet-related chronic non-communicable diseases will become the dominant global disease burden, often affecting even the poorer members of poorer nations for whom appropriate health care is unavailable[16,17].

The dietary choices that individuals make are influenced by culture, nutritional knowledge, price, availability, taste and convenience, all of which must be considered if the dietary transition that is taking place is to be counteracted. The evaluation and implementation of dietary solutions to the tightly linked diet–environment–health trilemma is a global challenge, and opportunity, of great environmental and public health importance.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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Supplementary Information is available in the online version of the paper.

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Author Contributions D.T. conceived this project and M.C. assembled data; both M.C. and D.T. analysed data and wrote the paper.

Author Information All data used in our analyses are publicly available from the original sources that we list, and are provided in the Supplementary Information. Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to D.T. (tilman@umn.edu).

METHODS

Lifecycle compilation and analyses. We identified and used in our analyses a total of 120 publications detailing 555 LCAs of GHG emissions from a total of 82 different food items. To find candidate publications, we searched for papers reporting LCAs for numerous food crops, livestock types, fishery species and aquaculture species using Web of Knowledge, PubMed, AGRICOLA and Google Scholar. We chose all published LCAs (Extended Data Table 1) that detailed the system boundaries of the study and that included and delimited the full 'cradle to farm gate' portion of the food/crop lifecycle GHG emissions, including emissions from pre-farm activities such as fertilizer and feed production as well as infrastructure construction, but excluding emissions from land-use change. The better to compare the emissions between different food groups, we calculated emissions per unit protein, per kilocalorie, or per USDA serving using data from the USDA's Nutrient Database[51] and the USDA's MyPlate[52]. Because few data were available on emissions from post-farm-gate activities (processing, packaging and transportation to the household), they are not included in our analyses. However, on the basis of data for 21 crop/food production systems for which data were available, inclusion of post-farm-gate food emissions would increase our otherwise calculated 2050 total global agricultural production emissions by about 20%.

For analysis, we aggregated food items into the 22 food groups shown in Fig. 1. Extended Data Table 2 lists food items included in each food group. Extended Data Table 3 has the number of data points as well as mean and standard error of GHG emissions for each food group. To minimize bias, we do not use in our analyses GHG emissions from uncommon ways of producing foods, such as greenhouse-grown vegetables (33 g of CO_2-C_{eq} per serving, versus 14 g of CO_2-C_{eq} per serving for field-grown vegetables), for an uncommon speciality food, lobsters caught via trawling (690 g of CO_2-C_{eq} per gram of protein), and one outlier, organic potatoes, with estimated emissions 16 times that of conventional potatoes.

Economic groups. Our analyses of dietary trends and of environmental impacts of alternative diets use data from the 100 most populous nations for which annual data were available from 1961 to 2009. We analyse data from the two most populous nations, China and India, individually and use aggregated data for all other nations, with these nations aggregated into six groups based on per capita GDP[23]. Group A contains the 15 nations with the highest per capita GDP, Group B has the next 15, and so on to Group F which contains the 24 nations with the lowest, except for Group C which has 14 nations (Extended Data Table 4). These eight economic groups/nations contain 89.9% of the 2009 global population. Nations that did not have continuous data available from 1961–2009 were excluded from the study.

Health impacts of different diets. We used Web of Knowledge, PubMed and Google Scholar to search for cohort-based peer-reviewed publications examining the health outcomes of Mediterranean-like, pescetarian (fish consumption $>$ once per month but all other meats $<$ once per month), or vegetarian (fish plus meat $<$ once per month, except $<$ once per week for one study[32]) diets relative to health outcomes of typical omnivorous diets of individuals in the same cohort. We report results for those cohort studies that followed more than 5,000 individuals for a period of at least one year, and that detailed (1) the number of individuals following each diet, including the average omnivorous diet in the studied cohort, (2) the average number of years of observation and (3) the relative risk of one or more of four medical conditions: type 2 diabetes incidence, all cancer incidence, heart disease mortality or mortality from all causes. In total, our analysis contains results presented in 18 publications[32–39,53–62] that, in aggregate, summarize approximately ten million person-years of observations, drawn from eight prospective health study cohorts (Extended Data Table 5). We use only published incidences that had been corrected, in the original publication, for effects of potential confounding variables.

In the case of the pescetarian and vegetarian diets, individuals either followed or did not follow these diets, based on the criteria described above. For the Mediterranean diet, we compared the health outcomes for individuals with a Mediterranean diet score of 6–9 (as defined by Trichopoulou[63,64] and altered by individual studies) to those with a score of 0–3.

