Human appropriation of land for food: The role of diet

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Abstract

Human appropriation of land for food production has fundamentally altered the Earth system, with impacts on water, soil, air quality, and the climate system. Changes in population, dietary preferences, technology and crop productivity have all played important roles in shaping today's land use. In this paper, we explore how past and present developments in diets impact on global agricultural land use. We introduce an index for the Human Appropriation of Land for Food (HALF), and use it to isolate the effects of diets on agricultural land areas, including the potential consequences of shifts in consumer food preferences. We find that if the global population adopted consumption patterns equivalent to particular current national per capita rates, agricultural land use area requirements could vary over a 14-fold range. Within these variations, the types of food commodities consumed are more important than the quantity of per-capita consumption in determining the agricultural land requirement, largely due to the impact of animal products and in particular ruminant species. Exploration of the average diets in the USA and India (which lie towards but not at global consumption extremes) provides a framework for understanding land use impacts arising from different food consumption habits. Hypothetically, if the world were to adopt the average Indian diet, 55% less agricultural land would be needed to satisfy demand, while global consumption of the average USA diet would necessitate 178% more land. Waste and over-eating are also shown to be important. The area associated with food waste, including over-consumption, given global adoption of the consumption patterns of the average person in the USA, was found to be twice that required for all food production given an average Indian per capita consumption. Therefore, measures to influence future diets and reduce food waste could substantially contribute towards global food security, as well as providing climate change mitigation options.

1. Introduction

Human appropriation of global net primary production (NPP) of vegetation is increasing, and has doubled since 1910 (Krausmann et al., 2013). This is due to rising populations, as well as changes in diets. Diet is linked with wealth (Tilman et al., 2011), urbanisation (Huang and Bouis, 2001; Seto and Ramankutty, 2016; Wu and Wu, 1997), and globalising food commodity markets (Pingali, 2007; Popkin, 2006; Yu et al., 2013). These changes, including rising incomes, have seen a concomitant increase in food consumption and shift towards higher rates of consumption of commodities that are more land-intensive to supply; in particular meat and milk (Godfray et al., 2010; Tilman and Clark, 2014; Weinzettel et al., 2013).

Shifts in diets have become an increasingly important driver for land use change over time (Alexander et al., 2015; Kastner et al., 2012), a process that is likely to continue even as the rate of population growth slows (van Vuuren and Carter, 2014). Although increases in yields and production efficiencies have offset additional demand for food commodities, agricultural land areas have been expanding (FAOSTAT, 2015a). Environmental impacts can occur either through the expansion of agricultural production and consequent loss of a previous land cover, or through the intensification of production, e.g. eutrophication or biodiversity loss (Smith et al., 2013). Land use and the environmental impacts associated with agricultural production are also increasingly displaced from the country of consumption, through international trade of food commodities (Erb et al., 2009; Weinzettel et al., 2013; Yu et al., 2013). Agriculture accounts for around a third of global anthropogenic greenhouse gas (GHG) emissions, and land-use change alone presently accounts for 10% of anthropogenic CO_2 emissions (Le Quéré et al., 2015). As well as causing environmental issues, dietary transitions have contributed to rising global rates of obesity and increases in associated diseases, e.g. diabetes and heart disease (Hu, 2011; Tilman and Clark, 2014).

Animal products contribute disproportionately low amounts of energy and protein to human diets (respectively 18 and 39 % globally in 2011), relative to their land-use footprint (pasture accounts for approximately 68% of agricultural land, plus around one third of cropland is used for the production of animal feeds (Alexander et al., 2015; FAO, 2006)). However, grassland is a broad category that covers a diverse range of intensities, from intensively managed pasture to extensively used savannahs with little or no inputs of fertiliser or other management, meaning that direct comparisons between different land use areas are difficult. Nonetheless, the expansion of pasture (62% of the expansion in agricultural area from 1961 to 2011 (FAOSTAT, 2015a)), as well as the increasing use of crops for feed, demonstrates the critical importance of animal products as a driver of land use change. Animal products also play a role in water consumption (Jalava et al., 2014), and agricultural GHG emissions not associated with land use change (Tilman and Clark, 2014). The impacts from food production, both of animal products and crops, are exacerbated by losses or inefficiencies that exist at each stage in the production system, from harvesting, through transport and storage, to processing and finally at the consumer (Gustavsson et al., 2011; Parfitt et al., 2010).

Future food requirements could be met through a combination of increasing production and reducing demand. However, substantial attention has been given to supply-side responses, including expanding land in agricultural use and increasing food yields, especially crops (e.g. closing the ‘yield gap’ or ‘sustainable intensification’) (Foley et al., 2011; Kastner et al., 2014; Mueller et al., 2012; West et al., 2014); or the potential benefits and trade-offs associated with increasing livestock intensities (Davis et al., 2015; Herrero et al., 2016). Such analyses tend to consider dietary change as an exogenous wealth-based factor, and anticipate continuations of current dietary trends (Engström et al., 2016; Schmitz et al., 2014). However, diets and the food preferences that shape them do not necessarily follow fixed trends. Instead, they alter over time influenced by technology, policies and changes in social norms, e.g. (Hollands et al., 2015). Modelling work has been done to project the impact of alternative assumptions regarding future diets (Bajželj et al., 2014; Haberl et al., 2011; Popp et al., 2010; Stehfest et al., 2009), and the ability of the agricultural system to supply the global population with a diet containing adequate calories has also been considered (Cassidy et al., 2013; Davis et al., 2014). Further studies in this area have taken a life-cycle analysis (LCA) approach that typically consider either GHG emissions, energy or water requirements for individual commodities (Carlsson-Kanyama and González, 2009; González et al., 2011; Marlow et al., 2009; Pelletier et al., 2011). However, few studies have quantified the impact of variations in existing diets. Erb *et al.* (2009) considered the impact of current variations in food consumption patterns on agricultural land use, by quantifying trade in the embodied human appropriation of biomass net primary production. But, despite the potential significance of consumer behaviours on land use, no attempt appears to have been made to quantify the land use impacts of existing diets, dissociated from the complicating effect of domestic production and international trade.

Here, we address this gap by proposing a new index and using it to quantify the land use requirements of diets by country and over time (from 1961 to 2011). The Human Appropriation of Land for Food (HALF) index expresses the land area required for the global population to consume a particular diet, as a percentage of the world land surface. HALF therefore provides a relative measure of the scale of the impacts of alternative diets on land use. Diet here is assumed to include the quantities of commodities lost and wasted after reaching the consumer. The index is calculated from global average production intensities and yields from a baseline year, primarily 2011. HALF is accordingly not predictive, as adaptive responses in production systems that may result from changes in demand are excluded. Rather, the HALF index is a metric that characterises the land use impact of alternative scenarios of dietary patterns. The results can be interpreted in terms of both methods and areas of production, with a given increase in the HALF index implying the same increase in agricultural areas, an equivalent increase in productive efficiency, or some combination of the two.

