

RESEARCH ARTICLE

Current global food production is sufficient to meet human nutritional needs in 2050 provided there is radical societal adaptation

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We present a quantitative analysis of global and regional food supply to reveal the flows of calories, protein and the micro-nutrients vitamin A, iron and zinc, from production through to human consumption and other end points. We quantify the extent to which reductions in the amount of human-edible crops fed to animals and, less importantly, reductions in waste, could increase food supply. The current production of crops is sufficient to provide enough food for the projected global population of 9.7 billion in 2050, although very significant changes to the socio-economic conditions of many (ensuring access to the global food supply) and radical changes to the dietary choices of most (replacing most meat and dairy with plant-based alternatives, and greater acceptance of human-edible crops currently fed to animals, especially maize, as directly-consumed human food) would be required. Under all scenarios, the scope for biofuel production is limited. Our analysis finds no nutritional case for feeding human-edible crops to animals, which reduces calorie and protein supplies. If society continues on a 'business-as-usual' dietary trajectory, a 119% increase in edible crops grown will be required by 2050.

Keywords: Food; Food security; Food sustainability

Introduction

The global food system has major impacts on the environment, through greenhouse gas emissions, water abstraction, soil, water and air pollution, land use change and loss of biodiversity, threatening food security and sustainability. Ensuring global food security is the second of 17 Sustainable Development Goals adopted by the United Nations as part of its 2030 Agenda for Sustainable Development (United Nations, 2015) but achieving this while reducing negative environmental impacts is one of the greatest challenges facing humanity.

Moving towards a sustainable global food system will become more difficult as global population increases. A common perception is that global food supply is currently sufficient to feed the world's population, with timely distribution required to avoid hunger (World Hunger Organisation, 2016), but that food production must increase dramatically in the next decades (Food and Agriculture Organisation of the United Nations, 2009) as

global population increases to ≈ 9.7 billion in 2050 (United Nations Department of Economic and Social Affairs, 2015). However, the challenge of sustainably producing sufficient food for the growing global population will not necessarily be solved by increases in production because there is a limit to the potential for efficiency gains, and many of these come with greater environmental costs, while increasing agricultural area by land use change almost invariably leads to losses of biodiversity. Changes in consumption patterns may also have detrimental environmental costs, e.g. if meat consumption increases globally (e.g. Rööös et al., 2017a). Finally, it is clear that social inequalities, which give rise to excesses and insufficiencies in supply, distribution and availability, exacerbate the sustainability challenge, not least by enhancing food waste and placing a proportion of the population outside the easy reach of micro-nutrient fortification and supplement programmes (Garnett, 2013). Achieving global food system sustainability is therefore a hugely complex but necessary goal.

Here we explore the potential for current global food production to feed the world, both now and in 2050. We do not take account of crop yield changes such as those that may result from new technologies, land use or demographic changes, farming practices or climate change, but simply keep crop yields at 2013 levels. The main focus of the paper is therefore to assess whether or not current crop yields are sufficient to meet human nutritional needs

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in 2050. To do this, we combine Food and Agriculture Organisation of the United Nations (FAO) data with food nutrient data, and information on animal grazing and on human nutritional needs, which we analyse by regional demographic profiles to quantitatively map the flows of food on its journey in seven stages from production to the meeting of human nutritional needs and other end-points, including waste and non-food uses (see Methods and S.I.). We do this at the global and regional scales. We do not explore issues of palatability but assume that human-edible crops fed to animals can be processed into acceptable human food or substituted without yield loss for edible alternatives. For example, the *Zea mays indentata* varieties grown in the United States for animal feed can be used to produce foodstuffs already commonly eaten in some societies or alternatively could be substituted without yield loss for other varieties of maize such as those already grown and eaten in South America and elsewhere (e.g. Gwirtz and Garcia-Casal, 2014; Ranum et al., 2014).

Previous analyses have explored FAO food balance sheet data (Food and Agriculture Organisation of the United Nations, 2016) for calorific flows (e.g. Bajželj et al., 2014; Cassidy et al., 2013; Kummu et al., 2012), and, for example, the effects of changing diet on greenhouse gas emissions (Stehfest et al., 2009; Popp et al., 2010) or on global food supply (Wirsenius et al., 2010; Foley et al., 2011; Smil, 2000), but much less attention has been paid to the analysis of protein (Röös et al., 2017b) and micronutrient supply. Here, as well as following the flow of all human-edible and non-human-edible food calories, we track protein, vitamin A, iron and zinc, because shortages of these have been identified as the major causes of ‘hidden hunger’ (e.g. Food and Agriculture Organisation of the United Nations, 2009; Von Grebmer et al., 2014; Muthayya et al., 2013), limiting growth, development, health and economic capacity. An additional critical micronutrient is iodine, but we do not consider it here as it is currently added to food-grade salt in over 120 countries, a fortification programme that could be extended globally at a cost of \$0.02–\$0.05/person/year (World Health Organisation, 2014).

Methods

Full details of the methods used and discussion of uncertainties in our analysis are shown in the S.I. In summary, data from the Food and Agricultural Organisation (FAO) Food Balance Sheets and Commodity Balance Sheets for 2013 (Food and Agriculture Organisation of the United Nations, 2016) and from various other sources (e.g. Tilman and Clark, 2014; United States Department of Agriculture, 2017; Davis and D’Odorico, 2015; Pennsylvania State University, 2003) are used to determine the flows of food from production to its end points, including human consumption. Energy delivered to animals from grass, pasture and stover (GP&S, which includes hay and silage), is estimated using the FAO Food Balance Sheet data and the metabolic energy contents of feed (Tilman and Clark, 2013) and feed cake (Davis and D’Odorico, 2015). Protein delivered to animals from GP&S is estimated using the

average protein to metabolisable energy ratio for 14 types of grass (Pennsylvania State University, 2003).

We use the FAO global population-weighted average dietary energy requirement (ADER) (World Health Organization & Food and Agriculture Organization of the United Nations, 2001) for the global average calorific intake required for healthy life (2353 kcal/p/d). The ADER for each region is derived from national ADER values, which vary with body size, activity level, age and gender, calculated using the FAO methodology (World Health Organization & Food and Agriculture Organization of the United Nations, 2001), with results taken from Our World in Data (2017). For protein, vitamin A, iron and zinc, we calculate population-weighted global and regional average recommended daily intakes using the Recommended Dietary Allowance (National Research Council, 1989) and Reference Nutrient Intake (British Nutrition Foundation, 2016) values, which vary by age, gender, pregnancy and breastfeeding status.