Relative disease risk for each study of a particular diet–disease combination was calculated as the reported risk of a particular medical condition for an alternative diet (Mediterranean, pescetarian or vegetarian) divided by the risk for the same condition for the cohort portion of that study consuming the local omnivorous diet, then expressed as a percentage. To determine the average relative risk for each disease and each alternative diet across all eight cohorts, we weighted the relative risk we calculated for each instance of a disease–diet combination by the number of person-years of observations for that particular medical condition and alternative diet combination.

Per capita GDP forecasts. We forecast the 2050 per capita GDP for each economic/national group as described in ref. 23, by using a differential equation model represented by a Kuznet-shaped curve fitted[65] to the observed 1961–2009 dependence of $(dP/dt)(1/P)$ on P, that is, the dependence of per capita real GDP growth rates on real per capita GDP, where P is per capita GDP data from the Total Economy Database of the Groningen Growth and Development Centre, New York[66].

Income-dependent diet. We use 'demand' to refer to food brought into a household, which we do not call 'consumption' because some portion of it is not eaten, but rather is wasted[13,31]. We used data from the United Nations Food and Agriculture Organization (FAO)[10] in 2013 to calculate per capita daily demand for various types of foods, for total dietary protein and for total calories for each year from 1961 to 2009 for each of the eight economic groups/nations. We then determined the dependence of demand on per capita GDP using GDP data for 1961 to 2009 from the Total Economy Database[66].

Total demand, proportion of total demand from plants (barley, maize, wheat, rice, other cereals, soybeans, oil crops other than soybeans, starchy roots and tubers, legumes, fruits, vegetables and sugar crops), demand for meat (beef, lamb, mutton and goat, pork, poultry, and seafood), demand for dairy and eggs, as well as demand for empty calories (refined animal fats, oils, sugars and alcohols) were modelled globally using a Gompertz 4p curve (Fig. 2). The Gompertz 4p is a logistic-like function that has both an upper and a lower asymptote. The Gompertz 4p equation is:

$$Y = a + (b - a)(\exp[-\exp[-r(x - d)]])$$

where a is the lower asymptote, b is the upper asymptote, r is the growth rate, and d is the inflection point. For each economic group, we assumed that the relative consumption of foods within each of the modelled food groups remained constant at 2009 proportions. Economic groups that followed a trend different from that of the global trajectory (India for meats, China and economic Group D for dairy and eggs, and China for empty calories) were modelled independently of the rest of the economic groups using demand against the square root of per capita GDP (Fig. 2).

By combining the fitted dependence of demand on per capita GDP with country-specific per capita GDP and United Nations population forecasts, we were able to estimate total annual demand in 2050 for each food group within each economic group.

Alternative diets. Per capita protein demand for the vegetarian diet is based on the General Council of Seventh-day Adventists Nutrition Council's recommended vegetarian diet[67]. The pescetarian diet was modified from the vegetarian diet, and includes a single one-ounce serving of fish per day but reduced milk, egg and cereal demand so that total per capita protein demand is 1.5 g less per day than that of the vegetarian diet. The Mediterranean diet is derived from recommendations from refs 68 and 64. Demand for 2010 through 2050 within each economic group was then calculated using United Nations population forecasts[10].

Marine fisheries and aquaculture. In this publication, we use FAO reported fisheries landings in 2009 (ref. 69) plus the increment in marine fisheries that is estimated to come from improved management[70] as the global maximum fisheries catch. For our projections of GHG emissions associated with alternative diets, we assume that any fish consumption beyond this limit is produced in aquaculture systems. Recent analyses discuss ways to more than double aquaculture protein production by 2050 while minimizing the environmental impacts of this increased production[71,72]. Global adoption of the Mediterranean or the pescetarian diet by 2050 would require 62% or 188% more seafood production, respectively. If wild-caught landings stayed at current levels, aquaculture, which grew at 6.1% per year for 2002 to 2012 (ref. 71), would have to increase at 4.1% per year from 2010 to 2050 to meet the demand of the pescetarian diet.

Agricultural cropland use. We estimate 2050 land demand to see whether alternative diets have consistent differences in their land demands even when allowing for a range of scenarios of future global agricultural development, as represented by suites of values for future yields, food waste, pasture productivity, livestock efficiency, and agricultural trade. Specifically, we explore 243 different scenarios consisting of all combinations of three values for each of five factors (the 2050 percentage increases in crop yields, in livestock productivity of pastures, in feed-use efficiency of livestock and aquaculture, and in international agricultural trade, and the 2050 percentage decreases in food waste). Statistical analysis of the dependence of the land needed in 2050 on diet type and on the values of each variable provides estimates of the effect of a 1% change in each variable on 2050 land demand, and of each diet on 2050 land demand (Fig. 4c, Extended Data Table 6). The values chosen for each variable represent small (15%) to moderate (30%) changes that seem plausible given past temporal trends.