2. Method

FAO country-level panel data for crop areas, production quantities, commodity uses and nutrient values were used to construct the HALF index (FAOSTAT, 2015a, 2015b, 2015c, 2015d, 2015e, 2015f). Global average production values and efficiencies for primary crops, processed commodities and livestock products were used to calculate the agricultural areas needed to meet per capita consumption for each country. The index is expressed as the percentage of the world's land surface required for the global population to adopt each country's diet. All diets are evaluated using the global average production system. Assessments of country average diet do not use production or international trade associated with that country, except as they contribute to the world average. The calculations and assumptions are described in more detail below, with a summary of assumptions available in Table S2.

(a) Allocating areas for food commodities

The areas associated with the production of 90 commodities (see Table S3), representing 99.4% of global food consumption by calorific value, were each allocated between three categories of use: food for human consumption, animal feed, and non-food related uses (primarily biofuels and fibre). The commodities comprise 50 primary crops that are directly grown, 32 processed commodities derived from them, and 8 livestock products. The FAO commodity balance data (FAOSTAT, 2015d) identifies the quantities used for food, feed, processing, other non-food related uses (primarily, bioenergy and fibre), seed and waste. To provide an assessment of the embedded areas required for delivering the consumed commodities two adjustments were made. Firstly, for each primary crop, the quantities used as seed and wasted (e.g. in storage and transport) were distributed across the remaining categories of use (i.e. food, feed, processing and non-food). The second adjustment deals with the difference between the total cropland area and the harvested areas (e.g. in 2011, respectively, 1556 Mha and 1378 Mha (FAOSTAT, 2015a, 2015c)) due to set-aside, multiple-cropping, and failed or unharvested crops. To account for these differences, the cropland area for each primary crop was adjusted by the ratio of these areas (e.g. in 2011 areas they are increased by a factor of 1.129). After applying both the adjustments, the cropland area for each primary crop was then allocated pro-rata between the categories of use (i.e. food, feed, processing and non-food), by the mass used for each category. This approach removes the areas used to produce commodities for bioenergy, fibre or other non-food uses. Example calculations are given in the SI Methods.

The areas used to grow the primary crops for processing were further mapped to the commodities output from the processing. Where multiple commodities are produced from a single crop, the areas used to grow the primary crop were allocated on an approximate economic value basis (Table S4). For example, processed oil crop areas were divided equally between the resulting oil (used primarily for food and biofuel), and the seed meals or cakes (used primarily for livestock feed). In 2011, 224.1 Mt of soybeans, which represent the single biggest vegetable oil crop (48% of the total), were processed globally into 41.6 Mt of oil and 174.7 Mt of meal (7.8 Mt is assumed lost during processing). This gives a similar total market value for the oil and meal (45% of value is in the oil and 55% in meal), at 2011 market prices of $1103/t and $321/t respectively (Index Mundi, 2016), suggesting that an equal division of input area is a reasonable approximation. Alternative allocations would introduce additional biases. For example, calculations on the basis of mass would be biased towards associating the area with the seed meals, while conversely accounting for them as a by-product with no area allocated would implicitly and incorrectly assume they can be freely produced and have no value.

(b) Allocating areas for animal feed and pasture

Animal nutrition derives from grassland and feed crops including forage crops. Data are available to quantify the area of pasture and quantities of crops used as feed (FAOSTAT, 2015a, 2015d). However, there are no empirical data to describe directly how these sources of nutrition are divided between livestock species, and hence between commodity types such as meat, milk and eggs. Instead, feed conversion ratios (FCRs), describing the efficiency of converting inputs into edible animal products, were used to estimate animal feed requirements (Table 1). Commonly, FCRs are expressed in terms of dry matter (DM) of feed per animal live weight (LW). To represent the production efficiency of meat consumed by humans, these ratios were adjusted to express feeding requirements per unit edible weight (EW), and also to account for the need to raise sire and dam animals (Smil, 2002).

The nutritional requirements of monogastric livestock (i.e. poultry and pigs) were assumed to be met solely from feed, while nutrients for ruminant species (e.g. cattle and sheep) come from feed and grazed pasture. Firstly, the produced masses from monogastric animals were multiplied by the feed conversion factors (Table 1) to give estimates of the feed requirements. These feed amounts, and the cropland areas needed to provide them, were allocated to the monogastric livestock products. Secondly, the remaining feed (23% in 2011 using feed dry matter content (INRA et al., 2016)), and associated cropland areas were allocated *pro rata* by the estimated feed requirements across the ruminant products. The same *pro rata* allocation was used to associate the pasture area with products derived from ruminant animals. See SI Methods for a worked example.

Table 1. Global average feed conversion ratios and efficiencies for animal products. The feed conversion efficiencies and direct energy for housing are given for reference, and are not used in the analysis.

Animal product	**Feed conversion ratio (kg DM feed/kg EW)**	**Percentage edible (% EW of LW)**	**Energy feed conversion efficiency (%)**	**Protein feed conversion efficiency (%)**	**Direct energy for housing or processing (MJ / kg EW)**	**Data source**
Poultry	3.3	70	13	19.6	4.5	(Macleod et al., 2013; Smil, 2013)
Pork	6.4	55	8.6	8.5	1.8	(Macleod et al., 2013; Smil, 2013)
Beef	25	40	1.9	3.8	0.08	(Opio et al., 2013; Smil, 2013)
Other meat *	15	55	4.4	6.3	0.09	(Opio et al., 2013; Smil, 2013)
Eggs	2.3	-	19	25	1.3	(Macleod et al., 2013; Smil, 2013)
Whole Milk	0.7	-	24	24	0.22	(Little, 2014; Opio et al., 2013)

Notes:
* The 'other meats' category, which forms 6.6% of all meats produced in 2011, is based on sheep and goat meat (65% by mass of 'other meat' in 2011), but includes other sources of meats, e.g. horse, rabbit and camelids.

(c) Assessing the land use impact of different diets

The average consumption per capita and per commodity were calculated globally and nationally (FAOSTAT, 2015b, 2015d). The area required to produce each commodity was determined from the global production system land use allocations (described above). The area needed to provide all the commodities for each country's diet if it were adopted by the global population could then be calculated (FAOSTAT, 2015g). This was expressed as a proportion of total global land area to obtain the Human Appropriation of Land for Food (HALF) value. HALF values were also calculated to quantify the land use impacts of changes in country-level diets over time. The values primarily used here were calculated with variable diet only, and a constant baseline population and production system (2011 was chosen as the most recent year with available values (FAOSTAT, 2015d)).