To construct our notional ‘healthy diet’ used in **Table 1**, we use the minimum or maximum intakes of fruit and vegetables, sugar and sweeteners, vegetable oils and meat and dairy as specified by the FAO/WHO (World Health Organization & Food and Agriculture Organisation of the United Nations, 2003), Harvard Medical School (Willett, 2001) and the American Heart Association (2014).

The Excel workbook containing our data and analysis is freely available at <https://doi.org/10.17635/lanaster/researchdata/222>.

Results and Discussion

Global flow of food calories

Figure 1a shows global food energy flows for 2013 in kilocalories/person/day (kcal/p/d where 1 kcal = 4.2 kJ). 5935 kcal/p/d of crops directly edible by humans are grown alongside 3812 kcal/p/d of vegetable matter eaten by other animals but not directly digestible by humans (i.e. GP&S). This total of 9747 kcal/p/d is more than four times the average dietary energy requirement for healthy life (ADER) of 2353 kcal/p/d (World Health Organization and Food and Agriculture Organization of the United Nations, 2001).

Of the 5935 kcal/p/d directly edible by humans, 338 kcal/p/d are left in the ground or lost during harvest and 332 kcal/p/d are lost post-harvest. Of the remaining 5265 kcal/p/d, 30% are exported internationally but only 29% are received as imports (the difference being a trading loss of 73 kcal/p/d). Globally, 808 kcal/p/d are directed to ‘non-food uses’, mainly biofuels, particularly liquid hydrocarbons (Serrano-Ruiz et al., 2012). Other uses include cosmetics, pharmaceuticals, paints etc. A further 126 kcal/p/d are invested for re-planting.

Of the remaining 4260 kcal/p/d directly edible by humans, 1738 kcal/p/d (41%) are fed to farmed animals, which also receive the equivalent of 3812 kcal/p/d from GP&S. Farmed animals therefore consume the equivalent of 5550 kcal/p/d in total. However, they return just 594 kcal/p/d to the human food chain in the form of meat (including 54 kcal/p/d of farmed and wild fish) and dairy products, while 4956 kcal/p/d are lost from the human

food chain. This 12% conversion rate of plant material to meat and dairy products is in line with previous estimates (Godfray et al., 2010; Herrero and Thornton, 2013; Tilman and Clark, 2013). However, a recent analysis estimated an overall 7% conversion efficiency of plant to meat and dairy calories in the USA (Shepon et al., 2016). Food eaten by wild-caught fish is not included in our analysis, but if it were it would slightly reduce our estimate of this conversion rate, but not below 11%. Because humans cannot directly access the nutrients in GP&S, a more meaningful measure of the global efficiency of current animal husbandry is the percentage of human-edible crops fed to animals delivered to humans as meat, dairy and fish (MD&F). This is 34%. However, animal nutrition from GP&S comes partially from land that could otherwise be used to grow human-edible crops and partially from land that can only be used for either animal food (not directly edible by humans, such as grass) or other ecosystem services (such as biofuel production). Therefore nutritional losses from GP&S do not fully translate into losses of human-available nutrients. Note, crop inputs also provide non-edible animal products and is fed to animals for companionship, labour and sport; and “fish” refers both to wild-caught fish and fish bred by aquaculture.

Combining the energy available in crops directly edible by humans with animal products gives a total of 3116 kcal/p/d available for human consumption prior to processing and distribution. Processing and distribution (both wholesale and retail, but not during international trade) result in wastage of 221 and 104 kcal/p/d respectively, leaving 2792 kcal/p/d delivered to consumers, who themselves waste 261 kcal/p/d. This leaves 2531 kcal/p/d actually eaten by humans. For comparison, National Household Survey food consumption data (Food and Agriculture Organisation of the United Nations, 2016) estimates global average consumption at 2653 kcal/p/d, 5% higher than that obtained by our analysis, perhaps explained by over-reporting in some food-scarce societies. This implies that, on average, humans consume 178 ‘excess’ kcal/p/d above the ADER. Significant regional differences in consumption patterns explain, in part, the large regional differences in obesity and malnourishment.

The sum of the separate wastes and losses identified above (excluding animal-related losses, investments, non-food uses and excess consumption) is 1329 kcal/p/d, or 22% of the human-edible crop calories grown globally. This compares with recent estimates of one quarter (Lipinski et al., 2013), one third (Gustavsson et al., 2011) and one half (Lundqvist et al., 2008) of food wasted (although the latter two refer to mass, not energy). The significant differences in food wasted by region, food group and supply chain stage (Table S1) have been discussed elsewhere (e.g. Food and Agriculture Organisation of the United Nations, 2011, Lundqvist et al., 2008).

The global flow of protein

The global flow of protein (**Figure 1b**) shows similarities to that of calories. 81 grams/p/d of protein are eaten compared with a global population-weighted aver-

age recommended intake (ARI) of 44 g/p/d, based on the Recommended Dietary Allowance (RDA) (National Research Council, 1989) and Reference Nutrient Intake (RNI) (British Nutrition Foundation, 2016) (see S.I.). This implies a net excess consumption of 84%, compared with net excess calorie consumption of 8%. However, we cannot infer from this that there is a lower incidence of protein deficiency within the global population than of calorie deficiency, particularly because individual protein intake is not as closely regulated by the negative impacts of over-consumption on health as is the case for energy.

