Abstract

In the next decades, an increasing demand for the amount and types of food will have to be produced on decreasing per-capita available land areas, while the current environmental impact of agriculture also needs to be reduced. This confluence of the need for an adequate and healthy diet for everyone and the need for a sustainable use of land requires new agricultural metrics that consider human nutrition as a primary objective of agriculture. In this case study for the United Kingdom, we link agricultural yield statistics with UK-specific food composition data to analyse the land use efficiency of food items for 23 different nutrients. We show that, from a land use perspective, roots & tubers and vegetables are the most land-efficient producers for these 23 nutrients. Our results indicate further that, across all 23 nutrients, roots & tubers and vegetables deliver enough nutrients to feed a median number of 43 and 42 people per hectare for one year, respectively, while a hectare of cereals feeds a median of 21 people. Eggs, the most land-efficient animal product, only feed a median of four people per hectare. We conclude that a focus on a wide range of nutrients may lead to different conclusions about an efficient use of land compared to previous analyses that tend to only consider dietary energy and protein.

Keywords

Food security; land use efficiency; micronutrients; agricultural metrics; sustainability

1. Introduction

Demand for food, and in particular demand for animal products, is projected to increase substantially in the coming decades, because of an increasing world population and rising wealth across the globe (Tilman et al. 2011). At the same time, this increasing demand for food has to be met on decreasing per-capita available areas of land. Currently, it is estimated that the agriculture and land use sector is responsible for about a quarter of all greenhouse gas emissions, and uses about 40% of the total global ice-free land area (Foley et al. 2011, Smith et al. 2014). Therefore, it is becoming increasingly important to consider humanity's need to produce and consume within planetary boundaries in order to safeguard global food security (Rockstrom et al. 2009, Lang et al. 2013). Food security and global environmental change are often not considered concurrently. Food security has commonly been conceptualised as resting on three pillars: food availability, access to food and utilisation of food, with the most common association with supply-side indicators, focusing primarily on dietary energy available per person (Barrett 2010). For instance, Food Balance Sheets (FBS) of the Food and Agricultural Organization (FAO) record the availability of protein, fat and energy per capita on a national level (FAOSTAT 2012). However, the recognition that food security is more than just the provision of calories and protein, has led to the inclusion of "access to safe and nutritious food" within the definition of food security at the World Food Summit in 1996 (FAO 1996, Pinstrup-Andersen 2009). Therefore, the last decades have seen a greater emphasis on "nutrition security" as a vital component of "food security" (FAO 2009). However, despite the stronger focus on nutritious food and not just protein or calories, only recently have scholars begun to link human health and environmental sustainability, as it is increasingly recognised that the nature of global diets is crucial to solve both environmental and human health problems.

In order to do so, several scholars have argued that global agricultural systems should be analysed from a "people nourished per hectare" perspective – i.e. assessing the number of people who would be able to obtain 100% of their recommended dietary requirements of nutrients for one year from a hectare of land – instead of limiting the focus on increasing the yield of commodities (Cassidy et al. 2013, DeFries et al. 2015, van Zanten et al. 2015). This approach offers a more explicit link between natural resource use (i.e. land) and nutritional output. Initially, studies primarily assessed how many people would be able to obtain 100% of their dietary energy or protein requirements from a hectare. These studies show that there are many places on earth that are relatively unproductive from a yield perspective, but are in fact feeding more people per hectare, at least in terms of dietary energy and protein, than highly productive areas that are used to produce animal feed or crops for bioethanol production (Cassidy et al. 2013). For example, many parts of Africa produce more food for human consumption per hectare than does an average U.S. hectare. Other studies show, for instance, that a hectare of millet is able to fulfil the annual iron requirement of 15.3 people, while higher-yielding rice fulfils the annual iron requirement of only 7.6 people per hectare (DeFries et al. 2015). In general, these efforts to assess how many people can be fed per hectare are hampered by the lack of reliable micronutrient data for agricultural commodities. Detailed nutritional data are widely available in developed countries; however these data are mainly available at the point of consumption (e.g. breakfast cereals). Detailed nutritional data at the point of production is less available (commodity level, e.g. rye) and food commodities can vary widely in nutritional content, based on, for example, type of commodity, yield, variety, time of harvesting, or storage. The lack of comprehensive nutritional data at the commodity level has hampered analyses to move beyond analysing calorie and protein availability at the national level. This limits the scope of scientific studies trying to analyse the productivity of certain agricultural systems or the magnitude of nutrient losses along the food chain. Therefore, recent studies have tried to link national-level food supply with individual-based dietary surveys to extend the nutritional scope of the FAO data (Del Gobbo et al. 2015), or have combined micronutrient data with FAO commodities (Kumssa et al. 2015, Wessells & Brown 2012 Smith et al. 2016).

Better estimates of "nutritional yields" are thus not only important in the context of food and nutrition security, but also in the context of environmental sustainability (DeFries et al. 2015, Berry et al. 2015). A growing world population with a growing appetite for animal products is increasing the pressure on scarce land resources (Kastner et al. 2012, Alexander et al. 2015). Therefore, the confluence of the need for efficient land use and an adequate diet for everyone *"calls for new alliances, metrics and analyses for incorporating human nutrition as a primary consideration for sustainable agriculture"* (DeFries et al. 2015). Metrics should explicitly consider the quality of agricultural products (i.e. nutrient content), and not just the quantity of food production (i.e. total yield) (Lang et al. 2013, DeFries et al. 2015).

In this paper, our main research aim is therefore to explore how the link between metrics for environmental sustainability and human nutrition can be strengthened. We do this by explicitly analysing the land use efficiency of commodities to deliver a wide range of nutrients, using the "people nourished per hectare" concept. We use the UK, a high-income country, which is heavily dependent on imports of food and feed, as a case study. We combine detailed micronutrient data for food products with FAO trade and food supply data for the UK, using methods derived from a recent study (Macdiarmid et al. 2018).

Our starting point is that a healthy diet consists of a range of different macro- and micronutrients for which dietary recommendations are set. These nutrient requirements can be met by consuming different commodities. Although, in reality, nutritional requirements are met through a combination of different food items, in this study we primarily focus on the efficiency of individual food commodities, and consider how the different food categories (e.g. cereals, oil crops) can achieve the supply of 23 nutrients (including dietary energy). We compare how many nutrients are derived from the same area of land. We highlight which food categories are most efficient in producing a wide range of nutrients, by comparing their relative efficiency for individual nutrients but also for a whole "basket" of nutrients. While the current study focuses on a limited number of nutrients and only on the environmental indicator land use, our methodology can also be used to analyse specific nutrients or other environmental indicators. Therefore, the methodology presented in this study will contribute to a more explicit link between metrics relevant for environmental sustainability and for population health.

2. Methods

In this study, we combined FAO data on food supplies, environmental land use data based on Kastner et al. (2014) and de Ruiter et al. (2017), and UK nutritional data using methods derived by Macdiarmid et al. (2018). Food supply data are for the period 2009-2011 and land use data for the ten-year period 2001-2011.

2.1. Food supply and land use data

For this study, a three-year average of the total food supply of the UK, using FAO food balance sheets for the years 2009-2011 was analysed. To obtain the country of origin for each of the commodities supplied to the UK, we used the same methodology as described in de Ruiter et al. (2017). We used this methodology to compensate for re-exports present in FAO's detailed trade matrix, which make it impossible in some cases to establish the country of origin. For instance, the UK imports bananas from the Netherlands, a non-producing country for bananas with no yield data on bananas. These re-exports can be traced to their country of origin using a mathematical approach, as originally described by Kastner et al. (2011) and Kastner et al. (2014). Consequently, our data consists of a matrix that shows the origin of 118 crops and six livestock products supplied to the UK from 199 countries of origin. Using country- and year-specific crop yield data, a corresponding matrix was created to show total annual cropland use related to each of the commodities in each of the countries. Cropland use for feed and food were established using FBS utilisation shares of food and feed for each of the countries, and cropland was assigned to the different animal products based on their relative feed conversion ratios (FCR), as described by de Ruiter et al. (2017) (top-left corner of Figure 1). We did not include the "other uses" category in the analysis because it does not contribute to foods for human consumption.

For the calculation of the grassland area associated with UK supply of ruminant animal products (i.e. beef, mutton and cow's milk), we used grassland factors for ruminant animal products obtained from de Ruiter et al. (2017), which is an adapted top-down methodology following Alexander et al. (2015) (bottom-left corner of Figure 1). In short, this methodology establishes the grassland area associated with animal products for all countries supplying animal products to the UK, including the UK itself. Grassland areas in a country are allocated to the different animal products based on the total production of a certain animal product, and the relative FCRs of the different livestock system. Supplementary Material Figure A-1 gives a stylised example of the calculation of grassland factors for different animal products. This procedure was followed for all countries supplying over 1.5% of a particular animal product to the UK, to prevent the possibility that relatively unimportant countries for UK supply with large marginal grasslands skew the grassland factors, as described in detail by De Ruiter et al. (2017).

Based on the procedure described above, all areas associated with UK's food supply were calculated and further used in our analysis.