National land footprints for food, i.e. an estimate of the actual agricultural land area used supply to each country's food, were also calculated based on domestic production and the land displaced through international trade. This used the same data as the HALF calculation, and accounted for imports and exports following the approach of previous studies (Alexander et al., 2015; Jalava et al., 2014). For each commodity, net exports were included using the domestic production yields, and net imports using the global mean yields of net exports (weighed by net export quantities). The country footprints were expressed as an area per capita using country populations (FAOSTAT, 2015g). Expressing as a fraction of global land area required for the global population, to match HALF values, could not be justified as the land footprints are country specific (e.g. in climate and soil).

(d) Decomposing dietary changes into quantities consumed and commodity profiles

The impacts of potential shifts in diets from the 2011 global baseline to that of a particular country was decomposed into two parts. The first part represents a shift in the total quantity of nutrients consumed while holding the proportional contribution of each commodity constant. The second part represents a shift in the ratio or profile of commodities consumed, while holding the total nutrient level constant. These two parts were expressed both in protein and energy terms, with nutritional values by mass for each commodity derived from global FAO food supply data (FAOSTAT, 2015e, 2015f). For example, the average energy consumed per capita globally is 11.9 MJ/person/day, while in the USA the average is 16.6 MJ/person/day, i.e. 40% more. Therefore, if the current global profile commodities remained unchanged, but the energy consumed increased to that of the USA, 40% more land would be required for production, in the absence of production intensification. This is reflected in a 40% increase in HALF. However, consumption in the USA also differs in the relative profile of the different commodities consumed. These differences also have an effect on the land required, evaluated without the influence of the quantity differences in the 'profile' type.

3. Results

(a) Global and country-level HALF

The total agricultural area used for human food production was 4484 Mha in 2011, of which 871 Mha was used for cropland for human consumption, and 3700 Mha for animal products (497 Mha of cropland for feed and 3203 Mha of pasture). The remaining cropland was used for biofuels (140 Mha), fibre (33 Mha), feed for non-food uses of animal products (9 Mha), and net variations in stock levels (7 Mha). Expressed as a percentage of the global land surface (13,009 Mha (FAOSTAT, 2015a)) the Human Appropriation of Land for Food (HALF) index is 35.1, or an average area per person of 0.65 ha. Expressing HALF as a percentage of global land surface includes land that is unlikely to be suitable for agriculture, e.g. ice-covered or desert areas. However, the use of an estimate of suitable land suffers from difficulty in definition and measurement, and also would vary with climate change. Consequently, the clarity of comparing to the global land surface was preferred.

There are large differences in HALF values between country-level average diets. For example, the global adoption of the diet in the USA would require over 6 times the agricultural area that adoption of the diet in India, with a HALF index of 97.7 compared to India's 15.8. Figure 1 shows the HALF index at 2011 for the average diets of 170 countries for which sufficient data were available (Table S5). The highest HALF values are for diets in New Zealand, Argentina and Australia at 135.8, 114.9 and 112.2 respectively, due to the high levels of animal products – particularly beef - consumed. At the other extreme are Mozambique, Liberia, Bangladesh and Sri Lanka all with a HALF index below 11.5, i.e. less than a third of the global average.

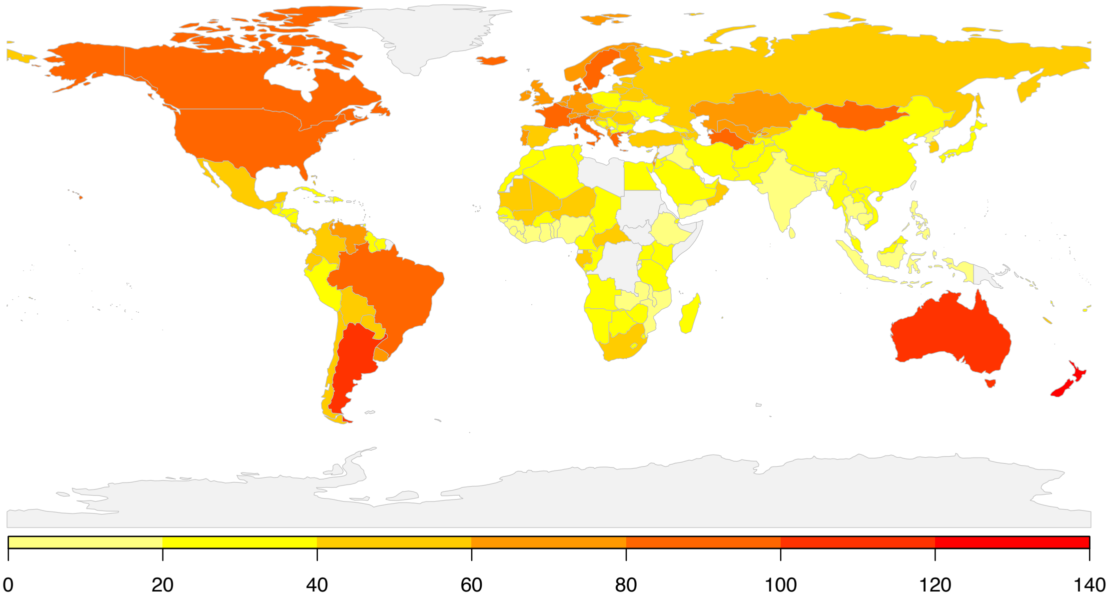

Figure 1. Map of HALF index for average country-level diets in 2011. Countries where the index could not be calculated due to no commodity consumption data being available (FAOSTAT, 2015d)*, e.g. Libya, Somalia and Greenland, are shown in light grey.*

The HALF results use global mean production efficiencies, and so no specific account is taken of domestic (national) production except as it contributes to the world average. The national food footprints (Figure S1) include aspects of diet and production within them, whereas HALF (Figure 1) only includes variations in diet. The distribution of these national footprints differ from the distribution of HALF values as a result (e.g. Mongolia has a per capita footprint 3 times greater than any other country (39 ha/person), due to the use of extensive grazing). Many developed countries have a lower land use footprint than implied by the HALF index, due to the high agricultural yields in these countries. For example, the USA was found to have a national food footprint of 1.0 ha/person, but a HALF of 1.8 ha/person. The first value addresses, “how much land is used to produce the food consumed in the USA?”, and the second “how much land would be used if the global population adopted the average diet in the USA”. The inclusion of production systems within the land footprint to some degree obscures the understanding of the role of diet in the global food system. HALF, therefore, provides both a clearer comparative metric between countries of the land requirements of different diets, and also a way to consider the impacts from changes in dietary patterns.