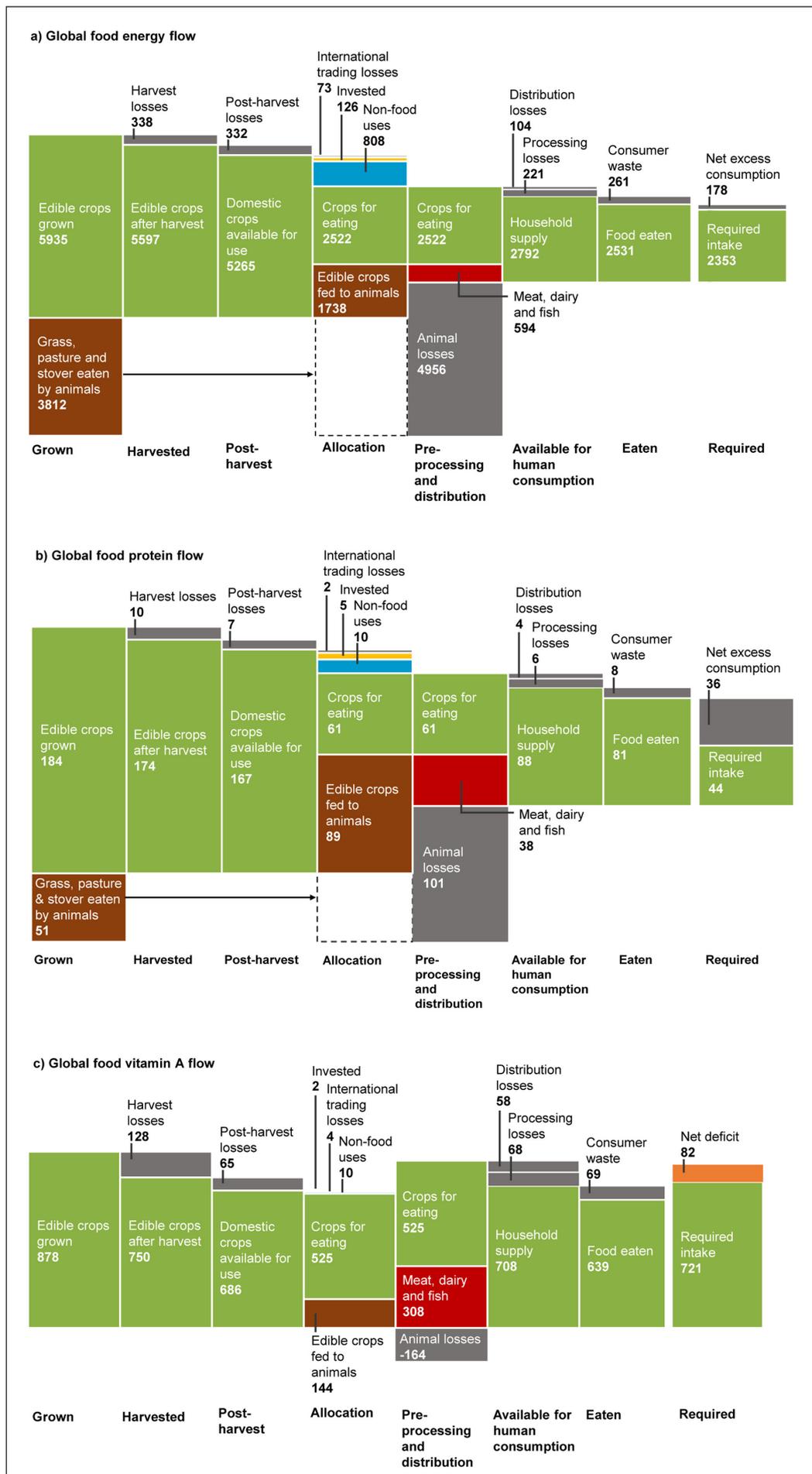
Only 5% of the protein in crops grown is diverted to non-food uses, compared with 14% of calories. MD&F contribute 38% of human protein intake, compared with the 19% contribution they make to calorie consumption (c.f. contributions of 37% and 18% respectively, estimated using a farm-based bottom-up inventory approach by Poore and Nemecek, 2018). The protein in MD&F delivered to the human food chain is 43% of the amount of protein in the human-edible crops fed to animals, compared with 34% for calories. Nevertheless, the overall effect of feeding human-edible food to animals is to decrease the overall available global protein supply by 51 g/p/d (or 116% of the global average RDA).

The global flows of vitamin A

The vitamin A in human-edible crops grown is 878 $\mu\text{g/p/d}$, 22% higher than the global requirement for healthy living, taken as 721 $\mu\text{g/p/d}$ (see Methods) (Institute of Medicine Panel on Micronutrient, 2000). Harvest and post-harvest losses are 22%, greater than for energy (11%). This leaves 686 $\mu\text{g/p/d}$ available for use. Only 1% of this is diverted to non-food uses, compared with 14% of calories. Animals provide more vitamin A than they are fed in human-edible crops, with a 214% return, and contribute 37% of the vitamin A eaten. This contrasts with the 34% and 43% returns of energy and protein respectively. Processing, distribution and consumer losses total 195 $\mu\text{g/p/d}$, leaving 639 $\mu\text{g/p/d}$ eaten. In the absence of fortification and supplements, therefore, the global consumption of vitamin A would be 11% less than that required to meet human needs. In many countries this deficit is largely resolved by widespread fortification of food (Saeterdal et al., 2012), although some individuals remain undernourished. The global flows of vitamin A are shown in **Figure 1c**.

The global flows of iron

The human-edible crops grown contain 74 mg/p/d of iron (**Figure 1d**). This compares with a global recommended intake of 11 mg/p/d (see Methods) (Institute of Medicine Panel on Micronutrient, 2000). Harvest losses, post-harvest losses, investment and non-food uses total 11 mg/p/d, leaving 63 mg/p/d in crops. Two thirds (41 mg/p/d) is fed to animals, which deliver only 3 mg/d/d to the human food chain as iron in MD&F, a return of just 7%. However, the bioavailability of iron is greatly improved by animal metabolism. After processing and distribution losses, 18 mg/p/d remain in crops, giving a total of 21 mg/p/d