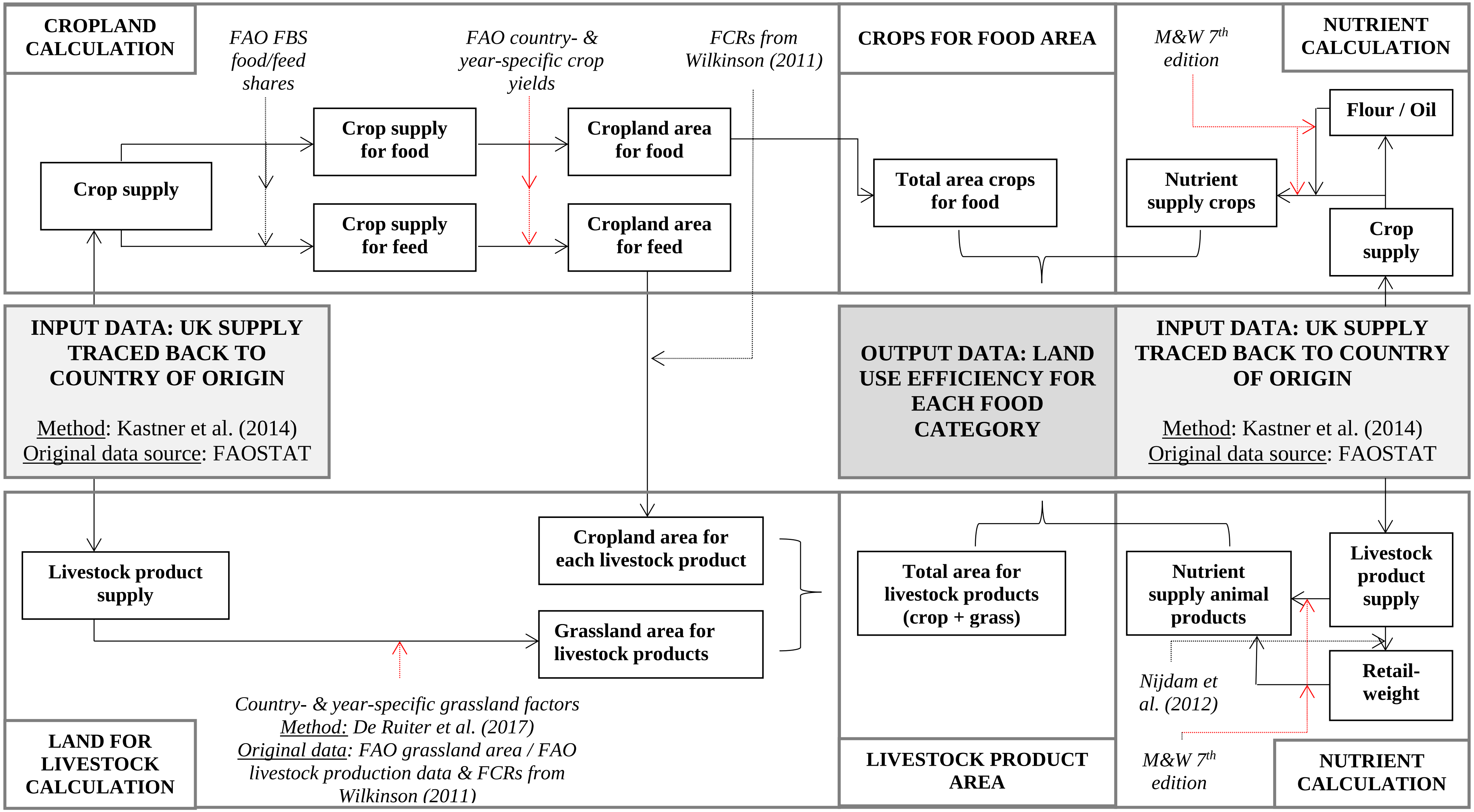

Figure 1. Overview of calculation steps and associated data sources and methods used in this study. Sensitivity analysis was carried out for calculation steps represented by the red arrows.

2.2. Conversion steps from supply to processed products

After establishing UK's food supply and associated land footprint, we performed some additional steps to convert a few primary commodities to processed products (top-right corner in Figure 1. We have converted most of the cereals – "wheat", "maize", "millet" and "rye" – to their respective flour, using an UK-specific wheat extraction rate of 80% for all four cereal crops (FAO 2001). This was done because these cereals are generally not consumed in their raw form, and nutrient data tend to be based on the form the food is typically eaten. Since fortification of wheat flour is mandated in the UK, we included fortification of wheat flour in our nutrient analysis. Furthermore, we performed some additional conversion steps for vegetable oils to convert our primary crop equivalent data into vegetable oil, since these oil crops are specifically grown for their oil used for human consumption and their by-products are not used for human consumption. We converted the primary oil crop commodities back to their processed products using the original dry matter conversion factors used by Kastner et al. (2014). If multiple products were associated with a particular crop (e.g. "olive oil" and "olives" obtained from the primary commodity "olives"), we used FBS food supply statistics to establish their relative proportion in the food supply (see Supplementary Material Table B-1). For animal products, we used conversion factors based on Nijdam et al. (2012) to convert between the primary equivalents of meat to boneless meat and nutrient values that are based on retail-weight meat (bottom-right corner in Figure 1). Most commodities were not converted back to their processed products since the objective of the current study was to analyse the efficiency of commodities at the point of supply of nutrients to the UK food system.

2.3. Nutrient data

To convert our crop- and livestock supply data to nutrient supply data, we matched our food supply data to nutrient data using the UK-specific McCance & Widdowson's (M&W) food composition table (7th edition), as described by Macdiarmid et al. (2018). When possible, a direct match between the food composition table and our primary crop was obtained (e.g. nutrient values of "bananas" for the primary commodity "bananas"). If multiple entries were found in the food composition table (e.g. two varieties of potatoes), nutritional values for both varieties were matched, after which one of these values was randomly selected for further analysis (see Section 2.4 for further details). For meat, weighted nutrient values based on the relative importance of the associated meat products (e.g. sausages, bacon and pork for pig meat) were used, based on household expenditure survey data (Office for National Statistics 2012). For milk we did not use weighted values based on milk products, i.e. we did not consider the nutrient composition of cheese, yoghurt etc., but we matched "milk, primary equivalents", from our FAO data with whole milk values in M&W food composition table. If no match was found in the M&W table, we used the median value for that crop as reported by Smith et al. (2016).

Including processed food commodities, such as the different vegetable oils, we were able to match nutrient data for 114 commodities (out of the 118 original primary commodities). For some commodities, it was not possible to find a match in the nutrient composition tables ("fonio", "Bambara beans", "vetches" and "kola nuts" – all crops with negligible contributions to UK's food supply). Supplementary Material Table E-1 shows an example of the input data.

2.4. Analysis

For our analysis, we grouped all commodities into 16 broad categories: 10 crop categories, and six animal product categories. By multiplying food supply data with the nutritional composition of commodities, we established the total nutrient supply for 23 nutrients (i.e. "nutrient supply crops" and "nutrient supply animal products" in Figure 1). First, these nutrient supply estimates were compared with the Reference Nutrient Intake (RNI), published by the UK Department of Health in 1991(Public Health England 2015). Reference Nutrient Intakes differ for age groups and gender, and therefore we weighted RNIs based on the demographic structure of the UK population. After this, we calculated nutrient productivity for each of the categories for all individual nutrients by dividing the total nutrient supply of the food category by its corresponding land footprint (i.e. "output data: land use efficiency for each food category" in Figure 1).

For a sensitivity analysis, we iterated this analysis 1,000 times with different nutrient input values and yield values, to account for the different nutrient values of the crops, and for the fact that yields can be different in each year (red arrows in Figure 1 represent calculation steps for which a sensitivity analysis was performed). We varied the yields based on the minimum and maximum yields over the last ten years of the major suppliers (>1% of total supply) of a particular commodity. From this range, we randomly selected a yield value, assuming yields could be uniformly distributed, and performed all additional calculation steps. For nutrients, a similar sensitivity analysis as Smith et al. (2016) was done. For each commodity for which we had different nutrient values in the M&W database (for example, two different varieties of potatoes), we randomly selected one of these nutrient values for each iteration. Contrary to yields, we did not establish a range for each nutrient input (e.g. between the calorie value for potato variety *A*, and the calorie value for potato variety *B*), since we do not know if these are the minimum and maximum values for these products because food composition tables contain average nutrient values and do not show the underlying sample data. We varied the input for each nutrient for each iteration (e.g. the same iteration could have the protein value of potato variety *A* and vitamin C value of potato variety *B*).

In sum, we iterated our analysis 1,000 times with a randomly selected yield value from an assumed uniformly distributed ten-year range of the UK's major suppliers, and a randomly selected nutrient value from one of the different varieties of a particular crop. All calculations were performed using MATLAB R2015a. Figures in the main text present the average value across 1,000 iterations for selected nutrients while Supplementary Material Figures C1 – C4 show the scatterplots for all 1,000 iterations for all nutrients.

2.5. Use of the term "people nourished per hectare"

In the current scientific literature, there are different usages of the term "people nourished per hectare". For instance, Cassidy et al. (2013) use this concept to calculate the number of people that are able to obtain 100% of their dietary energy or protein requirements from a hectare, by accounting for the dietary energy and protein lost when converting crops to animal feed or biofuels. However, "nourishing" people requires more than just supplying dietary energy or protein. Therefore, here we followed DeFries et al. (2015) in their definition of nutritional yield: the number of people who would be able to obtain 100% of the recommended RNI of different nutrients for one year from a food item or category produced annually on one hectare. Since we use 23 nutrients (including dietary energy) in the current analysis, our use of "people nourished per hectare", or "people fed per hectare" refers to the number of people able to obtain the RNI for these 23 nutrients, and not for all nutrients needed for human health. Because we have weighted RNIs based on UK's population structure, our total number of people refers to the average "UK person" and not to the number of adults as in the definition used by DeFries et al. (2015).

3. Results

The total supply of all nutrients is well above the per-capita RNI (Table 1), which is likely to be an overestimate since these data are for food supply and not direct measures of consumption data. These data suggest that the UK food supply delivers sufficient micronutrients per-capita. However, fibre is very close to the minimum dietary recommendations, suggesting that it will be difficult to meet the fibre recommendations at a population-level, particularly as we did not consider household waste. After fibre, dietary energy supply is closest to the dietary recommendation. The values in Table 1 are based on food supply, and do not account for food waste in the households.

Table 1. Calculated supply of nutrients (per capita per day) and Reference Nutrient Intake (RNI)[i]. Supplies are per capita for the year 2010 (3-year mean) and an average of 1,000 iterations.

	Supply of nutrients	RNI	Percentage of RNI
Energy (kcal)	3223	2118[ii]	152
Protein (g)	114	46	245
Fat (g)	132	< 82[iii]	161
Saturated fat (g)	40	< 26[iv]	153
CHO (g)	436		
Fibre (NSP) (g)	26	22	115
Na (g)	947	2300	41
Vit A (RAE) (mg)	1154	622	185
Vit B1 (mg)	3	0.8	404
Vit B2 (mg)	5	1.1	479
Vit B3 (mg)	33	14	236
Vit B6 (mg)	3	1.2	261
Vit B12 (mg)	8	1.4	585
Vit C (mg)	169	389	439
Folate (mg)	423	189	224
Ca (mg)	1280	687	186
Cu (mg)	2	1.1	208
Fe (mg)	19	10	190
I (mg)	255	134	191
K (mg)	5850	3210	182
Mg (mg)	644	267	241
P (mg)	2493	543	459
Zn (mg)	17	8	218

Abbreviations: NSP = Non-Starch Polysaccharides / RAE = Retinol Equivalent / CHO = carbohydrates

[i] The RNI is the amount of a nutrient that is enough to ensure that the needs of 97.5% of the population are being met and is set for age and sex-specific groups. Here we use a population-weighted average. See main text for details.