(b) Temporal trends

Calculating the time-dependent HALF index for dietary variations only, i.e. assuming a constant 2011 population and production systems, demonstrates the impacts of changes in food consumption patterns (solid lines in Figure 2). The global agricultural land required has increased by 8.7% due to dietary changes, from a HALF value of 32.3 in 1961 to 35.1 in 2011. For country-level average diets, results for Brazil and China show particularly substantial increases, due to the transitions in diets that are associated with increasing per capita wealth (Godfray et al., 2010), as well as the influence of urbanisation (Dong and Fuller, 2010; Huang and David, 1993; Popkin et al., 1999; Seto and Ramankutty, 2016) and globalisation of food markets (Meyfroidt et al., 2013; Popkin, 2006). The land required for the diet in Brazil more than doubled between 1961 and 2011, from 43.5 to 88.2, making it the eleventh highest ranked country globally in 2011. However, the Chinese diet’s HALF increased nearly 5-times, from 6.0 in 1961 (the lowest at that period), to 28.6 (but still below the global average). The gap between the USA and Indian diets has reduced slightly, from the USA value being 7.5 times the Indian value in 1961 to 6.2 times in 2011, with an 8% reduction in the USA and a 11% increase for the Indian diet.

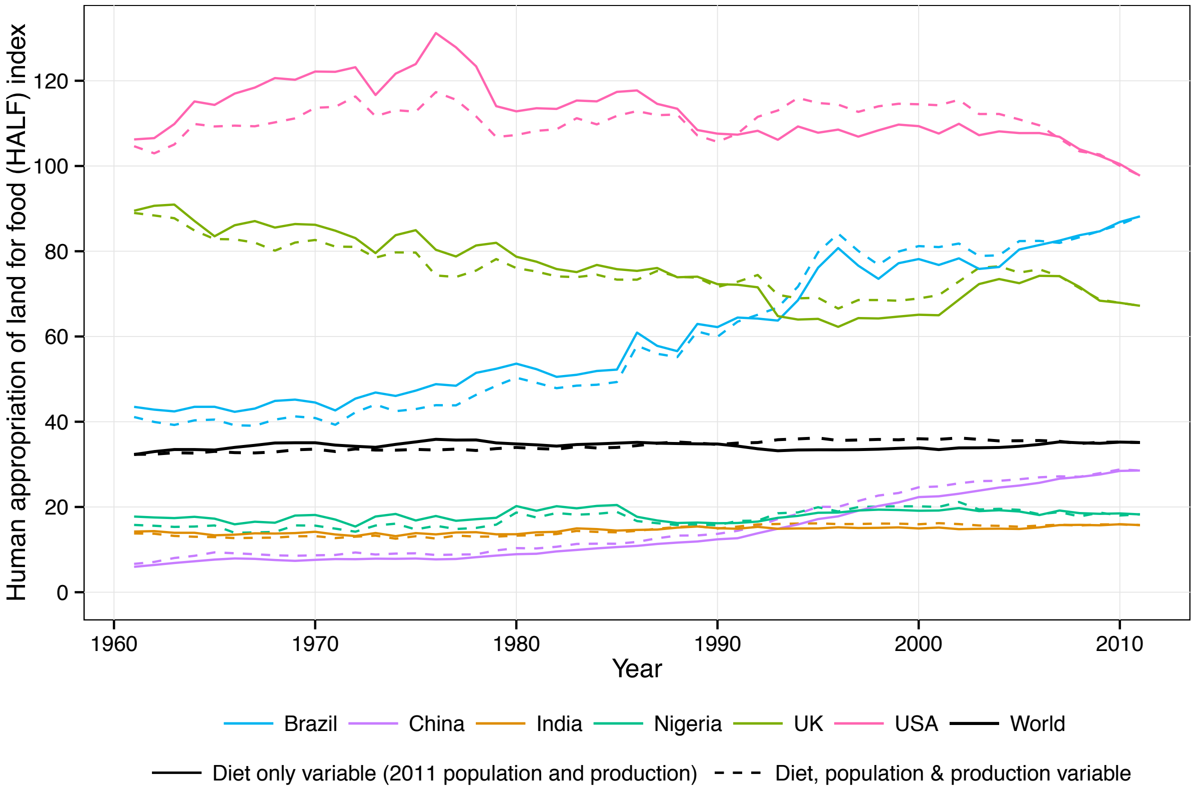

Figure 2. HALF index from 1961 to 2011, globally and for selected counties. Solid lines show variable diets, but constant population and agricultural production systems (at 2011 values). Dashed lines show variable diet, population and agricultural production systems over time.

When the time-dependent HALF indices are re-calculated to take account of changing production efficiencies and population sizes (Figure 2, dashed lines), they show a high degree of similarity to the diet-only case (Figure 2, solid lines). This is because increasing agricultural efficiencies and population growth in the past have acted in opposite directions on land requirements, largely offsetting one another. If production efficiencies from 2011 had been available and used in 1961, less than half of the agricultural land used at the time would have been required to feed the population at the time (Figure S2, dot-dashed line). However, populations have more than doubled since 1961, and therefore the 2011 population would have required more than twice the land for food production based on 1961 production systems (Figure S2, dotted line). The net effect is that if the mean global diet of 1961 had been consumed by the 2011 population, using 2011 production systems, agricultural land area would have remained largely unchanged from 1961 (just 5 Mha less land is estimated to have been needed than was used in 1961). When HALF values including variation in the production system and population (dashed lines in Figure 2) are lower than the HALF values for dietary changes only (solid lines), then cumulative improvements in agricultural efficiencies achieved by 2011 have not fully offset the rise in population. However, diets have also been changing. Dietary changes alone between 1961 and 2011 has caused the agricultural area for food to increase by 368 Mha or 2.8% of the land surface. HALF has increased less than the 464 Mha expansion of global agricultural land since 1961 (FAOSTAT, 2015a), as an increasing proportion of land is used for non-food uses of agricultural commodities, i.e. feedstocks for biofuels.