Crop yield scenarios. We used crop production data as reported by the FAO[10]. We calculated weighted average crop yields for each of the eight economic groups for several crop groups (barley, maize, rice, wheat, other cereals, soybeans, other oil crops, fruits, vegetables, pulses, roots and tubers, sugar crops and tree nuts). We then converted the weighted average crop yields into nutritious yields (kcal per ha and tonnes of protein per ha) using data from the USDA's Nutrient Database[51].

As our baseline scenario for future yields, we assume that crop yields will continue increasing along the linear trajectory fitted to the past 25 years for each crop group within each economic group. We use the previous 25 years of data, as opposed to all of the data available, because recent analyses suggest that the trajectories of crop yield increases have slowed during this time frame[73]. The other two yield scenarios are 'accelerated' compared to past trajectories (that occur at faster than historic rates), but limited so as not to exceed the 2009 yields of the highest-yielding economic group (usually Group A or B, depending on crop type). Accelerated yields increase from 2009 values linearly through the years such that by 2050 they have closed either 15% more or 30% more of the 2009 yield gap between an economic group and the highest-yielding economic group than would have been closed by following their historic yield trends. Thus our three yield scenarios accelerate the closing of the yield gap by 0%, 15% or 30%.

Food waste scenarios. We used available data[31] to calculate food waste for different sectors of the food production system (agricultural production, handling and storage, processing and packaging, distribution and household consumption) by crop groups (cereals, oil seeds and pulses, roots, fruits and vegetables, meats, milk, and seafood) and by geographic region[31].

When calculating the impacts of reduced food waste, we assume that food consumption (what is actually eaten) remains constant. For our land-use forecasts, we keep waste at its current levels[31] (0% reduction), or reduced waste in each of the aforementioned sectors of the food production system by 15% or 30%.

Livestock feed-use efficiency scenarios. Livestock operations that use animal feeds currently differ widely in their feed conversion efficiencies. Here we assume, as our base case, that by 2050 all livestock operations in all economic groups will achieve the feed conversion ratios of the best economic group in 2009 for each type of livestock. The two accelerated scenarios assume that 2050 feed conversion efficiencies of all economic groups are 15% or 30% greater than the efficiencies observed in the best economic groups of 2009 (Extended Data Table 7).

Pasture livestock production scenarios. Our three scenarios for pasture productivity are that global livestock production from pastures will remain at its current level (0% increase), will increase 15% by 2050, or will increase 30% by 2050. Increased pasture livestock production is assumed to displace livestock production in animal feeding operations, thus decreasing the land area needed to grow feed crops.

Agricultural trade scenarios. We define agricultural trade as the percentage of demand within each economic group for a given crop group that is met through international trade. For our scenarios we assume, for simplicity, that the magnitude of trade is the same for each crop group, with the exception of fruits and vegetables, which are assumed not to be traded in our model. Trade is assumed to be between a lower-yielding group and the economic group that has the highest yield for each given crop group. Our three scenarios have international trade that would provide 10%, 20% or 30% of domestic demand.

Cropland use forecasts. For each diet (income-dependent, Mediterranean, pescetarian and vegetarian), we forecast the cropland needed in 2050 for each scenario (each of the 243 combinations of three values for each of the five variables discussed above).

Food demand and crop yields for each economic group were determined as explained above. To forecast animal feed use, we used peer-reviewed publications to perform an analysis of animal diets[74–76] and to calculate protein conversion ratios (feed protein used to edible protein produced; Extended Data Table 7) and the average animal feed composition for beef, mutton and goat, pork and poultry, as well as for several aquaculture species. In combination with our food demand projections, this analysis enabled us to estimate animal feed use.

For each diet and each scenario (that is, each combination of values for waste, yields increases, pastureland productivity, efficiency of feed conversion and international trade), cropland use in 2050 for a given crop group within a given economic group is the total 2050 demand for the crop group (from both food and animal feed demand from within that economic group and from trade) divided by the 2050 crop yield for that economic. Global cropland demand for each scenario and diet is the summation across all crop groups and all economic groups of the land required for every crop group within every economic group.