[ii] Dietary energy is based on estimated energy requirements, and is not a RNI.

[iii] Based on population recommendation of <35% of total energy

[iv] Based on population recommendation of <10% of energy

The supply of cereals for human consumption is, on average, responsible for 8% of the total land footprint, but contributes 35% of the total calories and 31% of the total protein supply, respectively (Figure 2. See Supplementary Material Figures B1 – B4 for scatter plots with all 1,000 iterations). Food categories that have a higher share in the nutrient supply compared to their respective share in the land footprint are more efficient for producing that particular nutrient (above the orange "identity" line), whereas food categories below the identity line are less efficient. Note that the graphs are based on relative data (i.e. as percentage of total supply); a food category can be very efficient for a single nutrient, but still play a minor role in the total nutrient supply. For instance, pulses are among the most efficient producers of Zn, but Zn from pulses represents only 2% of the total Zn supply because the total share of pulses in UK's food supply is small.

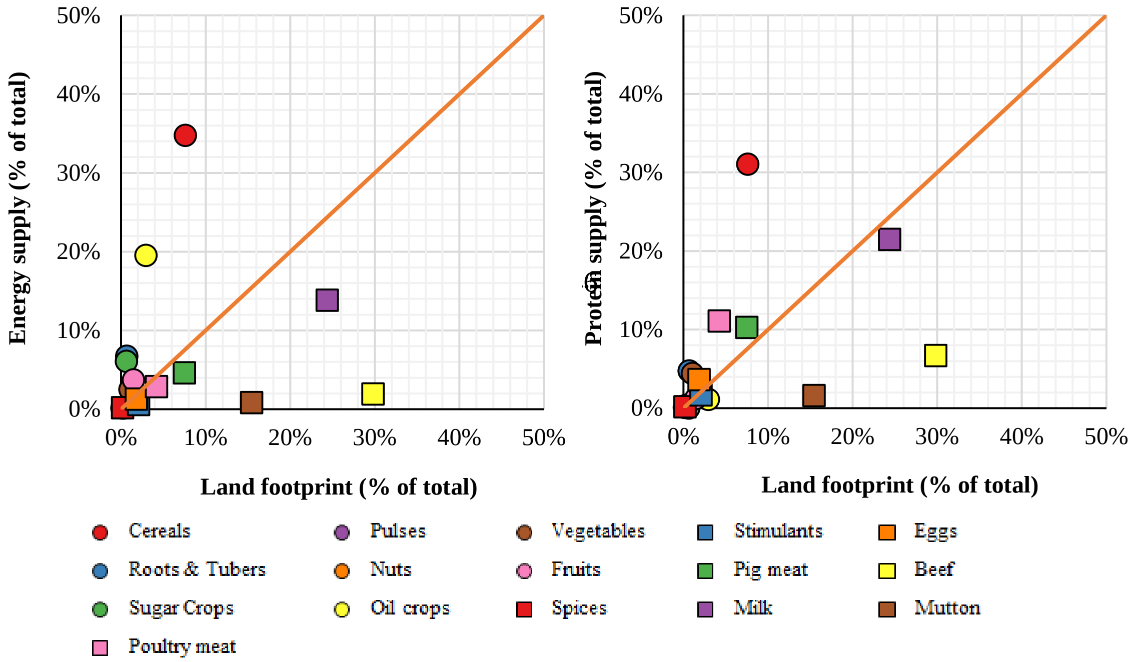

Figure 2. Relative share of food categories in total dietary energy supply and protein supply, and relative share in total land footprint. Values represent the average across all 1,000 iterations.

Of the 16 food categories analysed here, five categories (cereals, roots & tubers, sugar crops, oil crops and fruits) deliver relatively more calories in all iterations than their corresponding land share suggests. Nuts and vegetables also deliver more calories in almost all scenarios (92% and 98%, respectively), while spices deliver more calories in 80% of the scenarios but this contributes only a very small share of calories (See Supplementary Material Figure C-3 for calories and C-4 for protein for all 1,000 iterations). All other categories require more land comparatively to their share in the calorie supply. For protein, there are five categories that score higher in the protein supply compared to the share in the land footprint in all iterations: cereals, roots & tubers, vegetables, eggs, and poultry meat. Four categories score lower than their respective land footprint for protein supply in all iterations: sugar crops, oil crops, beef and mutton.

Table 2 shows how often (as % of all 1,000 iterations) food categories score higher in the macronutrient & energy supply than their corresponding share in the land footprint. Cereals score very high for dietary energy and protein, as well as for carbohydrates and fibre. However, if we only consider micronutrients, other food categories are most efficient, particularly vegetables and roots & tubers. Some categories, such as sugar crops and oil crops are relatively good at supplying energy and macronutrients (carbohydrates and fat, respectively), but less efficient in supplying micronutrients. On the other hand, because of its large land footprint, milk is not a very efficient supplier of energy and macronutrients, but is important for some micronutrients, such as iodine and vitamin B12 (Figure 3).

For instance, almost all iodine in the current food derives from milk supply (we have not considered iodine from fish and iodised salt added to processed foods in this analysis).

Table 2. Percentage of iterations in which the nutrient supply is higher than the corresponding land footprint[(i)]

Food category	Energy	Protein	Fat	CHO	Fibre	Average micro-nutrients (n=17)
Cereals	100	100	19	100	100	68
Roots & Tubers	100	100	0	100	100	81
Sugar Crops	100	0	0	100	0	23
Pulses	0	64	0	100	100	70
Nuts	92	74	100	0	54	28
Oil Crops	100	0	100	0	0	0
Vegetables	98	100	50	100	100	93
Fruits	100	33	0	100	100	74
Spices	80	76	17	96	0	59
Stimulants	0	39	0	3	100	43
Pig meat	0	98	85	0	0	34
Milk	0	1	0	0	0	34
Eggs	0	100	89	0	0	49
Beef	0	0	0	0	0	0
Mutton	0	0	0	0	0	0
Poultry meat	0	100	26	0	0	24

[(i)] For example, a 100 score means all iterations result in a higher contribution of that a food category to the respective nutrient supply than the corresponding share in the land footprint suggests, while a 0 score means the food category's share in the land footprint is always larger than the corresponding share in the nutrient supply.

All of our values are interdependent. Therefore, whether a particular food category scores higher in its contribution to the nutrient supply, depends partly on how much other food categories contribute to the total nutrient supply. For instance, we have four input values for vitamin B12 for milk, where three values are much higher than the fourth input value, which is for UHT milk (0.9 mg $100g^{-1}$ & 0.8 mg $100g^{-1}$ (twice) vs. 0.2 mg $100g^{-1}$, respectively). When the high input values for milk are used, the contribution of other food categories are pushed downwards, in some cases below the identity line (Supplementary Material Figure C1).

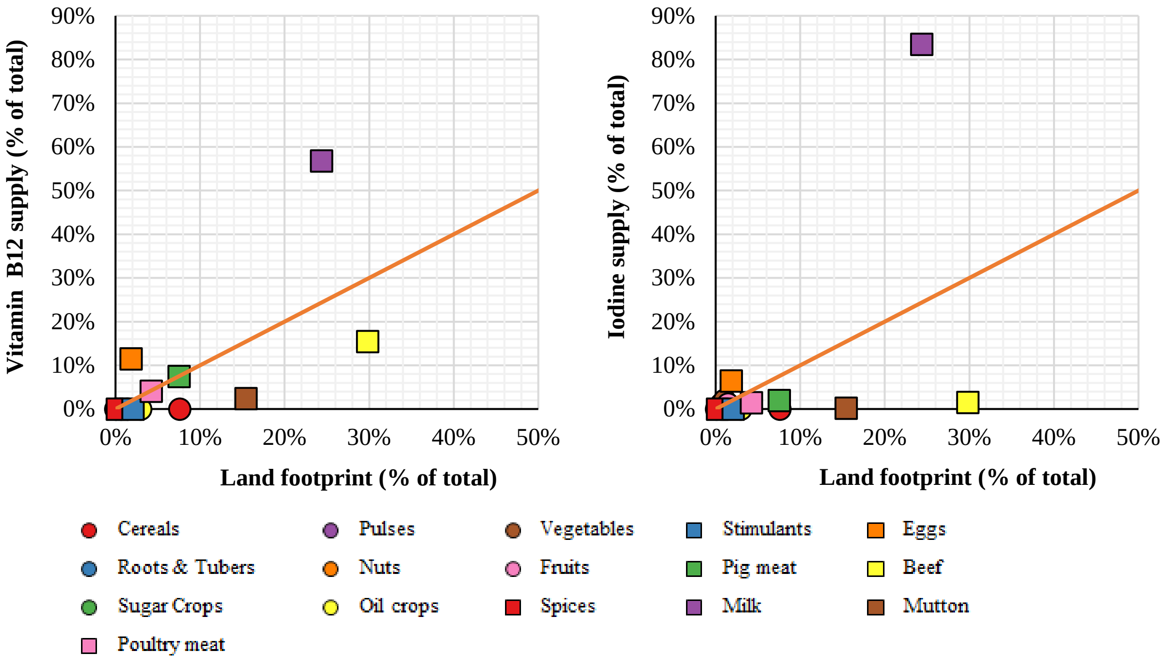

Figure 3. Relative share of food categories in vitamin B12 supply and iodine supply and relative share in total land footprint. Values represent the average across all 1,000 iterations.

3.1. Total range of nutrients

Our analysis shows that animal products, particularly ruminant products, are not very efficient in producing a wide range of nutrients. However, they are important for certain micronutrients, particularly vitamin B12, which cannot be obtained from plant sources, and iodine which is primarily obtained from milk (and fish, which is not considered in the current analysis) (Figure 3). Therefore, without fortification of other foods, animal products still play have a role in the overall diet. Vitamin B12 could also be obtained from fortified sources, and as such animal products are not necessary, but our analysis highlights that some food groups, while not efficient for producing a wide range of nutrients, could still be needed for the efficient production of one nutrient.

We further show the results for zinc and iron, two essential minerals to highlight that animal products can be a major source of micronutrients in the food supply, despite their relative land use inefficiency (Figure 4). For instance, beef is the third most important source of zinc in the total food supply, but the land footprint of beef is still greater (Figure 4 - *right panel*). Supplementary Material Figure C-2 (for iron) and Figure C-4 (for zinc) show the effects of refining whole grains. The contribution of cereals varies from 44% to 23% of total zinc supply, and from 56% to 28% of total iron supply, with the lowest contributions resulting from the model selecting the refined flour nutrient values.