The central role of the types of foods consumed in determining the agricultural land requirements of different diets, compared to the overall quantity of nutrients consumed, can be seen from the calculated energy intake and the percentage derived from animal products (Figure 3). Variation in total food energy consumed between countries and over time is substantially smaller than the variations in the land needed (Figure 3 & Figure S2). In 2011, the per capita land required to sustain a USA diet was 635% of that required for an Indian diet, even though the energy content of the food was only 65% greater (or 99% greater in terms of protein; see Figure S3). This disparity stems from the profile of commodities consumed, with 30% of energy derived from animal products in the USA and 9% in India (65% and 19% respectively for protein). This greater proportion of animal products increases the land requirements in comparison to a predominantly vegetarian diet, e.g. as in India.

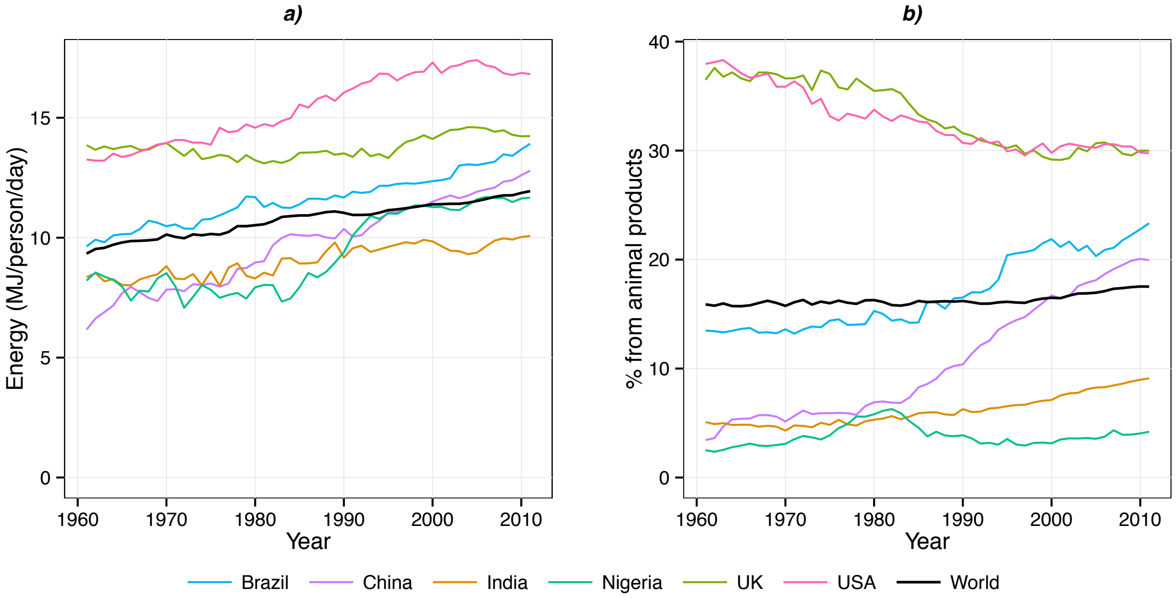

Figure 3. Mean energy per capita, a), and percentage energy derived from animal products, b), in foods consumed from 1961 to 2011 globally, and for selected countries, using global average nutritional values (FAOSTAT, 2015e, 2015f). This includes commodities wasted after reaching the consumer, but not in the food supply chain.

In developed countries such as the USA and the UK, per capita dietary land requirements have been falling (Figure 2) even while energy and protein consumption continue to rise (Figure 3a & Figure S3a). This apparent discrepancy is explained by the fall in the proportion of nutrients from animal products (Figure 3b & Figure S3b), and a shift in the mix of animal products consumed (Figure 4). The drop in the proportion of nutrients from animal products is in large part due to the increased consumption of vegetal products, particularly vegetal oil, e.g. soybean oil. For example, in the USA vegetal oils provided 9.6% of calories in 1961, but this expanded to 19.2% by 2011 (14.5% from soya bean oil alone). Consumption of these oils accounts for over half (55%) of the 3.2 MJ/person/day increase in energy consumed in the USA, with other sweeteners (i.e. corn syrup) and poultry meat respectively accounting for 26% and 18% of the rise.

The relative quantities of different animal products consumed changes over time, influencing the HALF results. The effects of this are evident in the results for China, where since 1961 the proportion of nutrients derived from animal products has increased towards that found in developed countries (Figure 3), but the HALF values have converged more slowly (Figure 2). The energy and protein intake and the percentages derived from animals are all higher than the global averages in China in 2011 (Figure 3 & Figure S3). Nonetheless, the HALF is lower in China compared to its global value (Figure 2). This is due to the high rates of consumption of the commodities derived from monogastric animals (Figure 4), which have lower feed conversion ratios and lower land requirements in comparison to ruminants, although direct energy inputs are higher (Table 1). For example, the average diet in China contained around half the global average amount of beef (53%), but more than twice that of pork (239%). The rise in global HALF (8.5%) is also modest (Figure 2), given the rise in nutrients (28% rise in energy and protein) and the proportions derived from animals (increased by 11% for energy and 25% for protein). Again this can be understood by reference to the changes in the relative quantities of meats consumed (Figure 4). Global consumption per capita of bovine meat has been broadly constant, while poultry and pig meat have seen substantial rises, with 399% and 91% increases respectively from 1961 to 2011. Global average per capita consumption of beef is now less then pork and poultry in mass, energy and protein.

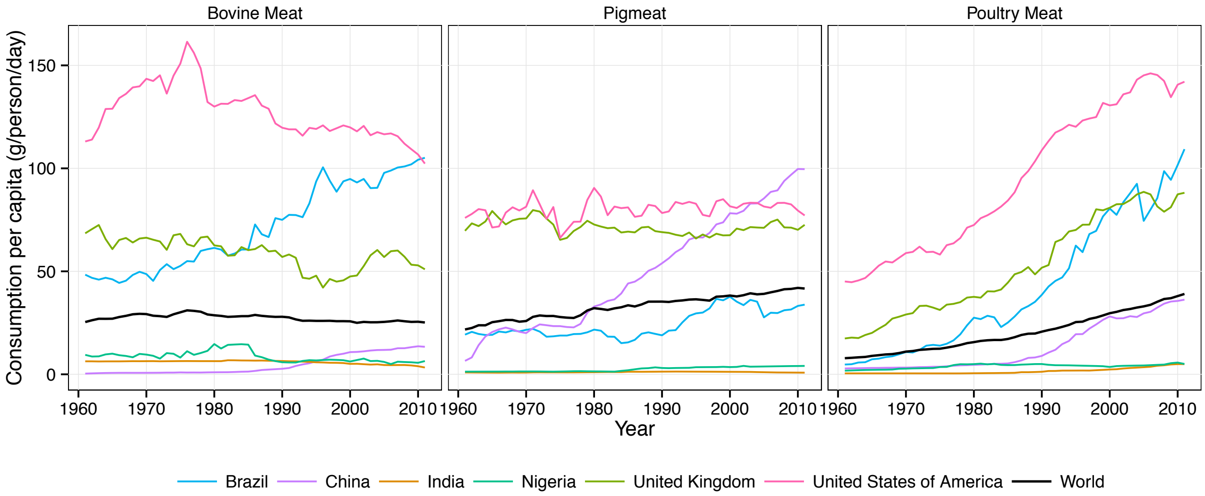

Figure 4. Per capita daily rates of bovine, pig and poultry meat consumption from 1961 to 2011. Data source: (FAOSTAT, 2015e).