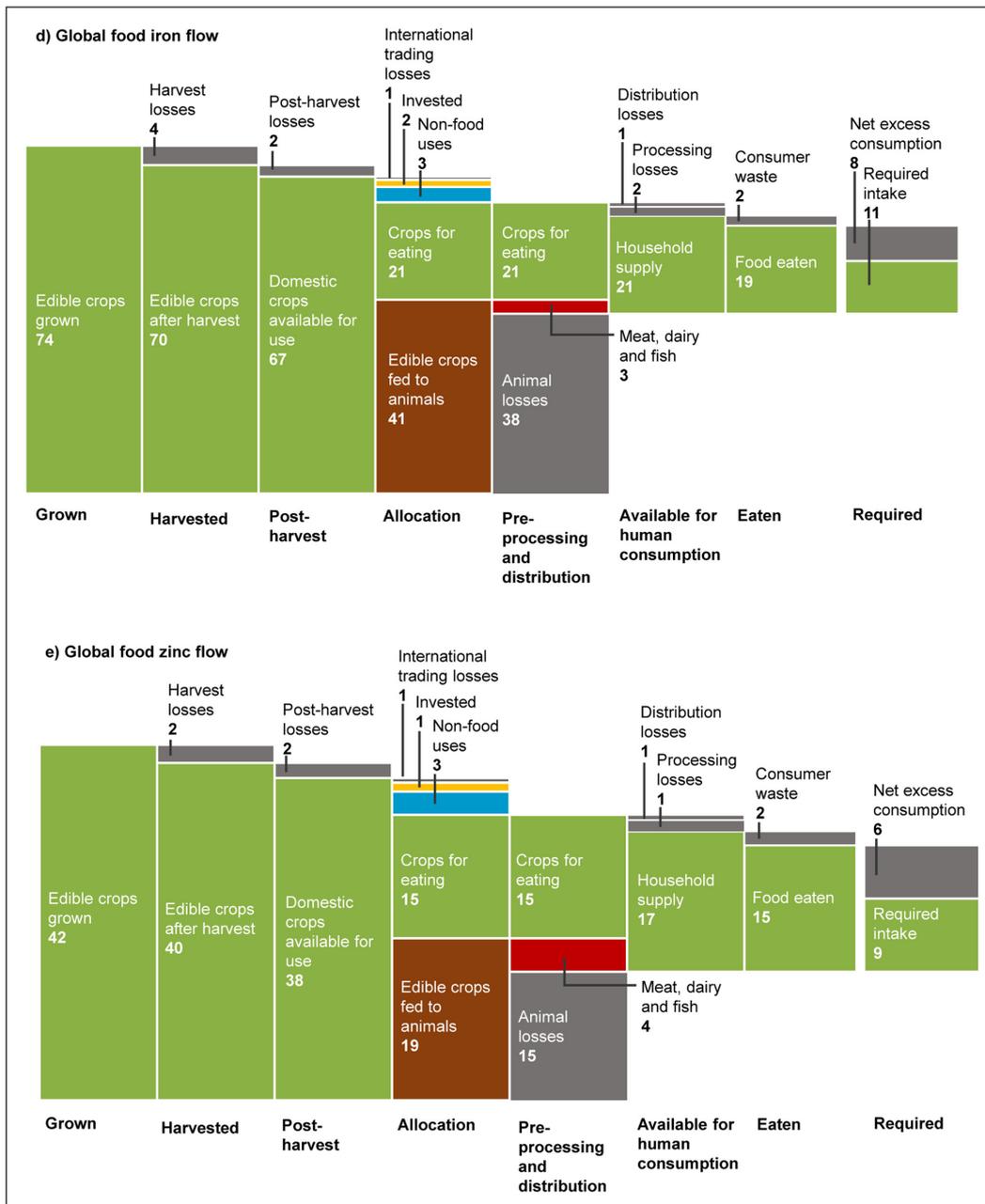


Figure 1: The flows of global food energy (kcal/person/day) (panel a), protein (g/person/day) (panel b), vitamin A ($\mu\text{g}/\text{person}/\text{day}$) (panel c), iron (mg/person/day) (panel d), and zinc (mg/person/day) (panel e) from the amount grown to the amount eaten. For crops fed to animals, the units are based on global human population, not animal population. The left-hand bar in panels a and b divides the crops grown into those that are directly edible by humans and the grass, pasture & stover that is only edible by animals. The right-hand bar divides the nutrients eaten into that required for healthy human living and net excess consumption or net deficit (panel c). Animal losses include all the losses inherent in animal husbandry, such as energy used for respiration, growth, movement and reproduction and the wastage of animal parts not used as food. DOI: <https://doi.org/10.1525/elementa.310.f1>

available for human consumption. As for other micro-nutrients, the ARI of iron is dependent on age, gender, lactation state and other factors. In addition, non-haem iron is less bioavailable than haem iron, hence vegetarians require an iron intake almost twice that of carnivores (Institute of Medicine Panel on Micronutrient, 2000). Absorption efficiency is also dependent on other dietary factors. However, the bioavailability of iron remains a topic of debate and uncertainty. Even after allowing for a conservatively high factor of four difference between the

bioavailability of haem and non-haem iron (Institute of Medicine Panel on Micronutrient, 2000), vegetable food remains the dominant source of absorbed iron in the global average human diet. If iron were not fed to animals in human-edible crops, the 3 mg/p/d of haem iron in the global average diet could be replaced by 41 mg/p/d, which after distribution and processing losses and consumer waste, would deliver 35 mg/p/d of non-haem iron for human consumption, taking the total consumed to 53 mg/p/d.

The global flows of zinc

The global flow of zinc (Figure 1e) bears similarities to that of iron. However, zinc is better conserved throughout the food chain. While there is 3.9 times as much iron in the crops grown as is consumed, for zinc the ratio is 2.8. In particular, animals return 21% of the zinc they eat in human-edible crops, three times more efficiently than for iron, but less efficiently than for energy, protein and vitamin A. The amount of zinc consumed is 15 mg/p/d, compared with a global recommended intake of 9 mg/p/d (Institute of Medicine Panel on Micronutrient, 2000) (see S.I.). As for iron and vitamin A, many foods are routinely fortified with zinc, and supplements are widely available, especially in wealthier countries.

Regional food calorie apportionment

Figure 2 and Table S2 show the apportionment of calories into various end points for each of seven regions of the world, together with the global average. The seven regions are those used by the FAO in their regional food waste analysis (Food and Agriculture Organisation of the United Nations, 2011). Each bar shows net edible crops available in the region (i.e. domestically grown plus any net imports minus seeds invested), and is divided into various endpoints. Net animal losses are the difference between the calories in human-edible crops fed to animals and the calories returned in MD&F. The ADERs shown are regionally specific (Our World in Data, 2017) (see S.I.).