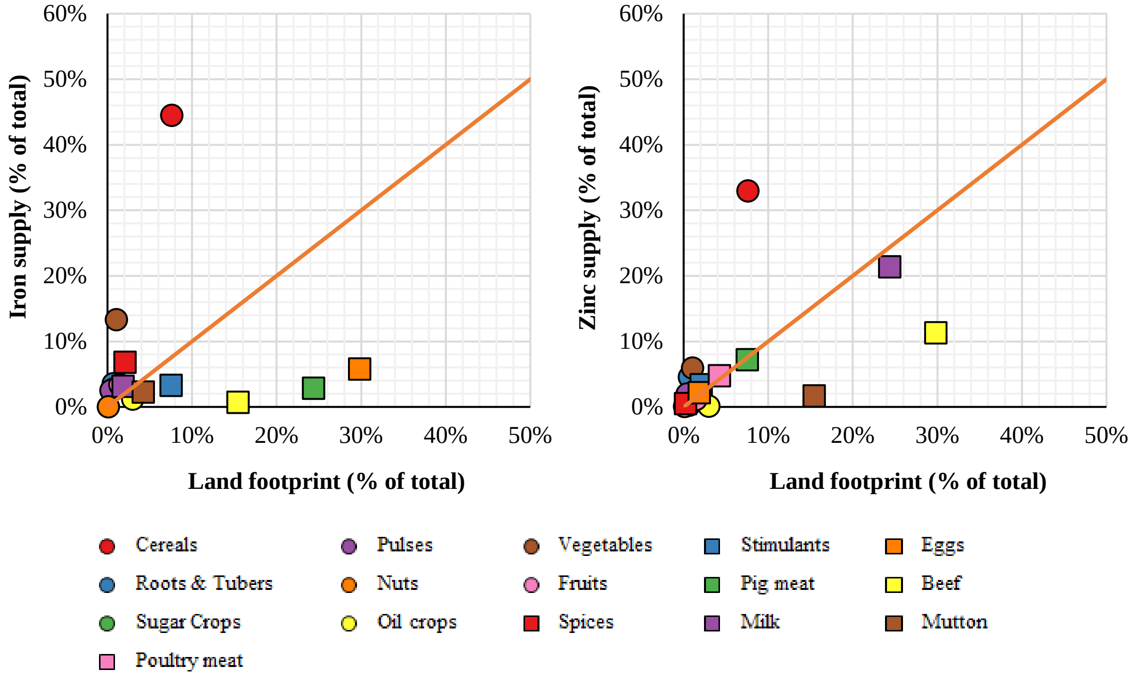

Figure 4. Relative share of food categories in iron supply and zinc supply and relative share in total land footprint. Values represent the average across all 1,000 iterations.

3.2. Comparison with GENuS data

We repeated our analysis using nutrient data from Smith et al. (2016) (another study that matched FAO commodities with nutritional information, and referred to as GENuS data, hereafter). The comparison between M&W & GENuS data shows that vegetables and roots & tubers are the most efficient suppliers of a wide range of micronutrients, with cereals and fruits also important in both scenarios (Table 3). The contribution of nuts differs substantially between the two scenarios because of the different nutrients values between the two food composition databases. In both cases, eggs represent the most efficient animal food category across all nutrients analysed, but milk is much more favourable when using M&W data. This can be explained because M&W tables give a higher value for “cow milk, whole” than the GENuS tables (e.g. 64 kcal in M&W *vs.* 47 kcal in GENuS). Nevertheless, using two different nutrient datasets leads to a mostly similar ranking for the crop categories (Spearman Rank Correlation = 0.94 for micronutrients and 0.93 for all nutrients), and shows that our conclusions about the relative efficiency of different food categories are robust across different food composition tables.

Table 3. Comparison of the percentage of iterations where nutrient share is larger than the corresponding share in the land footprint, using McCance & Widdowson's food composition data or GENuS food composition data.

Food category	GENuS – average for micronutrients %	M&W – average for micronutrients %	GENuS – average for all nutrients %	M&W – average for all nutrients %
Cereals	86	68	77	67
Roots and Tubers	93	81	86	77
Sugar Crops	11	23	17	26
Pulses	83	70	73	62
Nuts	70	28	68	40
Oil Crops	5	0	17	14
Vegetables	100	93	90	89
Fruits	93	74	77	66
Spices	84	59	72	54
Stimulants	56	43	42	38
Pig Meat	18	34	30	35
Milk	13	34	19	31
Eggs	39	49	40	50
Beef	0	0	0	2
Mutton	0	0	0	0
Poultry meat	39	24	50	26

3.3. People nourished per hectare

We have considered a food "efficient" if the share in the total nutrient supply is higher than the corresponding share in the land footprint. Thus, if a food category has a 20% share in the total land footprint, it needs to deliver more than 20% of a particular nutrient to be considered "efficient" in our analysis. However, while implicit in the Figures 2 to 4, this does not explicitly show the magnitude of the absolute differences between the food categories. For instance, while both vegetables and roots & tubers are efficient producers for most nutrients in almost all scenarios (i.e. they produce more nutrients than their corresponding share in the land footprint suggests), roots & tubers deliver many more calories per hectare than vegetables. Moreover, because several food categories, particularly the ruminant meat categories have very large land footprints, they skew the other food categories to appear more efficient relative to their land footprints. Therefore, we have calculated the number of people that would be able to obtain 100% of the RNI for different nutrients for one year, based on the "nutritional yield" per hectare (DeFries et al. 2015) (Figure 5). We use the population-weighted dietary recommendations from Table 1 for this analysis, and compare the four most efficient plant-based categories with the most efficient animal product category (Figure 5 - See Supplementary Material Figure D-1 for all food categories). It shows that the median number of people nourished across all nutrients for the most efficient category, roots & tubers, is 43 people. The most efficient plant-based category is able to feed about 10 times more people per hectare than the most efficient animal product category. However, since plant-based categories do not deliver vitamin B12, eggs are still needed for some micronutrients. The results also highlight the effects of analysing more nutrients than just macronutrients and dietary energy. For instance, the median number of people nourished per hectare is 20 people for cereals and only 10 for vegetables when only macronutrients and dietary energy are considered. Considering a wider range of micronutrients leads to a much higher median number of people nourished for vegetables, and decreases the importance of cereals.

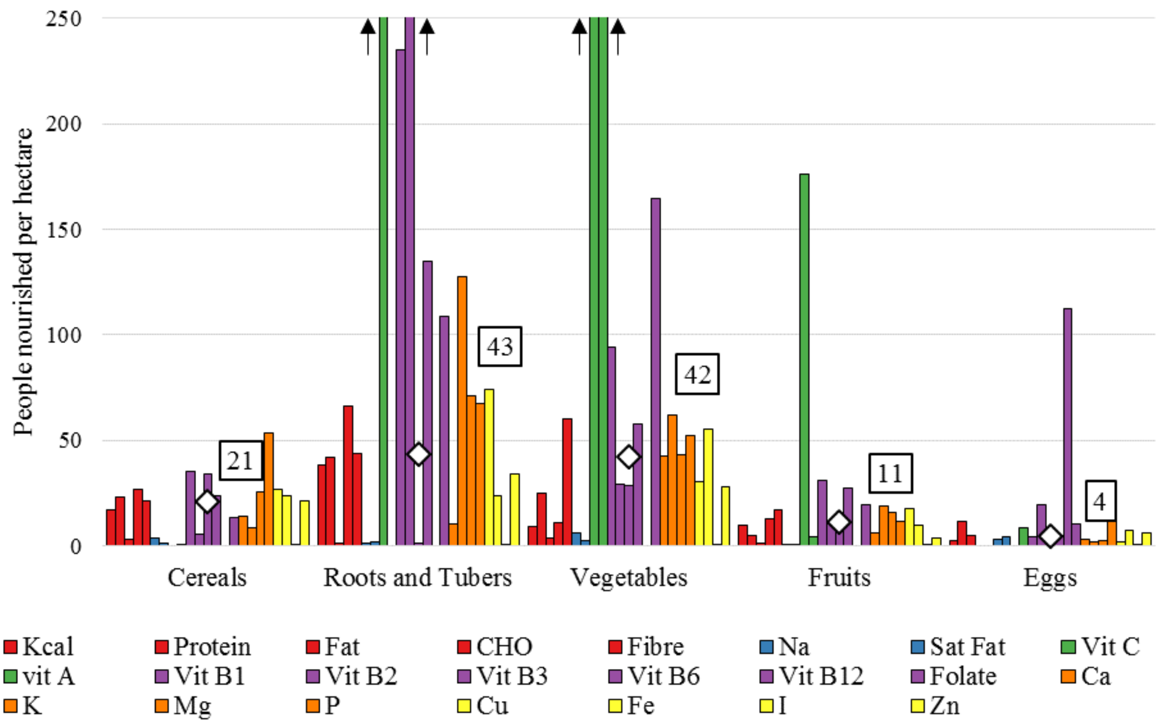

Figure 5. People nourished per hectare based on dietary recommendations of 23 nutrients for five food categories: cereals, roots & tubers, vegetables, fruits and eggs. Notes: median values across all nutrients (excluding saturated fat and sodium) are indicated by diamonds, with corresponding values in boxes. Arrows indicate values > 250.

4. Discussion

The current analysis is an exploratory study to link agricultural data with nutritional data in order to analyse the land use efficiency of different food categories. It builds on other studies that have emphasised the importance of creating new metrics for "nutritional yield" (Cassidy et al. 2013, DeFries et al. 2015). These new metrics are needed because traditional measures of agricultural output, such as yield per hectare, have neglected the importance of human nutritional needs (DeFries et al. 2015). In a world with decreasing agricultural land area per capita, an explicit focus on nutritional yields will be needed to feed a growing world population healthily while using natural resources more efficiently.

Therefore, our current analysis explores the land use efficiency of food categories in the current UK food supply and shows that, for instance, fruit and vegetables are very important providers of a wide range of nutrients, consistent with nutritional advice, despite the fact that they do not deliver many calories or much protein in the overall diet. Using metrics like “people nourished per hectare” makes it easier to link nutritional output with natural resource use. Here we have demonstrated the use of this metric for 23 nutrients and for the environmental indicator land use. Our methodology can be adapted for different countries and for other nutrients or environmental indicators. For instance, this methodology can be used to examine specific nutrients for which certain populations might be deficient. Also, this methodology might be adapted to link it to other environmental indicators, for instance one might consider the number of people nourished per tonne of CO_2. This will help address global environmental change and human nutrition simultaneously.

