



THE UNIVERSITY *of* EDINBURGH

Edinburgh Research Explorer

Drivers for global agricultural land use change: The nexus of diet, population, yield and bioenergy

Citation for published version:

Alexander, P, Rounsevell, MDA, Dislich, C, Dodson, JR, Engström, K & Moran, D 2015, 'Drivers for global agricultural land use change: The nexus of diet, population, yield and bioenergy' *Global Environmental Change*, vol. 35, pp. 138-147. DOI: 10.1016/j.gloenvcha.2015.08.011

Digital Object Identifier (DOI):

[10.1016/j.gloenvcha.2015.08.011](https://doi.org/10.1016/j.gloenvcha.2015.08.011)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Peer reviewed version

Published In:

Global Environmental Change

General rights

Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.



Drivers for global agricultural land use change: the nexus of diet, population, yield and bioenergy

Abstract

The nexus of population growth and changing diets has increased the demands placed on agriculture to supply food for human consumption, animal feed and fuel. Rising incomes lead to dietary changes, from staple crops, towards commodities with greater land requirements, e.g. meat and dairy products. Despite yield improvements partially offsetting increases in demand, agricultural land has still been expanding, causing potential harm to ecosystems, e.g. through deforestation. We use country-level panel data (1961-2011) to allocate the land areas used to produce food for human consumption, waste and biofuels, and to attribute the food production area changes to diet, population and yields drivers. The results show that the production of animal products dominates agricultural land use and land use change over the 50-year period, accounting for 65% of land use change. The rate of extensification of animal production was found to have reduced more recently, principally due to the smaller effect of population growth. The area used for bioenergy was shown to be relatively small, but formed a substantial contribution (36%) to net agricultural expansion in the most recent period. Nevertheless, in comparison to dietary shifts in animal products, bioenergy accounted for less than a tenth of the increase in demand for agricultural land. Population expansion has been the largest driver for agricultural land use change, but dietary changes are a significant and growing driver. China was a notable exception, where dietary transitions dominate food consumption changes, due to rapidly rising incomes. This suggests that future dietary changes will become the principal driver for land use change, pointing to the potential need for demand-side measures to regulate agricultural expansion.

Keywords

Land use; dietary patterns; land displacement; food security

1 Introduction

A growing global population increases the need for food, fuel and shelter (Foley et al., 2011), whilst increasing wealth is resulting in changing food consumption patterns towards commodities that are more land intensive to supply (Delgado et al., 1999; Godfray et al., 2010; Kearney, 2010; Keyzer et al., 2005; Tilman et al., 2011; Weinzettel et al., 2013). The location of food production is changing, due to the globalisation of food supply and increasing international trade in agricultural commodities (D’Odorico et al., 2014; Erb et al., 2009; Fader et al., 2013; Meyfroidt et al., 2013). Demands for land unrelated to food production are also increasing, for example from bioenergy feedstock supply, urbanisation and non-provisioning ecosystem services, e.g. through protected areas (Lambin and Meyfroidt, 2011; Schröter et al., 2005). Greater demands for agricultural commodities can be met by intensification (improved yield by greater inputs, such as fertiliser, pesticides or water, and or changes to management practices), agricultural expansion, or both (Cassman, 1999; Johnson et al., 2014; Tilman et al., 2011). Improvements in agricultural yield have helped to mitigate the impact on these demands (Foley et al., 2011), but still land use change has occurred (FAOSTAT, 2014a). Negative environmental impacts can result from land use change or agricultural intensification, including greenhouse gas emissions, deteriorating soil quality, use of scarce water resources, and biodiversity loss (Smith et al., 2013). For example, since 1990 land use change is believed to be responsible for 10-20% of global CO₂ emissions (Houghton et al., 2012; Le Quéré et al., 2009).

Pasture forms the largest component of agricultural land globally, but, to date, research on agricultural land use–environment–food security nexus has focused disproportionately on the role of arable crops (Wirsenius et al., 2010). Permanent pasture accounted for 69% of agricultural land (26% of total land) in 2011, while arable was 28% of agricultural land (11% of total land) (FAOSTAT, 2014a). Permanent pasture is land used for five years or more to grow herbaceous forage crops, either cultivated or growing wild (FAOSTAT, 2014a), and therefore ranges from intensively managed grassland through to savannahs and prairies. In addition to pasture, land used in the production of animal products (meat, milk and eggs) is further increased by the use of crops for animal feed. Due to the lower efficiency of animal products compared to vegetal crops (Fairlie, 2010; Smil, 2002), 90% of food calories are supplied from cropland (Kastner et al., 2012). Attempts have been made to quantify the impact of closing the crop ‘yield gap’ (Foley et al., 2011; Kastner et al., 2014; West et al., 2014), the use of crops for animal feed (Kastner et al., 2012), and the potential increase in available food supply if the latter were diverted for human consumption (Cassidy et al., 2013; Foley et al., 2011). But, the entire food-chain including animal products and dietary changes have received less attention (Wirsenius et al., 2010), although more recently the need for food demand management has been suggested (Bajželj et al., 2014; Tilman and Clark, 2014). There is also considerable debate about the true impact of the emerging demand for agricultural commodities as a bioenergy feedstock on food prices and volatility (Eide, 2008; Mitchell, 2008; Rathmann et al., 2010; Slade et al., 2011), and the level of indirect land use change (Haberl et al., 2012; Searchinger et al., 2008). However,

1 work has not been conducted to investigate and compare the impact on the
2 agricultural land use, including pasture, from additional demand, due to population
3 and dietary change and from demand from bioenergy feedstocks.
4

5 Here we address the lack of analysis by quantifying the impact from the
6 consumption of animal products relative to other drivers of land use change,
7 including bioenergy. We attempt to answer the following questions: How much
8 land and land use change has been associated with the production of animal
9 products and vegetal crops for human consumption, waste and biofuels? What has
10 been the relative importance of population, diet and yield as drivers for agricultural
11 land use change? How does land use change and its drivers differ between countries
12 and regions? The methodology followed is similar to Kastner (2012), with a number
13 of important advances including; consideration of the pasture area, identifying
14 bioenergy and waste uses, and a more spatially disaggregated analysis. Perhaps
15 most notably is the inclusion of pasture area, which provides a far more
16 comprehensive insight into the agricultural sector as a whole, the importance of
17 which is emphasised by the pivotal role of animal products in the results.