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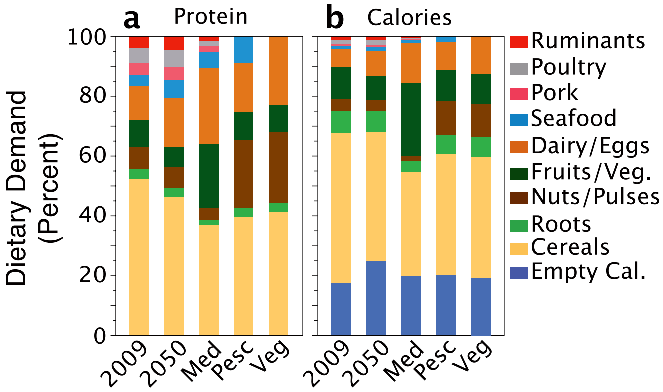

Extended Data Figure 1 | Dietary composition. The percentage of per capita total dietary protein (**a**) or calorie demand (**b**) that is met by each of ten food types is shown for each of five different diets: the global-average 2009 diet, the projected income-dependent diet for 2050, the Mediterranean diet, the pescetarian diet and the vegetarian diet.

Extended Data Table 1 | Original data sources for LCAs in Fig. 1

Lead Author	Year	Journal	Issue/URL	Pages	Food Types Examined
Abeliotis	2012	Jrn of Cleaner Prod	41	89-96	PUL
Alaphilippe	2013	Agro for Sust Devel	33	581-592	TEF
Arsenault	2009	Int Jrn of Agri Sust	7	19-41	DA
Aubin	2009	Jrn of Cleaner Prod	17	354-361	RA; NA
Ayer	2009	Jrn of Cleaner Prod	17	362-373	RA; NA
Basset-Mens	2005	Agri Eco and Env	105	127-144	PK
Basset-Mens	2009	Agri Econ	68	1515-1625	DA
Beauchemin	2011	Animal Feed Science and Tech	166-167	663-677	RM
Bengtsson	2013	Jrn of Cleaner Prod	41	291-300	PO
Bennet	2004	Plant Biotechnology Jrn	2	273-278	SC
Biswas	2008	Water and Env Jrn	22	206-216	W
Biswas	2010	Jrn of Cleaner Prod	18	1386-1392	W/RM
Blengini	2009	Jrn of Env Management	90	1512-1522	R
Bosch	2011	Options Méditerranéenes	100	125-130	RM
Bosma	2011	Int Jrn of LCA	16	903-915	NA
Brentrup	2003	Euro Jrn of Agro	20	265-279	W
Buchspies	2011	ESU Services Ltd	URL [1]		NA; TF
Canals	2006	Agri Eco and Env	114	226-238	TEF
Cao	2011	Env Science and Technology	45	6531-6538	NA
Casey	2005	Society for Eng in Agri, Food, and Bio Sys	URL [2]		RM
Casey	2006	Jrn of Env Quality	35	231-239	RM
Cederberg	2000	Jrn of Cleaner Prod	8	49-60	DA
Cederberg	2004	Swedish Institute for Food and Biotech	URL [3]		DA
Cerutti	2013	Jrn of Cleaner Prod	52	245-252	TEF
Charles	2006	Agri Eco and Env	113	216-225	W
Choo	2011	Int Jrn of LCA	16	669-681	OC
Clarke	2013	Jrn of Agri Science	151	714-726	RM
d'Orbcastel	2009	Aquacultural Eng	40	113-119	RA; NA
da Silva	2010	Jrn of Env Management	91	1831-1839	SOY
de Backer	2008	British Food Jrn	111	1028-1061	V
Dekker	2011	Livestock Science	139	109-121	EGG
Dekker	2013	Livestock Science	151	271-283	EGG
Devers	2011	Agrekon: Agri Econ Res, Pol and Prac in So Afr	51	105-128	PK
Driscoll	2010	Marine Policy	34	353-359	NF; TF
Dwivedi	2012	Agri Sys	108	104-111	TRF
Edward-Jones	2009	Jrn of Agri Science	147	707-719	RM
Ellingsen	2009	Marine Policy	33	479-488	NA
Eriksson	2005	Env Sys Analysis	10	143-154	PK
Fallahnpoor	2012	Env, Devel and Sust	14	979-992	B; W
Fat Tire Brewing Co.	2008		URL [4]		BEER
Foley	2011	Agri Eco and Env	142	222-230	RM
Gazulla	2010	Int Jrn of LCA	15	330-337	TEF
Girgenti	2013	Science of the Total Env	458-460	414-418	TEF
Gonzalez-Garcia	2013	Science of the Total Env	442	225-234	DA
Graefe	2013	Fruits	68	303-314	TRF
Gronroos	2006	Boreal Env Research	11	401-414	NA
Gunady	2012	Jrn of Cleaner Prod	28	81-87	TEF; V
Haas	2001	Agri Eco and Env	83	43-53	DA
Halberg	2010	Agro for Sust Devel	30	721-731	PK
Hokanozo	2012	Jrn of Cleaner Prod	28	101-112	R
Hortenhuber	2010	Renewable Agri and Food Sys	25	316-329	DA
Hospido	2005	Fisheries Research	76	174-186	NF
Hospido	2008	Int Jrn of LCA	14	381-391	V
Ingwersen	2012	Jrn of Cleaner Prod	35	152-163	TRF