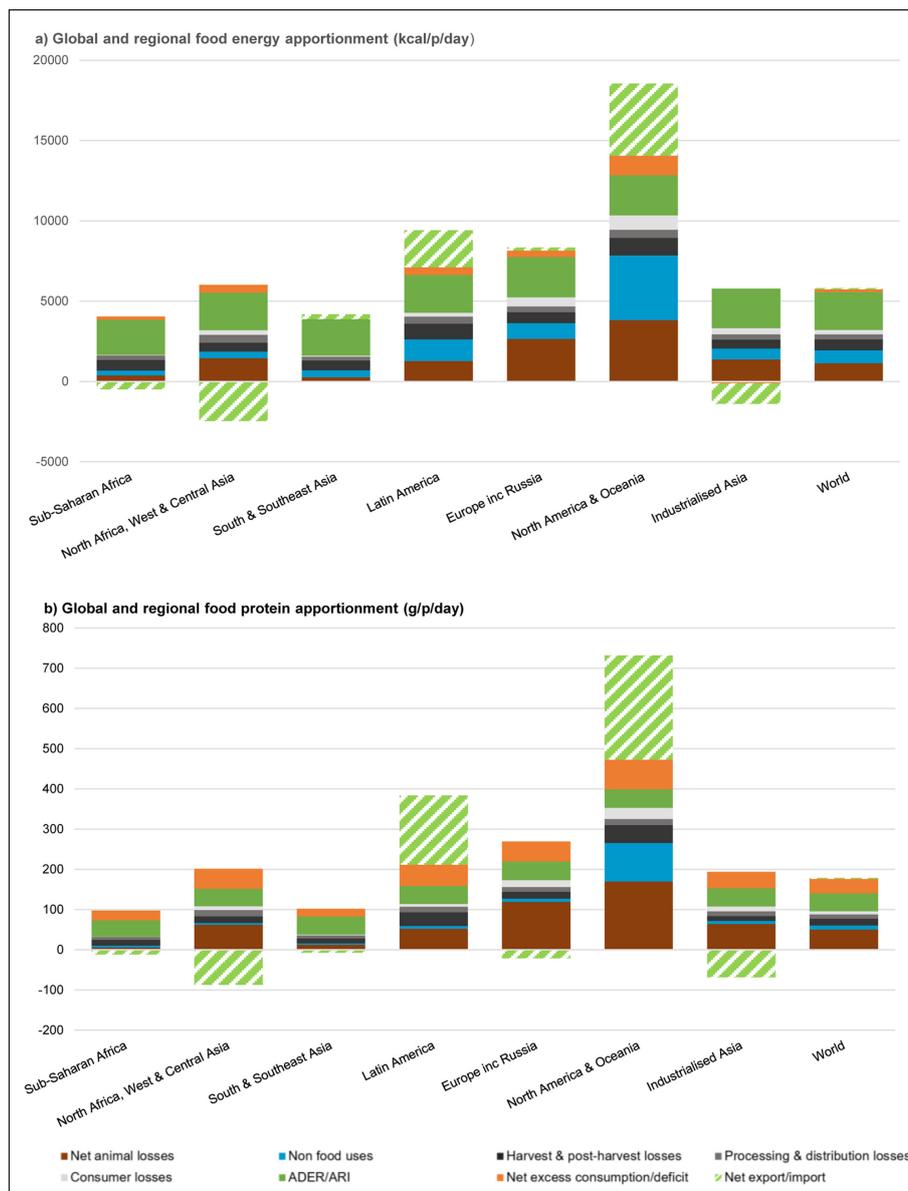


Figure 2: The apportionment of food calories (a) and protein (b) at the global and regional scales between various end points. The bar height above zero represents the amount of food available in the region. This is divided into the categories shown in the key. The global population-weighted average dietary energy requirement (ADER) and global population-weighted average recommended intake (ARI) values are regionally adjusted. The orange segments show net overconsumption, or, in the case of Industrialised Asia, a small net deficit. Hashed segments show net exports (above zero) and net imports (below zero) which contribute to the total available shown above zero. These data are shown in Table S2. DOI: <https://doi.org/10.1525/elementa.310.f2>

North America & Oceania has by far the greatest abundance of calories per capita, growing 18766 kcal/p/d, including 230 kcal/p/d invested as seeds. Of this, animals are fed 5514 kcal/p/d but return only 1310 kcal/p/d as MD&F. The net consumption of human-edible food energy by animals is therefore 21% of the net available crops in the region. A total of 4036 kcal/p/d (equivalent to 184 kcal/p/d at the global level, or 8% of global food requirements) are diverted to non-food uses in North America & Oceania. Almost all of this goes to biofuel production (US Department of Energy, 2017). This region therefore diverts 22% of its entire crop production to produce 2% of its primary energy use (or <<1% of global primary energy use). The amount of food wasted through all stages of the food chain in the region totals 2487 kcal/p/d (13% of the crops grown). The regional ADER is 2509 kcal/p/d, higher than the global average, because the average human mass in the region is above the global average (Our World in Data, 2017). This leaves a net excess consumption of 1209 kcal/p/d, which is absorbed through the inefficiencies of unhealthy body mass and increasing obesity within a proportion of the population.

Sub-Saharan Africa, Industrialised Asia and North Africa, West & Central Asia rely on the import of food calories with net export being almost entirely from the Americas. In the latter case, net imports exceed the ADER and animal-related losses are particularly high (1448 kcal/p/d). Sub-Saharan Africa and South & Southeast Asia exhibit particularly high food-system efficiencies through low animal-related losses and low non-food uses.

Regional protein apportionment

In contrast to food energy, in every region of the world more protein is consumed, on average, than is required for healthy living, with excess consumption being the least in South and Southeast Asia (43%). Every region except for the Americas has net imports of protein. This is largest in North Africa, West & Central Asia (202% of ARI) and Industrialised Asia (152% of ARI), where imports are relied upon to avoid deficits. In contrast, North America & Oceania and Latin America have net exports of 564% and 389% of their ARIs respectively. The efficiency of protein consumption is high in Sub-Saharan Africa and South & Southeast Asia with 66% and 62% of their total available (regionally grown plus net import) protein being eaten, compared to only 25% in North America & Oceania, the rest going into other end-points. Net protein loss due to animal husbandry occurs in every region. Unsurprisingly this is relatively greatest in North America & Oceania and least in Sub-Saharan Africa, in line with animal husbandry practices, specifically the relative importance of GP&S to total animal inputs.

Regional vitamin A apportionment

Industrialised Asia is the only region with a significant net surplus in human consumption above the ARI of naturally produced vitamin A. Every other region of the world has a deficit in vitamin A consumption, unless this is mitigated by fortification and/or supplements. This is in line with

the observed prevalence of vitamin A deficiency-related health effects (Muthayya et al., 2013). Industrialised Asia is also the only region in which animals are net consumers of vitamin A; elsewhere the supply of naturally produced vitamin A depends largely on its production by animals (see **Figure 1c** and Figure S1 for details).