We compare the land use efficiency of different food categories and consequently our results should not be should not be interpreted as indicating that consuming only vegetables and fruits will be most efficient in terms of delivering sufficient nutrients. To achieve a complete diet with a small associated land footprint, combinations of food categories will be more efficient. Our current analysis did not aim to analyse the most efficient combinations of foods to achieve sustainable diets. Other mathematical modelling techniques that can consider a single diet, such as linear programming, are better able to deal with the combination of the optimal amounts of different food items to meet nutrient requirements, while also limiting the environmental impact of individual diets. These studies that use linear programming are often focused on food products (e.g. breakfast cereals) and do not use the primary agricultural commodities, unlike our current analysis. Although we considered the mandatory fortification of wheat flour, we did not take into account other forms of fortification or processing that happen further down the food supply chain. Since processed foods are a very important part of “Western” diets (Weaver et al. 2014), it is likely that these processes have a significant influence on the nutrients that ultimately reach the consumer. Therefore, caution is needed when translating findings from an agricultural perspective, i.e. “sustainable food production”, into food consumption, i.e. “sustainable diets”. To illustrate this point, we repeated our analysis with nutrient composition data for the primary “wheat”, “rye”, “maize” and “millet” crops (obtained from Smith et al. (2016)), as opposed to using nutrient values for their flours. Using whole grains nutrient values leads to an estimated median of 29 people nourished per hectare, while converting these crops to a mix of whole grain and white flour and using nutrient values for these flour, leads to an estimated 21 people fed per hectare (almost a 1/3 reduction). Using only the nutrient composition for refined, white flour (though fortified) leads to an even lower estimate: a median of 15 people would be able to meet their dietary requirements for the nutrients considered in this study (only 1/2 compared to the primary whole grain). Moreover, most of the sodium is added in later processing stages and does therefore play a very minor role in our analysis since we primarily consider agricultural commodities.

Therefore, developing agricultural metrics that take nutrient output of agricultural production into account is valuable, but they need to be combined with robust data about what happens further down the food supply chain and to take into account what is ultimately consumed.

4.1. Supply and consumption

The objective of the current study was to examine the relative efficiency of different food categories to produce a wide range of micronutrients. We show that crops with a high yield, and/or crops with high nutrient densities were particularly efficient in delivering nutrients and nourish a larger number of people per hectare. Animal products, particularly ruminant products, but also discretionary food categories, such as sugar crops and stimulant crops, are poor in delivering micronutrients from the same area of land and thus in providing essential nutrients to a large number of people. At the same time, animal products might still be needed to obtain some specific micronutrients such as vitamin B12.

The current study analyses food supply data and therefore will be different to actual intake of micronutrients, which will vary across the population. It is well known that FAO data differs significantly from actual household food consumption (Del Gobbo et al. 2015). Moreover, FAO data does not take into account household food waste, which is very significant, especially for certain products like vegetables and milk. For instance, it is estimated that about 25% of all fruit and vegetables are wasted in the UK (WRAP 2009). Therefore, even though certain food categories, such as vegetables, may be very efficient in the production of a wide range of nutrients, they may not always be the most efficient in delivering these nutrients to the consumer if these categories are more prone to be wasted due to their perishable nature.

We only considered the mandatory fortification of wheat flour, and did not take into account other forms of fortification, such as soil fertilisation, biofortification and food fortification (Miller and Welch, 2013). Also, supplementation of animal feed might be an important mechanism to obtain certain micronutrients, which we did not consider. For instance, it has been suggested that iodine supplementation in dairy herds has been a major factor in the disappearance of endemic goitre (Phillips, 1997).

4.2. Bioavailability of nutrients

Animal products are important for certain micronutrients, for example for iron and zinc (Figure 4). However, our analysis indicates that, in relative terms, animal products are not the most efficient sources of these nutrients in the context of what is supplied. It should be noted, however, that we did not consider the differences in bioavailability between the different food categories. Iron, for example, is more readily available in the form of haem-iron (animal products), compared to non-haem iron sources found in plants (Collings et al. 2013), and other diet-related factors, such as interactions with other organic components like phytates, can inhibit the uptake of some nutrients, and therefore have a greater influence on the bioavailability in plant foods (Gibson et al. 2006). For instance, we did not consider the effect of milling on phytic acid, while it is known that the ratio of, for example, Zn/Phytic acid affects Zn bioavilability (Gupta et al. 2015). Moreover, nutrient composition of crops is highly variable based on variety, time of harvest, region of origin and so on. For a better linking of agricultural output with nutrition, monitoring of nutritional quality at the stage of production would be a major improvement.

We have considered a selection of 23 nutrients (including macronutrients and calories) in our current analysis, and not all micronutrients that are required for human health. This may have an impact on our conclusions about which food category is most efficient in delivering micronutrients, particularly for fat-soluble vitamins that are primarily present in vegetable oils, such as vitamin E. Currently, our analysis shows that oil crops are poor providers of micronutrients but this may change when more micronutrients are taken into account. Future work could include more micronutrients for a fuller assessment.

4.3. Sustainable use of land

Our analysis is solely based on the UK's food supply and therefore care needs to be taken in drawing generic conclusions. For example, it does not compare the highest yielding commodities from one food category with the highest yielding commodities from other food categories. It might be possible that the UK imports cereals primarily from low-yielding countries, while it imports vegetables primarily from high-yielding countries. From a land footprint perspective, therefore, a global study would provide a more robust comparison based on a more appropriate scale to analyse the efficiency of producing a wide range of micronutrients. However, nutritional composition tables differ between countries, and local circumstances will influence the nutrient content of food products and thus the corresponding conclusions about nutritional yields.

Furthermore, we do not distinguish between different types of land in this study. Particularly the difference in grasslands and croplands is relevant since they often cannot be used to produce food interchangeably. Therefore, from a land use perspective, it could be argued that ruminant animal products are the best way to obtain micronutrients from marginal grassland and as such they could be vital in achieving global food security (van Zanten et al. 2015).

4.4. Uncertainty

For our sensitivity analysis, we have randomly selected nutrient values from the different varieties of a food where information was available in the food composition tables. Our sensitivity analysis shows wide variation in the contribution of different food categories to the nutrient supply, depending on our selected yield value and nutrient value (Supplementary Material Figures C-1 - C-4). Also, because we express contributions as a percentage of the total nutrient supply, selecting, for instance, a low value for cereals increases the relative contribution of other food categories. Since our main aim was to compare food categories relative to each other, this wide range gives us a good indication of the relative ranking when using different input parameters.

Protocols for dealing with uncertainty are well-established in the environmental sciences. For instance, the IPCC has robust guidelines on how to quantify the uncertainty associated with climate change analyses (IPCC 2006). Often, input parameters are varied based on their underlying distribution. Food composition tables, however, do not typically give a range or distribution for nutrients, but only the average nutrient value for a particular food item. Establishing a range within nutrient composition tables would allow for better quantification of uncertainty. Future food security analyses should incorporate micronutrient values and understanding their underlying input distributions will allow more robust analyses.

5. Conclusion

This exploratory study has linked land use data with nutritional information and shows that analysing a wide range of nutrients gives a more complete and nuanced picture of the number of people that can be nourished per hectare. Certain food categories, particularly beef and mutton, and sugar crops and oil crops, are relatively poor at delivering a wide range of nutrients and thus produce nutritional value for only a few people per hectare. Other categories, such as roots & tubers, cereals and vegetables are much better at nourishing a large number of people per hectare. A more holistic approach where multiple nutrient outputs are assessed in the context of a sustainable use of natural resources, and how these “sustainable foods” translate into people’s diets, will improve our understanding of what a sustainable food system might look like.