Iribarren	2010	Science of the Total Env	408	5284-5294	NA; NF; TF
Jerbi	2012	Aquacultural Eng	46	1-60	NA
Khoshovisan	2013	Euro Jrn of Agro	50	29-37	TEF
Kim	2008	Int Jrn of LCA	14	160-174	M
Knudsen	2010	Jrn of Cleaner Prod	18	1431-1439	SOY
Koroneos	2005	Jrn of Cleaner Prod	13	433-439	BEER
Leinonen	2012	Poultry Science	92	8-25	PO
Leinonen	2012	Poultry Science	92	26-40	EGG
Leinonen	2013	Agri Sys	121	33-42	EGG; PO
Leng	2008	Jrn of Cleaner Prod	16	374-384	SR
Lindelauf	2009	Livestock Science	128	140-148	DA
Liu	2010	Jrn of Cleaner Prod	18	1423-1430	TEF
Lovett	2008	Livestock Science	116	260-274	DA
Martinez-Blanco	2011	Jrn of Cleaner Prod	19	985-997	V
Mellenhorst	2006	Poultry Science	47	405-417	EGG
Michos	2008	Ecological Indicators	13	22-28	TEF
Moudry	2013	Jrn of Food, Agri and Env	11	1133-1136	W
Mouron	2006	Agri Eco and Env	114	311-322	TEF
Neto	2013	Int Jrn of LCA	18	590-602	WINE
Nguyen	2012	Jrn of Cleaner Prod	28	215-224	PK
Nilsson	2012	Int Jrn of Agri Sust	15	916-926	BU
Obrien	2012	Agri Sys	107	33-46	DA
Ogino	2013	Soil Science and Plant Nutrition	59	107-118	PK
Oleson	2005	Agri Eco and Env	112	207-220	DA
Page	2011	Horticultural Science	46	324-327	TEF; TRF
Page	2012	Jrn of Cleaner Prod	32	219-226	V
Pattara	2012	Env Management	49	1247-1258	WINE
Pelletier	2008	Env Management	42	989-1001	M; OC; SOY; W
Pelletier	2008	Agri Sys	98	67-73	PO
Pelletier	2009	Env Science and Technology	43	8730-8736	NA
Pelletier	2010	Jrn of Industrial Ecology	14	467-481	NA; RA
Pelletier	2013	Jrn of Cleaner Prod	54	108-114	EGG
Pergola	2013	Jrn of Env Management	128	674-682	TRF
Peters	2010	Env Science and Technology	44	1327-1332	RM
Phong	2011	Livestock Science	139	80-90	NA
Pishgar-Komleh	2012	Jrn of Cleaner Prod	33	183-191	SR
Point	2012	Jrn of Cleaner Prod	27	11-20	WINE
Ramjeawon	2004	Int Jrn of LCA	9	254-260	SC; SUGAR
Ramos	2011	Int Jrn of LCA	16	599-610	NF; TF
Reckmann	2013	Livestock Science	157	586-596	PK
Renouf	2011	Int Jrn of LCA	16	125-137	SC
Ridoutt	2013	Agri Sys	120	2-9	W
Roer	2011	Agri Sys	111	75-84	B; CER; W
Samuel-Fitwi	2013	Aquacultural Eng	54	85-92	NA; RA
Saunders	2008	Political Science	60	73-88	V
Schau	2009	Jrn of Cleaner Prod	17	325-334	NF
Schils	2005	Nutrient Cycling in AgroEco	71	163-175	DA
Schmidt	2010	Int Jrn of LCA	15	183-197	OIL
Seabra	2012	Biofuels Bioproducts and Biorefining	5	519-532	SC; SUGAR
Thevenot	2013	Jrn of Cleaner Prod	57	280-292	PO
Thomassen	2008	Agri Sys	96	95-107	DA
Thrane	2004	Jrn of Industrial Ecology	8	223-239	NF; TF
Thrane	2006	Int Jrn of LCA	11	66-74	TF
Tuomisto	2012	Annals of Applied Biology	161	116-126	W
Tyedmers	2001	Fisheries Impacts on North Atlantic Eco	URL [5]		NF; TF
Tzilivakis	2005	Agri Sys	85	101-119	SC
van Middelaar	2013	Agri Econ	121	9-22	DA
Vasquez-Rowe	2012	Jrn of Cleaner Prod	27	92-102	TEF
Vazquez-Rowe	2011	Fisheries Research	110	128-135	NF; TF
Wang	2009	Int Jrn of Sust Devel and World Ecology	14	400-407	M; W
Wang	2010	Int Jrn of Sust Devel and World Ecology	17	157-161	R
Williams	2006		URL [6]		EGG; DA; OC; PK; PO; RM; V
Yan	2013	Jrn of Dairy Science	96	857-865	DA
Zafiriou	2012	Jrn of Cleaner Prod	29-30	20-27	V
Ziegler	2003	Int Jrn of LCA	8	39-47	NF; TF
Ziegler	2011	Jrn of Industrial Ecology	15	527-538	TF