Regional iron and zinc apportionment

In every region of the world there is a net surplus consumption above the ARI of both iron and zinc (see Figure S1b; c and Table S2). However, because of variations in the bioavailability of iron in different diets, variations in individual requirements (especially for adult females) and the prevalence of unbalanced diets, this does not mean that all individuals consume sufficient iron, and in fact iron deficiency is a significant global health problem (Muthayya et al., 2013).

Is the current global food supply compatible with a healthy diet?

To assess whether the current global food supply is compatible with a healthy diet for all, **Table 1** and Figure S2 compare the current consumption of four food types in seven regions and globally with their minimum or maximum intakes as specified by the FAO/WHO (World Health Organisation & Food and Agriculture Organisation of the United Nations, 2003), Harvard Medical School (Willett, 2001) and the American Heart Association (American Heart Association, 2001). Global average fruit and vegetable consumption is 38% below the healthy minimum level, and only in Industrialised Asia is enough eaten. Global sugar and sweetener intake is 26% above healthy limits, with net excess consumption in every region except Industrialised Asia. This is most extreme in North America & Oceania, followed by Latin America, then Europe. Only in North America & Oceania does average consumption of vegetable oils exceed healthy levels (by 74%) although Europe is borderline. Global average meat and dairy consumption exceeds that commensurate with a healthy diet by 20%, with very high consumption in North America & Oceania and Europe.

Food supply under future hypothetical scenarios

To explore how the world could be fed now and in 2050 we describe nine scenarios (described in **Table 2**, and shown in **Figure 3** and Table S3). Although total agricultural yields and yields per unit area have consistently increased in the past, and current rates of increase would provide ~67%, 42%, 38% and 55% more maize, rice, wheat and soybean respectively in 2015 (Ray et al., 2013), future yield increases are unpredictable. It is therefore relevant to consider the capacity of current food supplies to meet future food needs in the absence of yield gains. Therefore, in these scenarios we keep the total amount of edible crops grown and the amount of GP&S eaten at 2013 levels. This allows us to compare current supplies with future needs and to explore what societal changes would be required to allow current supplies to be sufficient (or not) for future needs. In the four 2013 scenarios (A_{2013} – D_{2013}), the calories consumed (both

required and 'excess') and the calories invested are held at 2013 levels.

The "base" case for 2013, A_{2013} , describes the actual end-points of global food calories in 2013. A_{2050} shows the effect of population rising to 9.7 billion with unchanged total food production, and with waste streams and investment decreasing per capita, in proportion to the rise in population. Household waste remains the same per capita. MD&F availability in A_{2050} falls to 439 kcal/p/d (due to the population growth), substituted, but inadequately, by vegetal intake. Even with the elimination of non-food uses (which we take to be the lowest priority of all uses of crop calories, as they do not contribute to the human diet), there is an energy deficit of 40 kcal/p/d in 2050, indicating that current (2013) food production would be insufficient to feed the projected population of 9.7 billion in 2050 without dietary or wastage changes.

The "no animal feed" scenario for 2013, B_{2013} , shows the effect of not feeding crops that are directly edible by humans to animals. Human-edible crops currently fed to animals that are diverted into the human food chain in this scenario are assumed to experience the same proportional losses at each step in the supply chain as all

other foods. Because most animal nutrition comes from GP&S, the availability of MD&F is only reduced from 594 to 408 kcal/p/d in this scenario, with a commensurate increase in human vegetal consumption to make up the calorific intake to the current consumption level. Despite more crops being eaten by humans, the large increase in the available supply also allows the calories available for non-food use to increase from 808 to 2359 kcal/p/d. In our framework, the availability of crops for non-food uses can be viewed as an indicator of the spare capacity in the food system, acting as a buffer, and creating the opportunity to use land for other ecosystem services such as carbon sequestration, biodiversity or biofuel production, or allowing responses to food security threats such as reductions in crop yields, market pressures diverting food to non-food uses or a more rapid rise in population. For perspective, sufficient liquid biofuel to meet 2013 global aviation energy needs (Moody, 2012) would require human-edible crop inputs of ≈ 2100 kcal/p/d, assuming a 50% conversion efficiency of food energy to aviation fuel (Huang and Zhang, 2013). B_{2050} shows that not feeding human-edible crops to animals would allow the projected global population in 2050 to be adequately fed, without

Table 1: Comparison of global and regional food consumption with requirements for a "healthy diet". The maximum recommended intake of meat and dairy is 567 kcal/p/d; the intake of fish is kept at current consumption levels of 54 kcal/p/d. DOI: <https://doi.org/10.1525/elementa.310.t1>

Food type	Healthy diet (kcal/p/day)	Current (2013) global and regional consumption (kcal/p/day)							
		World	Industrialised Asia	North America & Oceania	Europe inc. Russia	Latin America	South & South-east Asia	North Africa, West & Central Asia	Sub-Saharan Africa
Fruit and vegetables	255 (minimum)	159 ^b	294	129 ^b	142 ^b	112 ^b	82 ^b	154 ^b	193 ^a
Sugar and sweeteners	150 (maximum)	189 ^a	68	383 ^b	264 ^b	297 ^b	195 ^a	214 ^b	153 ^a
Vegetable oils	360 (maximum)	219	179	626 ^b	359	296	116	304	173
Meat, dairy and fish	624 (maximum)	499	624	1059 ^b	1035 ^b	637 ^a	257	404	170

^aIndicates consumption outside healthy dietary limits (World Health Organisation & Food and Agriculture Organisation of the United Nations, 2003; Willett, 2001; American Heart Association, 2001).

^bIndicates consumption more than 33% outside healthy dietary limits (World Health Organisation & Food and Agriculture Organisation of the United Nations, 2003; Willett, 2001; American Heart Association, 2001).