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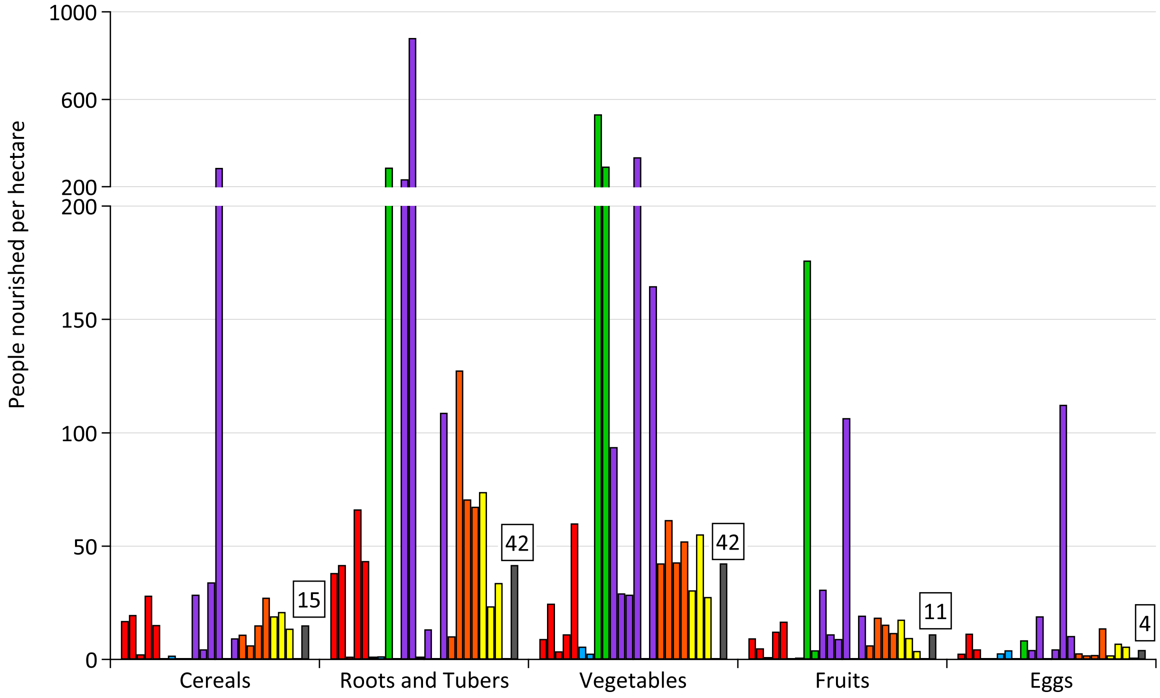
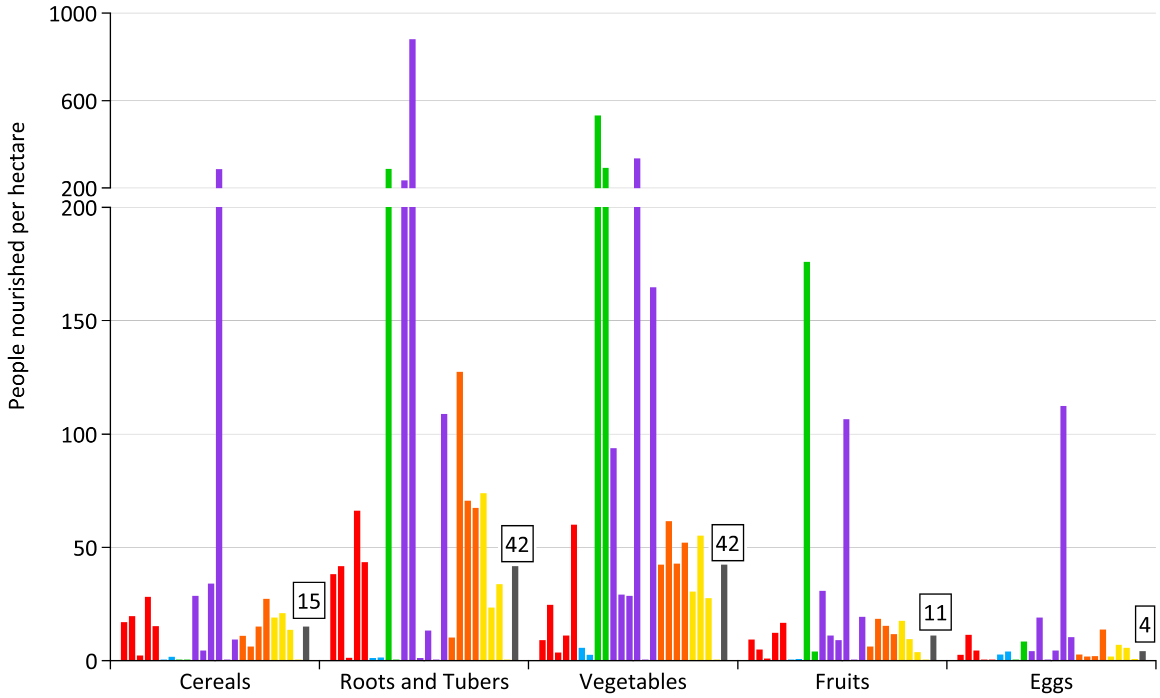


People nourished per hectare
1000
600
200
200
150
100
50
0
15
42
42
11
4
Cereals
Roots and Tubers
Vegetables
Fruits
Eggs



People nourished per hectare
1000
600
200
200
150
100
50
0
15
42
42
11
4
Cereals
Roots and Tubers
Vegetables
Fruits
Eggs

Supplementary Material

"*Moving beyond calories and protein: micronutrient assessment of UK diets and land use*"

Supplementary Material consists of four parts:

A) Overview grassland allocation
B) Conversion factors for processed commodities
C) Scatter plots for all 23 nutrients studied
D) Median number of people fed per hectare for all food categories
E) Example of input data used in this study

A. Overview grassland allocation

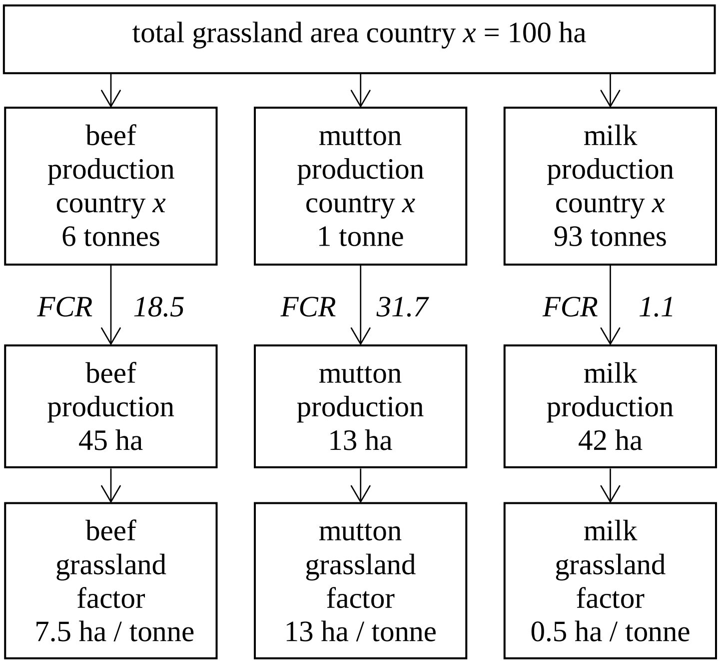


Figure A-1. Stylised example of establishing grassland factors for a given country in a given year. This procedure was followed for all countries supplying over 1.5% of animal products to the UK. Obtained from De Ruiter et al. (2017)

B. Conversion between primary products and processed products

Table B-1. Ratio between primary product and processed products, and conversion factors used in this study to convert between primary product and processed product.

FAO commodity	Food supply quantity (tonnes)[i]	Conversion factor (Kastner et al 2014)	Supply (tonnes)	Ratio processed product
Olives	34985	1.00	34985	
Olive oil	58586	2.50	146464	81%
Soya beans	4965	1.00	4965	
Soya bean oil	228605	1.11	254006	98%
Sunflower seed	0	1.00	0	
Sunflower seed oil	172598	1.08	185589	100%
Sesame seed	6376	1.00	6376	
Sesame seed oil	1798	1.06	1913	23%
Rapeseed	0	1.00	0	
Rapeseed oil	534644	1.14	607550	100%
Oilcrops, nes	630	1.00	630	
Oilcrops, nes, oil	29995	1.11	33328	98%
Coconuts	66096	1.00	66096	
Coconuts oil	12026	1.67	20043	23%
Grapes	697372	1.00	697372	
Wine	1176970	0.79	929807	57%

[i] **Based on FAO Food Balance Sheet for UK (average for 2009-2011)**

C. Scatter plots for all 23 nutrients

Graphs are sorted alphabetically.

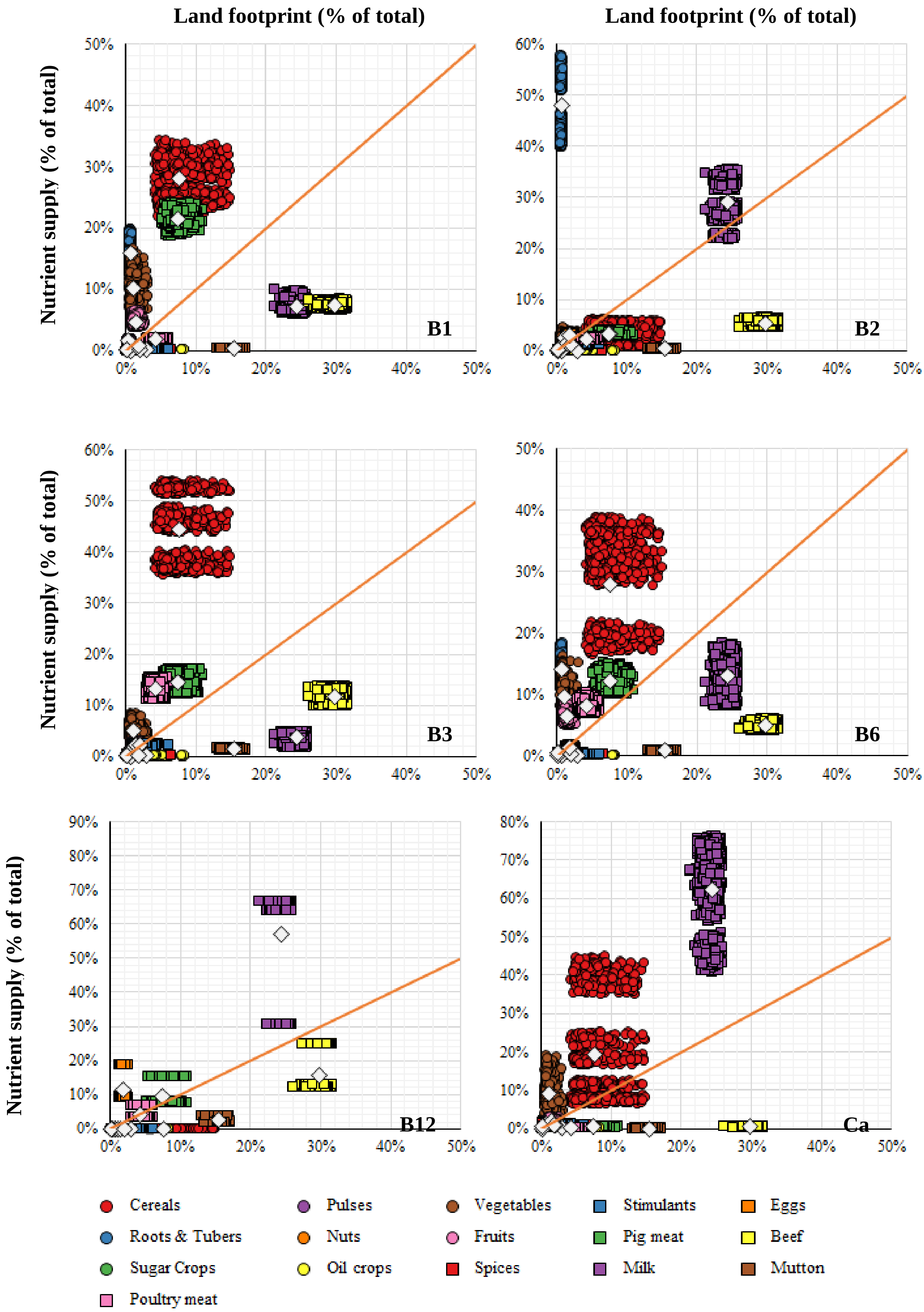


Figure C-1. Relative share of food categories in nutrient supply (y-axis) and relative share in total land footprint (x-axis) for selected nutrients. Diamonds represent the average value across all 1000 iterations.