Abbreviations for food types are: B = barley; BEER = beer; BU = butter; CER = cereals minus barley, maize, rice and wheat; DA = dairy; EGG = eggs; PUL = pulses; M = maize; NA = non-recirculating aquaculture; NT = non-trawling fisheries; OC = oil crops; OIL = oils; PK = pork; PO = poultry; R = rice; SR = starchy roots; RA = recirculating aquaculture; RM = ruminant meat; SC = sugar crops; SOY = soybeans; SUGAR = sugar; TF = trawling fisheries; V = vegetables; W = wheat; WINE = wine; TEF = temperate fruits; TRF = tropical fruits.

[1] http://www.esu-services.ch/fileadmin/download/buchspies-2011-LCA-fish.pdf

[2] https://elibrary.asabe.org/azdez.asp?AID=19478&T=2

[3] http://www.sik.se/archive/pdf-filer-katalog/SR728(1).pdf

[4] http://www.newbelgium.com/Files/the-carbon-footprint-of-fat-tire-amber-ale-2008-public-dist-rfs.pdf

[5] http://www.google.com/url?sa=t&rct=j&q=energy%20consumed%20by%20north%20atlantic%20fisheries&source=web&cd=1&ved=0CCgQFjAA&url=https%3A%2F%2Fwwz.ifremer.fr%2Fpeche%2Fcontent%2Fdownload%2F40520%2F552957%2Ffile%2FEnergie%2520consomm%25C3%25A9e%2520(GB).pdf&ei=7OtCU7aJA6igyAHXm4DQBg&usg=AFQjCNEviRn3L9pf2Jkcn3-HVM_uWkAtVg&sig2=ff3wbuD91tSz6nwAmbWu6Q&bvm=bv.64363296,d.aWc

[6] http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=11442

Extended Data Table 2 | Food group composition

Food Group	Food Items
Aquaculture (NR)	Catfish, Salmon, Sea-bass, Shrimp, Tilapia, Trout
Barley	Barley
Butter	Butter
Dairy	Cheese, Milk, Yogurt
Eggs	Eggs
Fishery (NT)	Alfonsino, Cod, Flat fish, Herring, Lumpfish, Mackerel, Mussels, Pollock, Pout, Rock fish, Snapper, Sea-bass, Swordfish, Turbot
Legumes	Prespa bean, Soybean
Maize	Maize
Oil Crops	Canola, Palm
Oils	Canola Oil, Palm Oil
Other Cereals	Barley, Oats
Pork	Pork
Poultry	Chicken
Recirculating Aquaculture	Char, Trout, Turbot
Rice	Rice
Roots	Cassava, Potatoes
Ruminant Meats	Beef, Goat, Mutton, Lamb
Sugar	Table Sugar
Temperate Fruits	Apple, Blueberry, Chinese Pear, Grape, Peach, Raspberry, Strawberry
Trawling Fishery	Anglerfish, Cod, Crab, Flat fish, Herring, Mackerel, Pollock, Shrimp, Snapper, Squid
Tropical Fruits	Andean blackberry, Avocado, Golden berry, Kiwi, Lemon, Lulo, Mango, Orange, Passionfruit, Tree tomato
Vegetables	Asparagus, Leek, Mushroom, Onion, Romain lettuce, Tomato
Wheat	Wheat

Specific food items included in each of the 22 food types detailed in Fig. 1 of the main text.