Table 2: Description of scenarios. DOI: <https://doi.org/10.1525/elementa.310.t2>

Scenarios	2013 (population 7.2 billion)	2050 (population 9.7 billion)
Base – current global food production with losses and animal feed unchanged	A_{2013}	A_{2050}
No animal feed – current global crop production with no human-edible crops fed to animals	B_{2013}	B_{2050}
No waste and no excess consumption	C_{2013}	C_{2050}
50% less human edible crops fed to animals, waste and excess consumption (compared to Base)	D_{2013}	D_{2050}
Meat and dairy consumption per capita at 2013 levels	–	E_{2050}
Meat and dairy consumption per capita at FAO 2050 prediction	–	F_{2050}

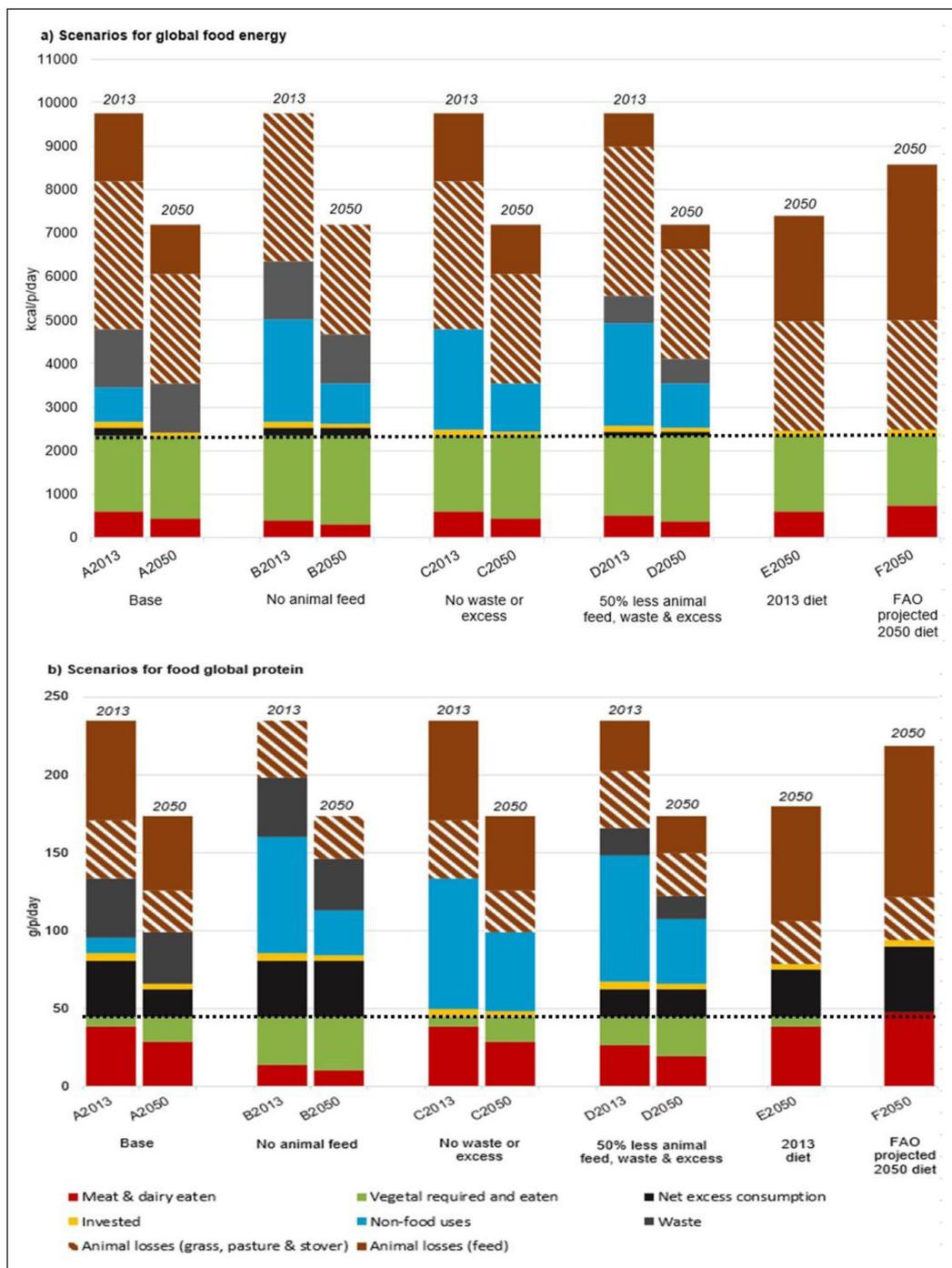


Figure 3: Distribution of energy (panel a) and protein (panel b) between various end-points for the current system (A_{2013}) and nine scenarios: three in 2013 with a global population of 7.18 billion and six with a projected population of 9.7 billion for 2050. In scenarios A to D, the amount of edible crops grown and the amount of grass, pasture and stover fed to animals remain constant at 2013 levels. A_{2050} shows the effect of population rise with waste streams staying unchanged (i.e. reducing per capita), except for household waste which remains the same per capita. B_{2013} and B_{2050} show the effect of not feeding crops that are directly edible by humans to animals. C_{2013} and C_{2050} show the effect of eliminating all waste and net excess consumption. The B and C scenarios are theoretical best cases that show the maximum that can be achieved through each lever. D_{2013} and D_{2050} , more realistically than the B and C scenarios, show the combined effects of reducing the amount of human-edible crops fed to animals, waste and net excess consumption all by 50% compared to the A scenarios. E_{2050} holds meat and dairy consumption per capita at current levels while F_{2050} allows meat and dairy consumption per capita to increase by 23%, in line with FAO projections. E_{2050} and F_{2050} are only possible with an increase in total crop production (see text). For clarification, animal losses in solid brown represent those associated with human-edible food. The hatched brown shows ‘losses’ associated with grass, pasture and stover and represents the inefficiencies of conversion of nutrients from vegetable matter to meat and dairy. The horizontal dotted lines show the ADER for calories (panel a) and the ARI for protein (panel b). DOI: <https://doi.org/10.1525/elementa.310.f3>

reducing waste or net excess consumption, while allowing non-food uses to increase to 927 kcal/p/d. However, a reduction in MD&F availability to 301 kcal/p/d would result.

The “no waste and no excess consumption” scenarios, C_{2013} and C_{2050} , show the effect of eliminating all waste and net excess consumption. In C_{2013} this allows non-food uses to increase to 2312 kcal/p/d. In C_{2050} global food availability is sufficient to feed the increased population. Although MD&F availability falls to 439 kcal/p/d in proportion to population increase, availability for non-food uses rises to 1092 kcal/p/d.