(c) Alternative diet scenarios

Changes in diets and dietary impacts on land use are uncertain and are influenced by multiple factors, both economic and environmental. Two contrasting alternative scenario were used as exemplars to analyse the impacts of diet on global agricultural land use; the global adoption of the current diets of India and the USA. Although these countries are not the most extreme cases, they are major economies, with large populations, in which diets lie close to the lowest and highest land use requirements respectively (of the 170 countries included, India has the 13th lowest HALF value and the USA has the 6th highest, Table S5). Consideration of the adoption of these diets by the global population therefore provides a broad envelope within which human appropriation of land for food is likely to vary, but these are intended to be illustrative rather than represent equally plausible alternative futures. The net change in land use from a shift in global diet was decomposed into two parts; one considering a change in the quantity of nutrients consumed, and a second the profile of commodities consumed. The profile of commodities (i.e. the sources from which nutrients are derived) was found to have a greater impact on land use than the quantities of nutrients consumed, in the dietary transitions considered (

Table 2). For both dietary scenarios, changes in quantities and profiles act in the same direction, intensifying the overall impact.

*Table 2. Changes in HALF from transitions of average global diet to that of India or the USA in 2011, divided into the impact from quantity of consumption ('quantity') and the types of commodities consumed ('profile'). For the quantity and profile cases, the change in areas are calculated based on providing the same energy and protein as current consumption. The overall type includes changes in quantities and profile of foods consumed, and by definition (1+overall change rate) = (1+profile change rate) * (1+quantity change rate), in terms of energy or protein. A single "overall" row is given for each dietary scenario, as this is equal in both nutrient terms.*

Dietary scenario country	**Type and nutrient basis**	**Cropland area for food change (%)**	**Total cropland area change (%)**	**Livestock (feed & pasture) area change (%)**	**Agricultural area change (%)**
India	Profile: Energy	+13	-22	-61	-47
India	Profile: Protein	+27	-12	-56	-40
India	Quantity: Energy	-16			
India	Quantity: Protein	-25			
India	**Overall**	**-5**	**-34**	**-67**	**-55**
USA	Profile: Energy	-11	+21	+122	+97
USA	Profile: Protein	-17	+13	+109	+85
USA	Quantity: Energy	+41			
USA	Quantity: Protein	+50			
USA	**Overall**	**+25**	**+71**	**+214**	**+178**

The impact of contrasting diets is much larger for the livestock area compared to cropland area used for food for human consumption. A more than 3-fold increase is required in livestock area (pasture and cropland for feed) under the USA diet scenario, increasing HALF by 178%. This area is needed both to support the increased quantities of nutrients consumed and the changes in dietary profile towards a greater proportion of animal products. Conversely, the lower overall consumption and the lower proportion from animal products in India suggests the livestock area would drop to less than a third of the current area, and reduce the overall HALF by 55%. The changes in cropland required to produce food for human consumption are comparatively modest with both the Indian and USA diets, with a 4% fall and a 21% rise respectively. The profile of the Indian diet is weighted towards vegetal crops, but the impact of this is offset by the lower level of nutrient intake overall. The opposite is the case for the average diet in America, with lower emphasis on crops, but higher overall consumption. Figure 5 shows the 2011 HALF index values for these scenarios, with cropland (for food and feed) and pasture identified separately.

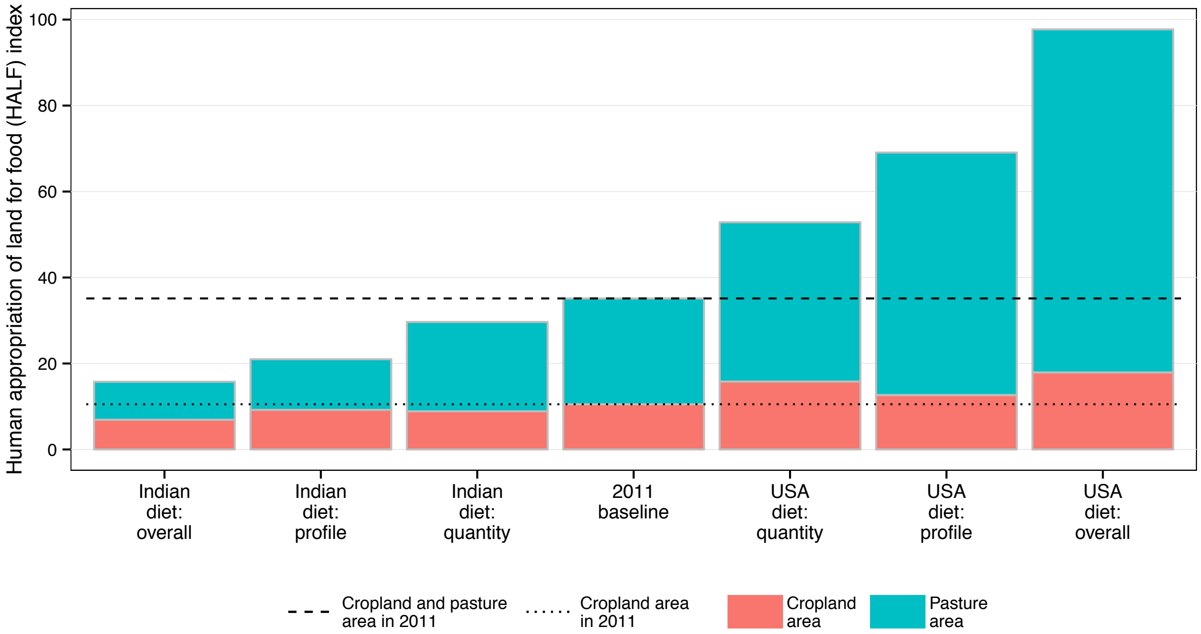

Figure 5. Cropland and pasture required to produce food under alternative dietary scenarios, expressed as required percentage of world land, or HALF index, using global 2011 population and production systems. For each scenario (from

Table 2) the case are shown that provides at least equal amounts of both energy and protein, e.g. the protein case is shown for the Indian diet profile, as the energy case provides insufficient protein.