Extended Data Table 3 | Mean food production emissions

Food Types	# of Studies	C emissions (mean +- s.e.m.)		
		g/kcal	g / Serving	g / g-protein
Maize	11	0.03 +- 0.004	3.0 +- 0.36	1.2 +- 0.14
Wheat	34	0.06 +- 0.009	5.2 +- 0.86	1.2 +- 0.2
Rice	6	0.14 +- 0.02	14 +- 2.1	6.5 +- 0.95
Other Cereals	12	0.05 +- 0.005	5.4 +- 0.46	1.9 +- 0.17
Sugar	2	0.02 +- 0.00004	0.9 +- 0.002	n/a
Oils	12	0.16 +- 0.04	20 +- 5.4	n/a
Oil Crops	5	0.05 +- 0.02	7.2 +- 2.4	n/a
Temperate Fruits	34	0.10 +- 0.02	6.4 +- 1.2	n/a
Tropical Fruits	15	0.14 +- 0.04	9.1 +- 2.5	n/a
Vegetables	14	0.68 +- 0.25	14 +- 3.5	n/a
Starchy Roots	3	0.03 +- 0.02	0.84 +- 0.4	1.7 +- 0.67
Legumes	13	0.02 +- 0.002	1.9 +- 0.22	0.25 +- 0.04
Butter	3	0.33 +- 0.03	33 +- 2.8	n/a
Eggs	60	0.59 +- 0.03	24 +- 1	6.8 +- 0.29
Dairy	63	0.52 +- 0.04	74 +- 2.5	9.1 +- 0.3
Fishery (NT)	77	1.6 +- 0.25	40 +- 5.7	8.6 +- 1.3
Trawling Fishery	35	4.8 +- 1.3	108 +- 29	26 +- 6.7
Aquaculture (NR)	25	2.0 +- 0.41	60 +- 11	12 +- 2.3
Recirc. Aqua	5	4.4 +- 1.9	160 +- 75	30 +- 14
Poultry	30	1.3 +- 0.05	52 +- 2.1	10 +- 0.39
Pork	27	1.6 +- 0.1	61 +- 3.6	10 +- 0.61
Ruminant Meat	64	5.6 +- 0.41	330 +- 18	62 +- 3.4

Number of studies, mean CO_2-C_{eq} emissions, and standard error of the mean associated with food production for each of the 22 food types.

Extended Data Table 4 | Economic group country composition

Economic Group	Analyzed Nations	Percent of world population 2009 (2050)
A	Australia, Austria, Canada, Denmark, Finland, France, Germany, Ireland, Japan, The Netherlands, Norway, Sweden, Switzerland, United Kingdom, and United States	11.1 (9.4)
B	Argentina, Chile, Greece, Israel, Italy, Malaysia, Mauritius, New Zealand, Portugal, Saudi Arabia, South Korea, Spain, Trinidad and Tobago, Uruguay, and Venezuela	4.9 (4.3)
C	Botswana, Brazil, Colombia, Costa Rica, Ecuador, Guatemala, Iran, Jordan, Mexico, South Africa, Syria, Thailand, Tunisia, and Turkey	10.0 (9.1)
China	China	20.0 (14.2)
D	Algeria, Bolivia, Cuba, Dominican Republic, Egypt, El Salvador, Indonesia, Jamaica, Lebanon, Morocco, Paraguay, Preu, Philippines, Sri Lanka, Swaziland	7.0 (6.9)
E	Bangladesh and Pakistan, Benin, Cameroon, Cote d'Ivoire, Ghana, Honduras, Libya, Mozambique, Myanmar (Burma), Nicaragua, Nigeria, North Korea, Senegal, and Vietnam	12.5 (15.5)
F	Burkina Faso, Central African Republic, Chad, Democratic Republic of the Congo (Former Zaire), Eritrea and Ethiopia, Gambia, Guinea, Haiti, Kenya, Madagascar, Malawi, Zambia and Zimbabwe, Mali, Nepal, Niger, Rwanda and Burundi, Sierra Leone, Sudan (former), Tanzania, Togo, and Uganda	7.5 (12.2)
India	India	17.7 (18.2)
	Total of all Groups/Nations	89.9 (90.8)

List of nations and the percentage of the world's population included in each economic group or nation in 2009. In parentheses are such percentages based on 2050 population forecasts. The 100 nations were ranked by their 2000–2007 average per capita GDP (in 1990 international dollars), with the top 15 assigned to Group A, the next 15 to Group B, and so on, but with the last 25 assigned to Group F, except that China (economically in Group C) and India (economically in Group E) were each designated as its own 'group' because of their large population sizes.