D_{2013} and D_{2050} , more realistically than the B and C scenarios, show the combined effects of reducing the amount of human-edible crops fed to animals, all waste and net excess consumption by 50% compared to the “base” (A) scenarios. For the 2013 population, this requires a 16% cut in MD&F consumption to 501 kcal/p/d but would allow non-food uses to rise to 2385 kcal/p/d. D_{2050} shows that for the 2050 population, MD&F availability falls by 38% to 370 kcal/p/d while non-food uses could still rise to 1023 kcal/p/d.

All the above scenarios for 2050 entail a reduction in MD&F consumption, contrary to current FAO projections (Alexandratos and Bruinsma, 2012). E_{2050} holds MD&F consumption at the 2013 level of 594 kcal/p/d while F_{2050} increases MD&F consumption to 730 kcal/p/d, in line with FAO projections (Alexandratos and Bruinsma, 2012). To make E_{2050} possible, we eliminate waste, non-food uses and excess energy consumption. Even when this is done, additional (5%) crop production above 2013 levels is required to provide sufficient human food for the projected population in 2050. In F_{2050} a 31% increase in crop production above 2013 levels is required. Current (2013) crop production is therefore not adequate to feed the projected population of 9.7 billion people in 2050 with these levels of meat and dairy consumption. Without these increases in crop production, the deficits in supply would be 203 and 1337 kcal/p/d for E_{2050} and F_{2050} respectively (i.e. an additional global supply of 1.95×10^{12} and 12.8×10^{12} kcal/d respectively would be required to feed 9.7 billion people).

Finally, for calories, we calculate the effect of society in 2050 not reducing waste and maintaining per capita non-food uses at current levels while increasing MD&F consumption in line with FAO projections to 730 kcal/p/d. This would require a 119% increase in human-edible crops grown. This is slightly higher than the previous estimate made by Tilman et al. (2011).

Current protein production is sufficient to feed the global population in A_{2050} , although net excess consumption reduces from 36 to 18 g/p/d, and, as with calories, there is none available for non-food uses. The B, C and D scenarios all show a greater per capita abundance of protein than currently, even in 2050. In E_{2050} MD&F consumption remains at 2013 levels per capita and this is achieved by eliminating non-food uses, waste and excess energy consumption. Excess protein consumption reduces from 82% to 69% above the RDA. In F_{2050} the meeting of energy requirements through the

consumption of a higher MD&F diet results in a rise in protein consumption to almost double the RDA (196%).

We do not conduct the same scenario analysis for vitamin A, iron or zinc because their supply can be increased through cost-effective fortification and/or supplements (Horton, 2006) without making changes to the amount or type of food produced. However, as with energy and protein, even an excess in supply does not ensure adequate intake by every individual.

Conclusions

A global food system that is sustainable, both environmentally and for human health and wellbeing, may be thought to have four requirements. Food production must be sufficient, in quantity and quality, to feed the global population without unacceptable environmental impacts. Food distribution must be sufficiently efficient, such that a diverse range of foods containing adequate nutrition is available to all, again without unacceptable environmental impacts. Socio-economic conditions must be sufficiently equitable, such that all consumers can access the quantity and range of foods needed to enable a healthy diet. Lastly, consumers need to be able to make informed and rational choices, such that they consume a healthy and environmentally sustainable diet.

Whether or not global society can adapt to meet these four extremely challenging requirements is debatable, given the enormous and complex obstacles in current political economy, socio-cultural norms and inequalities in wealth, access and social power. However, they represent an idealised state towards which the global food system must move in order for it to become sustainable. Here, we do not consider the social (e.g. Dong et al., 2007), behavioural or cultural (e.g. Timmer, 2009), or socio-economic (e.g. Benton, 2016) dimensions of food security, or any impacts of environmental or technological changes on yields. Rather, we focus solely on the flows of currently grown crops into various end-points, one of which is the food eaten.

Although animals do play an important role in converting grass, pasture and stover into human-available nutrition, our analysis shows no nutritional case for feeding human-edible crops to animals. It may be that meat and dairy, particularly that produced from grass, pasture and stover, is of dietary importance to people who do not have access to diverse food types or are beyond the physical, financial or cultural reach of fortification or supplementation programmes. However, overall, industrialised meat and dairy production, which currently relies on feeding 34% of human-edible crop calories to animals globally, is highly inefficient in terms of the provision of human nutrition, since it reduces the energy, protein, iron and zinc supplies potentially available to humans from crops, and is incompatible with a sustainable global food system as currently conceived.

Current and probable future regional differences in per capita production highlight the absolute necessity for the global trade of food, without which there would be shortages in some regions of the world. Regional differences in population growth are likely to exacerbate this.

Currently 16% of crops available for eating are diverted to non-food uses but increasing market pressures for bio-fuels could raise this and further stress the global food system.

The current global production of fruit and vegetables is not sufficient to provide a healthy diet for all, and supply-side changes are required to address this. Vitamin A production is also not sufficient, although this is largely resolved through fortification and supplements. In other respects, the current production of crops is sufficient to provide enough food for the projected global population of 9.7 billion in 2050, although very significant changes to the socio-economic conditions of many and radical changes to the diet of most will be required.

There is currently widespread emphasis on increasing crop yields and reducing waste as the main mechanisms for ensuring global food security. The case for reducing food wastage, at all stages of the supply chain, and for reducing excess consumption above that required for healthy living, is self-evident. However, we show that, in the absence of increases in yield, both are quantitatively less important than reducing the amount of human-edible crops fed to animals (see also Shepon et al., 2018 who use a different approach to arrive at the same conclusion for the United States). Furthermore, the potential nutritional benefits of increased crop yields would be entirely lost if the additional crop production was diverted to biofuels and largely lost if diverted to animals.

Data Accessibility Statement

The Excel workbook containing our data and analysis is freely available at <https://doi.org/10.17635/lancastr/researchdata/222>.

Supplemental files

The supplemental files for this article can be found as follows:

- **Text S1.** Details of methods used; Data and analysis; Discussion of uncertainties; Food waste by stage and food type at the regional and global levels; The apportionment of food Vitamin A, iron and zinc at the global and regional scales between various end points; Is the current food supply compatible with a healthy diet?; Food supply under future hypothetical scenarios. DOI: <https://doi.org/10.1525/elementa.310.s1>

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Competing interests

The authors have no competing interests to declare.

Author contributions

M.B.-L. and C.N.H. designed the research, analysed and interpreted data and wrote the manuscript. C.K. and R.W. obtained and analysed data and contributed to discussions.

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