4. Discussion

(a) Comparisons to previous studies

The results show that global adoption of diets already consumed by hundreds of millions of people could lead to a magnitude of change greater than a doubling or halving of current agricultural land area. There have been few previous studies that have quantified the impact of such substantial shifts in diets on agricultural land areas. Stehfest *et al.* (2009) is one example, where dietary scenarios for 2050 are considered, including a 'healthy diet' (low rates of ruminant meat and pork and moderate poultry and consumption) and a no-meat diet. The current diet in India falls between these scenarios (i.e. rates of animal product consumption are lower than the Stehfest *et al.* 'healthy diet', but higher than the no-meat diet), and likewise the land use results found here lie between those of Stehfest et al. (2009). The impact of a 'healthy diet' was also considered in Bajželj *et al.* (2014), and showed a somewhat lower drop of 32% in pasture areas in 2050 compared to the authors' business-as-usual scenario. The few studies published to date have shown that shifts in dietary preferences have a substantial impact not only on agricultural land use, but also on externalities such as GHG emissions and bioenergy potential (Haberl et al., 2011; Popp et al., 2010). Further studies that do not include land use change have also shown substantial GHG emissions implications from alternative diets, e.g. a 55% reduction from a vegetarian diet (Tilman and Clark, 2014). Considering the trade-offs between land for bioenergy production or afforestation (Williamson, 2016), reducing agricultural GHG emissions and meeting the food requirements of a growing population, a greater focus is justified in examining demand side measures, including waste reduction (Smith and Gregory, 2013).

The impact of global dietary changes since 1961 found here (Figure 2) is lower than that previously published (Alexander et al., 2015). The differences arise primarily from the alternative approaches to allocating areas of monogastrics livestock. In Alexander *et al.* (2015) poultry and pigs were allocated a proportion of pasture area, which increases the land use associated with these products, and conversely reduces the ruminant products' footprint. However, monogastrics' nutrient requirements are met from feed, while ruminants can also consume grass-based forage (Bellarby et al., 2013; Schader et al., 2015). Therefore, in this study a more accurate assumption was made where only ruminants are allocated a proportion of pasture area. As dietary changes have included larger increases in monogastrics (than ruminant) derived productions (Figure 4) the resulting bias in Alexander *et al.* (2015) associates dietary change with a greater land use impact than that found here. In 2011, 37.8% of the world surface was used for agricultural purposes (FAOSTAT, 2015a), and here 34.5% was found to be associated with food production. The difference between these rates is due to the other non-food uses of agricultural commodities, such as bioenergy and fibre (Alexander et al., 2015; Rulli et al., 2016).

(b) Uncertainties in the analysis

The results presented are derived under a set of assumptions with related uncertainties. Domestic consumption is assumed to be supplied from the global production system. For example, countries where grass-fed beef production systems predominate are treated identically to countries where housed or feed-based systems are more common, as all use global average values. The distribution of high HALF index values (Figure 1), appear to be associated with countries with substantial grassland areas and high levels of beef production. This is not due directly to the production system, but to these countries having high levels of beef consumption. The same effect occurs with vegetal commodities, where countries with high production intensities and yields are assigned the same global average as lower-yielding countries. Consequently, in countries with above-average yields, the HALF areas associated with growing that crop would be higher than domestic production implies. The national agricultural land footprints (Figure S1), gives the results of a similar calculation, but based on domestic production and accounting for international trade (rather than a global average). Given the research aims, we believe the approach of using a global average production systems is reasonable because of the global scale of the analysis (considering global adoption of alternative diets), and also because of the levels of international trade in agricultural commodities and the associated globalised markets (D'Odorico et al., 2014; Fader et al., 2013; Meyfroidt et al., 2013). Most importantly, the approach allows the impact of variations in diets to be quantified without the obscuring influence of differences in the production system.

The disaggregation of feed by animal products uses the feed requirements calculated from feed conversion ratios (FCR; Table 1). FCR are difficult to estimate, and have been the subject of misrepresentation by both sides of the sustainability - meat consumption debate (Fairlie, 2010). The FCRs used here are for the global average production, derived in FAO studies (Macleod et al., 2013; Opio et al., 2013). While some uncertainty in FCRs remains, changes in the ratios only affect the disaggregation of the global pasture and feed areas between animal products. Biases introduced by inaccurate FCRs will cancel out in the baseline case. When alternative consumption profiles are considered they may not perfectly cancel out, and result in a residual bias in the required land areas calculated. This is likely to be small relative to the scale of the overall effects shown, due in part to the offsetting between animal products. As a check on the accuracy of the FCRs used, the allocation of feed between monogastic animal and ruminants was compared against the results of a survey of the feed use from 134 countries (Alltech, 2013). This survey showed that 26% of total feed use was for ruminants in 2012, while 23% of feed was calculated as used for ruminants in 2011 in the results presented here. The level of agreement between these values gives additional confidence in the FCR rates used.

(c) Obesity, malnutrition and waste

The findings presented here are based on the average food reaching consumers rather than human nutritional requirements, and it is important to consider the extent to which these differ within a population. Distinctions arise due to over-eating and, conversely, malnutrition, through waste of food by consumers (Eshel and Martin, 2006), and also inequalities in distribution (Porkka et al., 2013). Losses and waste occur at each stage of the food supply chain, with overall food waste, accounting for losses in production and at the consumer, estimated to be around 25-40% of total food production (Godfray et al., 2010; Kummu et al., 2012). HALF values include losses both in the production system (e.g. unharvested crops and losses in storage, transportation, and processing) and at the consumer. Production system losses are derived from the global production efficiencies, and therefore are considered only as a global average. By contrast, food waste by consumers are included at a country specific level, as this is included in the FAO commodity balance data used (FAOSTAT, 2015d). Consequentially, the HALF index includes (but does not separately identify) the variations in the rates of per capita food waste by consumers. 95-115 kg/year of food has been estimated to be wasted per capita after reaching the consumer in Europe and North-America, while in sub-Saharan Africa and South/Southeast Asia this is only 6-11 kg/year (Gustavsson et al., 2011), which equates to 9-12% and 1-3% of food delivered to consumers respectively. Applying the mean values of these rates for USA and India suggests that the HALF values for consumer wastes alone is 10.3 and 0.3, respectively.