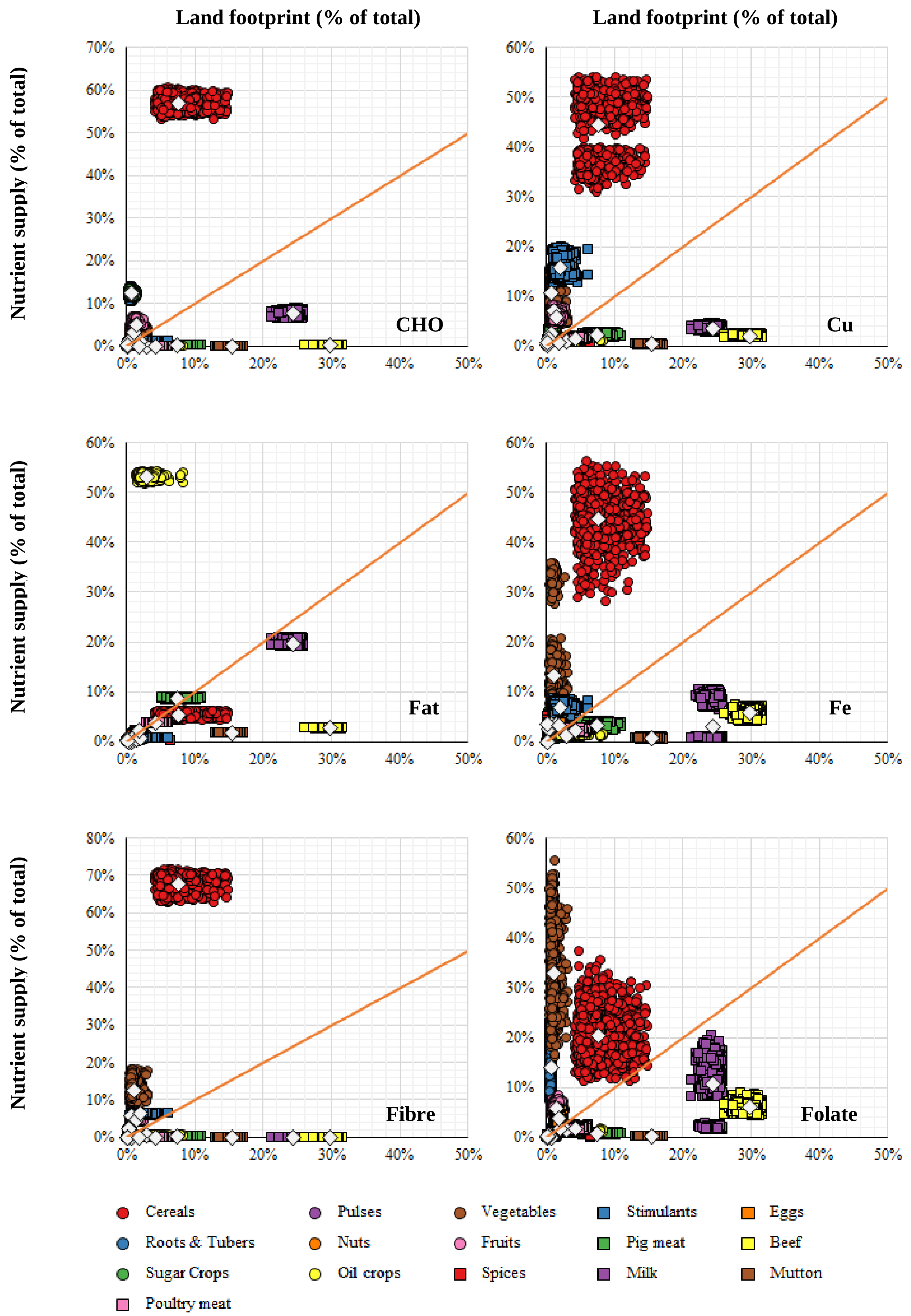


Figure C-2. Relative share of food categories in nutrient supply (y-axis) and relative share in total land footprint (x-axis) for selected nutrients. Diamonds represent the average value across all 1000 iterations.

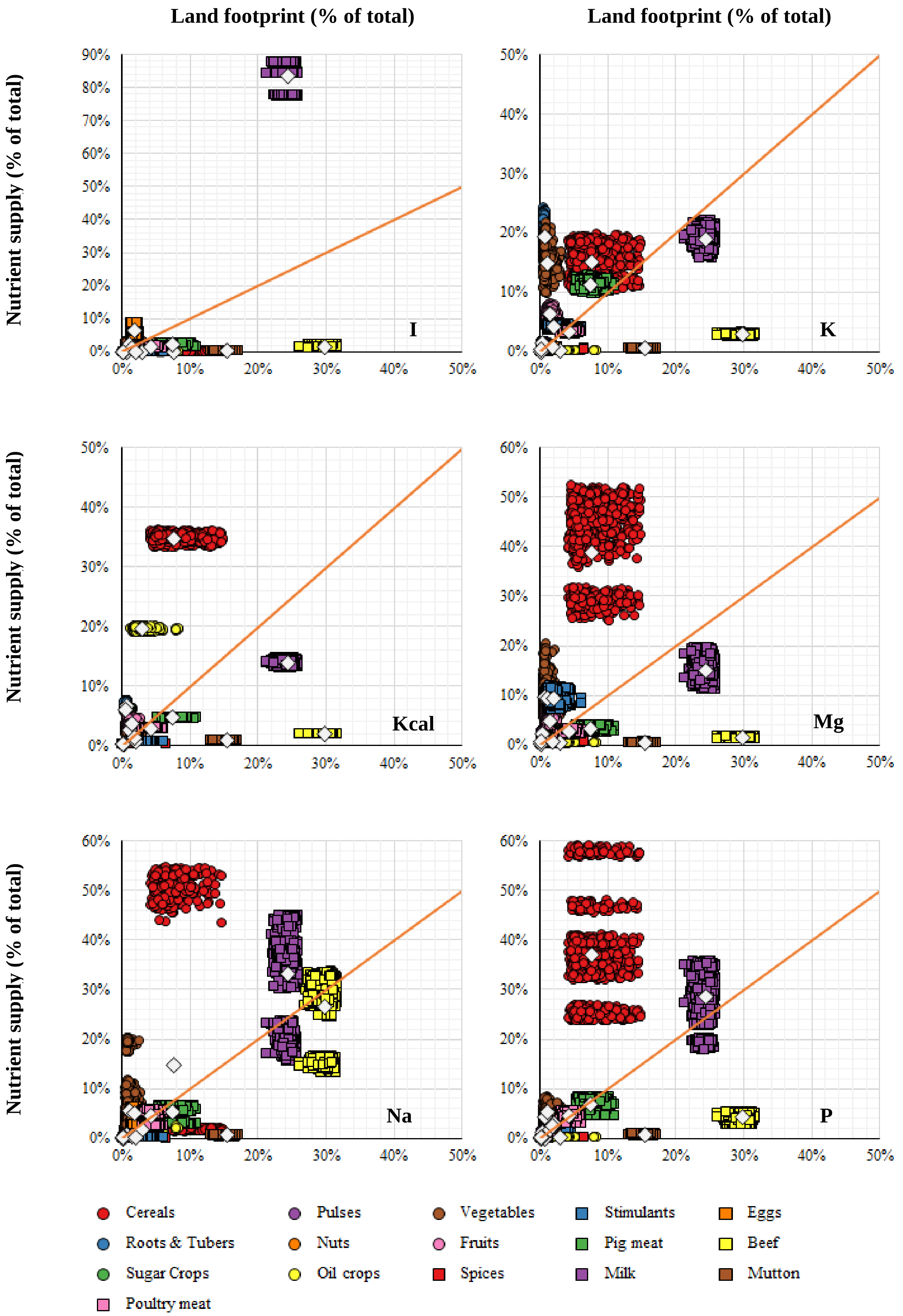


Figure C-3. Relative share of food categories in nutrient supply (y-axis) and relative share in total land footprint (x-axis) for selected nutrients. Diamonds represent the average value across all 1000 iterations.

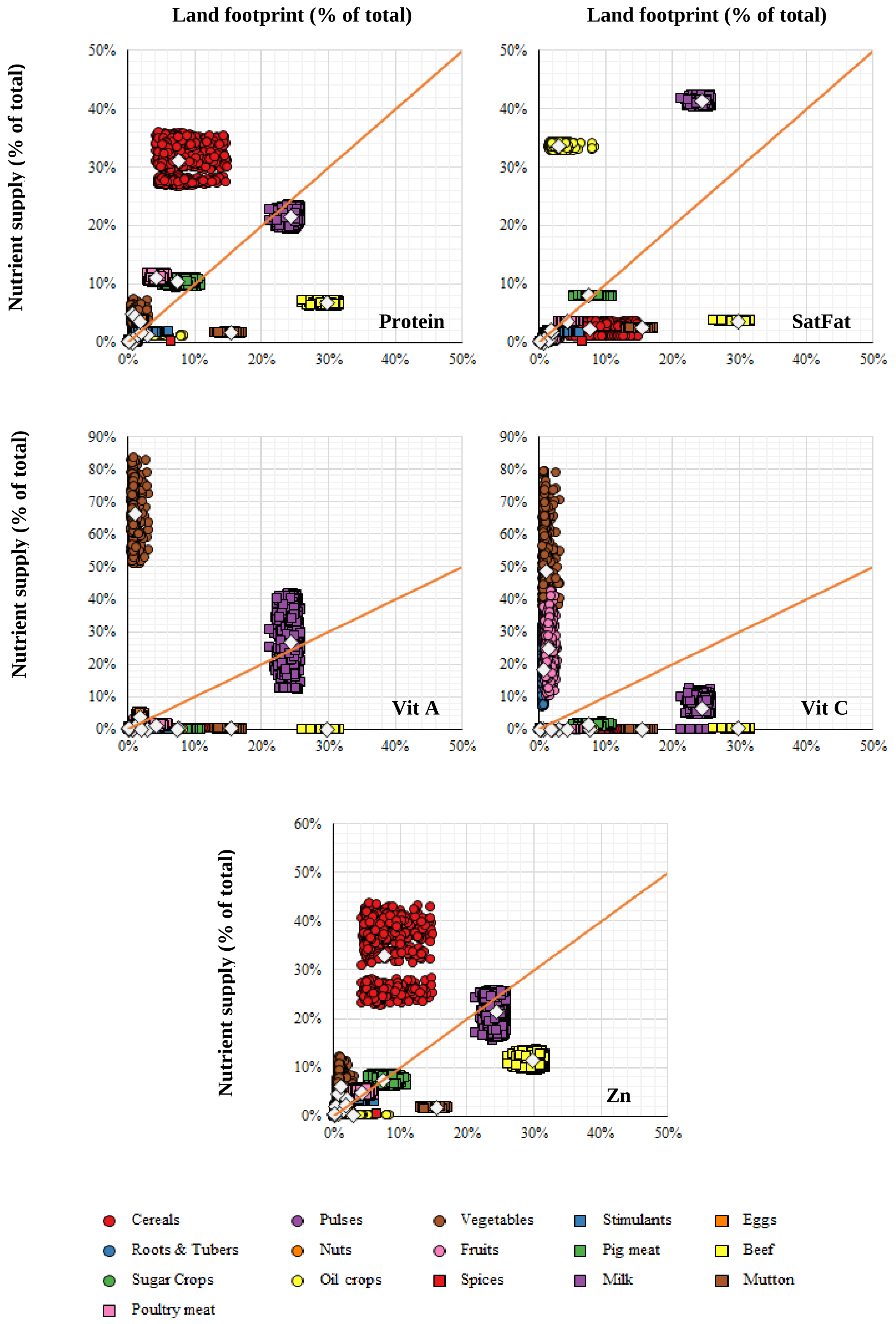


Figure C-4. Relative share of food categories in nutrient supply (y-axis) and relative share in total land footprint (x-axis) for selected nutrients. Diamonds represent the average value across all 1000 iterations.