Extended Data Table 5 | Cohort studies and health conditions examined

Primary Author (Reference #)	Year	Cohort	Diet(s)	People Years	Health Condition Examined
Mitrou, P.N. (36)	2007	AARP	Med	1,300,000	HD; ACM
Couto, E (58)	2011	EPIC	Med	4,200,000	C
Hoevenaar-Blom, M.P. (59)	2012	EPIC	Med	90,000	HD
Romaguera, D (58)	2011	EPIC	Med	130,000	D
Key, T.J. (33)	1996	EPIC	Veg	180,000	ACM
Key, T.J. (55)	2009a	EPIC	Pesce/Veg	610,000	C
Key, T.J. (56)	2009b	EPIC	Pesce/Veg	690,000	HD; ACM
Trichopoulou, A (53)	2005	EPIC	Med	550,000	ACM
Fung, T.T. (39)	2009	NHS	Med	560,000	HD
Tantamango-Bartley, Y (61)	2012	AHS	Pesce/Veg	510,000	C
Orlich, M.J. (60)	2013	AHS	Pesce/Veg	370,000	HD; ACM
Snowdon, D.A. (32)	1984	AHS	Veg	360,000	HD
Tonstad, S (57)	2009	AHS	Pesce/Veg	57,000	D
Tonstad, S (62)	2013	AHS	Pesce/Veg	78,000	D
Martinez-Gonzalez, M.A. (38)	2008	SUN	Med	17,000	D
Mann, J.I. (34)	1997	UK VEG	Veg	130,000	HD; ACM
Lagiou, P (35)	2006	UHCR	Med	290,000	ACM
Brunner, E.J. (37)	2008	Whitehall	Med	110,000	D

For each of the publications[32–39,53–62] used to quantify effects of three alternative diets on health conditions, its cohort, diet, person-years of data and health conditions examined are listed below. Abbreviations are: AARP = American Association of Retired Persons; EPIC = European Prospective Investigation into Cancer; NHS = Nurses Health Study; AHS = Adventist Health Studies; SUN = Seguimento Universidad de Navarra; UK Veg = Vegetarian Society of the United Kingdom: UHCR = Uppsala Health Care Region; Whitehall = Whitehall; C = Cancer; D = Diabetes, HD = Heart Disease; ACM = All Cause Mortality.

Extended Data Table 6 | Effects of agricultural development variables on forecast 2050 cropland use

a

Diet Type	Agricultural Trade	Pasture Productivity	Reduced Waste	Feed Use Efficiency	Accelerated Yields
Income Dependent	-8.17	-2.37	-6.21	-7.7	-8.57
Mediterranean	-6.08	-2.47	-7.83	-5.29	-8.78
Pescetarian	-6.44	-1.29	-5.57	-3.34	-5.71
Vegetarian	-6.71	-1.49	-5.93	-2.65	-6.86

b

Diet Type	Increase in Land Demand Relative to 2009 (10^6 ha)
Income Dependent	590
Mediterranean	130
Pescetarian	26
Vegetarian	-16

Increases in agricultural trade, pasture productivity, animal feed efficiency, waste reduction and accelerated yields consistently result in diet-dependent decreases in cropland requirements. **a**, Analysis of results by diet type gives the reduction in 2050 global agricultural land use (million ha) associated with a 1% increase in each of the five variables, based on a separate multiple regression analysis for each diet type of the forecasted 2050 cropland requirements for each of the 243 scenarios. **b**, Median forecasts of the additional cropland needed by each diet in 2050 relative to 2009 (Methods).

Extended Data Table 7 | Protein conversion ratios of livestock production systems

Food Item	# of data points	Protein Conversion Ratio (mean +-s.e.m.)
Beef	40	20.0 +- 0.82
Mutton and Goat	63	14.5 +- 0.21
Pork	29	5.7 +- 0.63
Poultry	52	4.7 +- 0.24
Eggs	52	2.6 +- 0.29
Milk	37	3.9 +- 0.53
Carp	15	12 +- 0.72
Catfish	47	8.8 +- 0.04
Char	19	4.8 +- 1.43
Cobia	6	11.6 +- 0.11
Cod	19	4.8 +- 0.42
Crayfish	4	11.5 +- 0.09
Halibut	4	4.4 +- 0.08
Salmon	83	4.6 +- 0.2
Sea-bass	11	6.0 +- 0.29
Seabream	6	7.1 +- 1.67
Shrimp	91	18.3 +- 2.15
Snapper	15	16.5 +- 0.57
Tilapia	13	5.7 +- 0.51
Trout	35	4.1 +- 0.24
Turbot	10	14.6 +- 2.32

Number of studies and mean protein conversion ratios (feed protein used/edible animal protein produced) in examined terrestrial and aquatic livestock production systems with high use efficiencies. Data sources are listed in Extended Data Table 1.