The protein requirement of adult men and women depends on body weight. For an average body weight of 60kg, 50 g/day of protein is the minimum safe limit (WHO et al., 2007). No country with a population of more than 20 million currently falls below this limit, although several smaller countries consume 40-50 g/person/day, i.e. Guinea, Guinea-Bissau, Haiti, Liberia, Madagascar, Mozambique, Zambia and Zimbabwe. The energy requirements also vary by sex, weight and the level of physical activity. For instance, average energy requirements for the population of UK adult females and males, are respectively 8.7 MJ/day (2079 kcal/day) and 10.9 MJ/day (2605 kcal/day) (SACN, 2011). To compare with the calculated energy in-takes, we assume the mean energy requirement value is 9.8 MJ/person/day (2342 kcal/person/day). This value is somewhat higher than the 2100 kcal/person/day energy intake used in some previous studies (Eshel and Martin, 2006; Kummu et al., 2012), and likely to exceed the in-take needed to avoid hunger or malnutrition (WFP, 2016). The average Indian consumption appears close to the population's energy requirements, given the relatively low levels of consumer waste in South & Southeast Asia (Gustavsson et al., 2011), just 1% more, assuming 2% food is discarded.

Even if there is sufficient food to avoid malnutrition within a country or region, this does not mean that these foods are distributed equitably. Globally, 37% of men and 38% of women were overweight in 2014 (Ng et al., 2014), while approximately 12% of people were undernourished between 2010 and 2012 (FAO et al., 2015). The populations living in countries with critically low food supply (<2000 kcal/cap/d) has also been dropping over time, from 52% in 1965 to 3% in 2005 (Porkka et al., 2013). In India (ranked 25th worst in the 2015 Global Hunger Index Report (Grebmer et al., 2015)) 20% of the population are over-weight (including nearly 5% obese) and 15% undernourished (FAO et al., 2015; Ng et al., 2014), while the for adults in the USA 66% are over-weight, including 33% obese (Ng et al., 2014). Given there are three-times more overweight people than undernourished, and that levels of malnutrition have been declining over recent years, better national and international distribution of food is more relevant to achieving global food security than additional production.

The USA per capita energy consumption is 16.6 MJ/day, which suggests that 41% of food (in energy terms) is either due to overeating or consumer waste (34% of energy intake is in excess of requirements, assuming 10.5% food waste (Gustavsson et al., 2011)). This is in line with a previous finding, showing that in the USA, overeating and food discarded by consumers accounted for 44% of food distributed to consumers (Eshel and Martin, 2006). The results suggest that under the global adoption of USA consumer behaviours the land required to produce the food wasted by consumers (including over-consumption), would be sufficient to provide more than twice the entire food requirements assuming adoption of Indian consumption patterns.

(d) Plausibility of dietary scenarios

Two contrasting scenarios were used to examine how changes in food consumption preferences and behaviours might affect agricultural commodity demand and land use. These scenarios explore the consequences of a wide range of consumption patterns, but do not represent equally plausible future states. The first scenario considers the average global diet transitioning to the current average USA diet. Although this (time-independent) scenario is unlikely in the short term, consumption patterns have been shifting in this direction, due to increases in per capita incomes in developing countries (e.g. China and Brazil), rural-urban migration and globalisation, leading to more overall per capita food consumption, and a greater percentage consumption of animal products (Lambin and Meyfroidt, 2011; Seto and Ramankutty, 2016; Tilman et al., 2011). However, a substantial gap in consumption patterns remains between countries, with the US diet requiring 2.8 times the land area of the global average diet, and 3.4 times that of the Chinese diet. Consequently, given current yields and production systems, it would clearly not be possible for the world's population to consume food as in the US; indeed, this would require 98% of all land, including snow-cover and deserts. Apart from being physically impossible, changes to approach this level of consumption would also generate strong market signals that would act to increase the price of food, suppress demand and intensify production practices (additional inputs, e.g. irrigation water, fertiliser or labour, leading to higher yield). Conversely, if more land were to be used for agriculture, suitable land would become more scarce, and the additional land would tend to be of lower quality and produce lower yields, leading to a greater area requirements (Lambin and Meyfroidt, 2011). Price signals may be particularly large for the less efficient and potentially costlier commodities, e.g. beef. Arguably, these impacts are already evident, with a shift towards chicken and away from beef (Figure 4) supported by intensification of chicken production and the associated efficiency increases (Havenstein, 2006).

The contrasting scenario considers the global diet becoming equivalent to the average diet of India. This is more plausible from an environmental and agricultural system viewpoint. However, it implies shifts in consumption that are the opposite of the global consumption trends that have occurred over previous decades, as per capita incomes have increased in developing countries. A reversal of these trends would either require a substantial shift in consumer preferences (towards the consumption of vegetal crops, e.g. higher rates of vegetarianism), or a catastrophic global economic collapse reducing per capita incomes, particularly in wealthier countries. Changes in food preferences may be achievable through either behavioural or economic approaches. For example, less food is consumed when people are offered smaller-sized portions, packages or tableware than when offered larger-sized versions, leading to the possibility of policies to reduce consumption (Hollands et al., 2015). Economic approaches such as taxes (e.g. a fat tax or a tax on sugar-sweetened beverages) and subsidies (e.g. on fruit and vegetables) could be used to provide fiscal incentives to change behaviours (Thow et al., 2010; Wang et al., 2012). However, the effectiveness of taxation and subsidies alone to alter diets, without other policies that target a number of different levels within society, has been questioned (Tiffin and Arnoult, 2011).

5. Conclusions

Dramatically different requirements for land for food production could arise depending on the course of dietary change – both in terms of quantity of food consumed per person, but more importantly in terms of the mix of food commodities. A wide range of human appropriation of land for food was found based on global adoption of current country-level average diets, far wider than the divergence in energy or protein in-takes, with the difference due to the types of commodities in each diet, and in particular the level of ruminant animal products. For example, if the diets of India or the USA were adopted globally the impact from the change in the mix of commodities would be about twice that from the quantities consumed. What we individually eat (or even waste), rather than how much, appears to be more important for agricultural land requirements. However, waste and over-eating are still important issues, with the results suggesting that the land required to produce the food wasted by consumers (including over-consumption) given USA consumption, could provide more than twice the food required under adoption of Indian consumption patterns.

Shifts toward diets of Western counties, exemplified here by the average diet in the USA, for the global population are not sustainable or desirable for environmental and health reasons (Tilman and Clark, 2014). Given the possibility that intensification alone may be insufficient to satisfy changes in dietary preferences and population growth, other methods of avoiding increases in agricultural areas are needed to target consumer behaviours or preferences. Behavioural and economic mechanisms need to be better understood to establish how more equitable, healthy and environmentally benign food consumption can be achieved.

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