D. Median number of people fed per hectare for different food categories

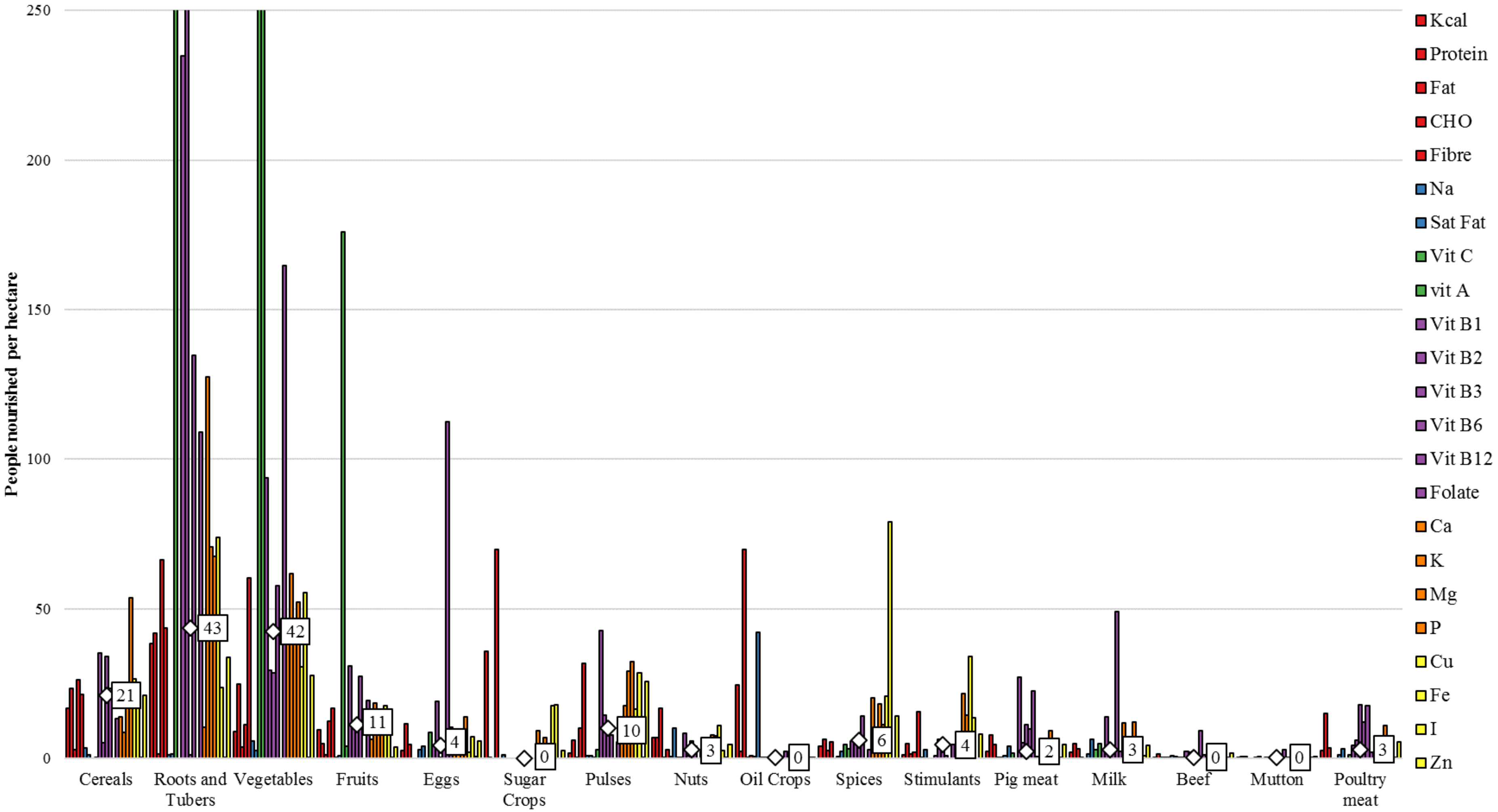


Figure D-1. Number of people nourished per hectare for selected nutrient. Median number of people nourished across all nutrients in diamonds and associated text boxes

E. Example of input data

Table E-1. Example of data input. Not all commodities and nutrients are shown.

FAO code	Food commodity	Database	Energy	Protein	Fat	SATFAT	CHO	Fibre	B1	B12	B2	B3	B6	Ca	Cu	Fe	Folate	I	K	Mg
15	Wheat flour	*GENUS*	340	13.2	2.5	0.4	72.0	5.8	0.5	N/A	0.2	5.0	0.4	34.0	0.4	3.6	44.0	N/A	363.0	137.0
15	Flour, wheat, bread/strong, white	*M&W*	353	11.3	1.2	0.31	79.2	3.1	0.3	0	0.03	4.1	0.15	134	0.15	1.92	16	0	166	26
15	Flour, wheat, brown	*M&W*	339	12.2	2	0.29	72.5	6.9	0.39	0	0.1	6.3	0.41	28	0.32	2.38	44	0	295	72
15	Flour, wheat, brown, bread/strong	*M&W*	341	13.4	1.9	0	72	4	0.39	0	0	6.0	0.35	52	0.27	2.3	29	0	261	61
15	Flour, wheat, white, plain, soft	*M&W*	352	9.1	1.4	0.44	80.9	3.4	0.28	0	0.05	3.7	0.18	96	0.15	1.94	16	0	175	23
15	Flour, wheat, white, self raising	*M&W*	348	8.9	1.5	0.39	79.6	3.1	0.28	0	0.05	3.7	0.18	280	0.12	1.74	18	0	190	25
15	Flour, wheat, wholemeal	*M&W*	327	11.6	2	0.29	69.9	8.8	0.36	0	0.1	7.9	0.5	32	0.37	2.47	27	0	358	83
15	Flour, wheat, wholemeal, bread/strong	*M&W*	327	14.2	2.2	0	66.7	8.3	0.38	0	0.1	7.9	0.5	32	0.32	3.07	34	0	359	107
15	Flour, wheat, wholemeal, self raising	*M&W*	359	10.8	1.9	0	69.3	5.4	0.43	0	0	5.6	0.35	333	0.37	2.81	30	0	362	87
27	Rice (paddy)	*GENUS*	351	6.4	0.5	0.1	77.6	2.7	0.2	N/A	0.1	4.0	0.1	6.9	0.2	1.6	6.9	N/A	75.5	22.5
27	Rice, white, basmati, raw	*M&W*	344	7.9	0.5	0.1	82.1	0.9	0.0	0.0	0.0	0.0	0.0	9.8	0.3	1.7	11.8	0.0	75.5	20.6
27	Rice, white, Italian Arborio risotto, raw	*M&W*	347	6.3	1.0	0.2	83.5	0.9	0.0	0.0	0.0	0.0	0.0	4.9	0.2	0.2	12.7	0.0	84.3	29.4
27	Rice, white, long grain, raw	*M&W*	348	6.6	1.0	0.2	83.4	0.9	0.0	0.0	0.0	0.0	0.0	15.7	0.2	0.3	13.7	0.0	85.3	24.5
27	Rice, white, pudding, raw	*M&W*	345	5.5	0.9	0.2	83.9	0.8	0.0	0.0	0.0	0.0	0.0	5.9	0.2	0.2	13.7	0.0	82.4	25.5
27	Rice, white, basmati, easy cook, raw	*M&W*	343	7.9	0.4	0.1	82.2	0.9	0.0	0.0	0.0	0.0	0.0	22.5	0.3	0.9	19.6	0.0	125.5	23.5
27	Rice, white, long grain, easy cook, raw	*M&W*	340	6.9	1.1	0.2	80.7	1.1	0.0	0.0	0.0	0.0	0.0	22.5	0.3	0.4	17.6	2.0	152.9	26.5
44	Barley	*GENUS*	354	9.9	2.3	0.5	77.7	17.3	0.2	N/A	0.1	4.6	0.3	33.0	0.5	3.6	23.0	N/A	452.0	79.0
44	Barley, pearl, raw	*M&W*	360	7.9	1.7	0.0	83.6	0.0	0.12	0.0	0.05	4.8	0.22	20.0	0.4	3.0	20.0	0.0	270.0	65.0
56	Maize flour	*GENUS*	365	9.4	4.7	0.7	74.3	7.3	0.4	N/A	0.2	3.6	0.6	7.0	0.3	2.7	19.0	N/A	287.0	127.0
56	Corn flour*	*M&W*	365	9.4	4.7	0.7	74.3	7.3	0.4	0.0	0.2	3.6	0.6	7.0	0.3	2.7	19.0	0.0	287.0	127.0
71	Rye	*GENUS*	338	10.3	1.6	0.2	75.9	15.1	0.3	N/A	0.3	4.3	0.3	24.0	0.4	2.6	38.0	N/A	510.0	110.0
71	Flour, rye	*M&W*	319	7.3	1.6	0.2	73.5	11.8	0.4	0.0	0.1	0.9	0.4	33.0	0.3	2.4	60.0	0.0	419.0	85.0