18 **2 Materials and methods**

19 The analysis uses FAO data from 1961 to 2011 to determine the land used to
20 produce each commodity consumed, including land displacement through
21 international trade, i.e. the domestic area used to produce a commodity consumed is
22 notionally increased for net importing countries, or decreased for net exporting
23 countries. The land used for animal products includes both pasture for grazing, and
24 the area harvested to cultivate the animal feed consumed. Land displacement was
25 considered in both the supply of animal feed, and in the trade of animal products. A
26 decomposition analysis was performed to investigate the impact of population, diet
27 and yield as drivers for change in land allocated to food production, for each
28 commodity and country.
29

30 **2.1 Data sources**

31 The primary data source used was FAO data on agricultural production, commodity
32 balance, and land use between 1961 and 2011 at a country level (FAOSTAT, 2014a,
33 2014b, 2014c, 2014d, 2014e, 2013). The unprocessed data covers 219 countries in
34 2011, and provides production values for 182 crop plus 57 livestock types. The
35 commodity balance data provides an itemisation of the consumption of each item,
36 and as well as the quantity of production, stock variation, imports and exports that
37 provide that supply. The animal feed conversion ratio, i.e. the efficiency of the
38 production of animal products, was estimated from various sources (FAO, 2014,
39 2009; Little, 2014; SAC Consulting, 2013; Smil, 2002). The analysis was conducted at
40 country level, in R (R Core Team, 2014) with Rworldmap used to produce global
41 maps of results using associated geographic data (South, 2011).
42

2.2 Joining production and consumption data

The dataset for crop production and consumption use different categorisation for crops and commodities. Consumption categories were mapped onto the agricultural commodity used, to allow them to be associated with the harvested areas. A few products were a trivial one-to-one mapping, e.g. bananas and oats; some others required multiple production categories to be mapped onto one category of consumption. For example consumption of "Oranges Mandarines" were mapped onto two items of production, "Oranges" and "Tangerines mandarins clementines satsumas". In the case of the "Vegetables Other" consumption was mapped onto the production of 34 crops. Rice was handled in paddy equivalent terms, and sugarcane in unrefined form, as consumption data was given in multiple unit (e.g. refine, unrefined and raw equivalent). The outcome was 51 consumption types, mapping onto one or more crop production items.

2.3 Displacement of land

To understand the full extent of land used in the production of commodities consumed, the import and export of goods needs to be considered. Land displacement has been defined as the migration of activities to another place, causing land change in the other location (Lambin and Meyfroidt, 2011; Weinzettel et al., 2013). Here we follow an approach similar to Yu *et al.* (2013), where the consumption of embodied land used to produce a commodity is used to measure land displacement. The imported or exported land area is then combined with the area for domestic production, to obtain a net land use, for that commodity, country and year. When calculating the displaced land, the areas associated with net imports are considered to occur at the global mean yield of exports, weighed by net export quantity. Net exports are taken as domestically produced, to reduce that country's land allocation on a proportional basis.

2.4 Crop consumption types

The category of consumption, for each crop commodity and country, was allocated between four categories; food for human consumption, animal feed, bioenergy and waste, based on FAO data (FAOSTAT, 2014b, 2014c). The four categories were mapped from the 6 types of consumption in the FAO data, i.e. food, feed, waste, processing, seed and other. The FAO defines the food, as the quantity available for human consumption, feed as the amount fed to animals, and waste as the losses in transport and storage prior to reaching the consumer. These were allocated to the categories used for food for human consumption, animal feed and waste, respectively. The processing type is also assumed to be used for human consumption, in line with the FAO description that it is "put to manufacture for food use" (FAOSTAT, 2014b, 2014c), and so aggregated into the food type used here. The FAO type for seed was allocated to the remaining categories on a pro rata basis. The FAO 'other' consumption type covers the use primarily for biofuels or materials, but also covers tobacco and potentially other non-food or feed use. The items with significant 'other' consumption were reviewed and assigned to either bioenergy or

1 material. Only those commodities used for bioenergy were considered in the rest of
2 the analysis, as the areas related to production of materials was relatively small and
3 constant, for example the area of cotton in 1961 was 31.8 Mha, and 35.5 Mha in
4 2011, or around 0.7% of agricultural land, see Table S1.

5
6 One area that required additional processing were oil seed crops, which are largely,
7 but not exclusively, processed into oil and seed meal. Typically the seed meal or
8 cake is primarily used for animal feed, while oil is used for human consumption and
9 as a bioenergy feedstock. The analysis traced back the usage of the processed oil and
10 meal, to the location and category of use, and allocating it pro rata by weight based
11 on the associated oil seed production area. The associated quantity of oil seed crop
12 was removed from the quantity of oil crop processed, and instead allocated based on
13 the usage for each of the oil and meal, therefore avoiding potential double counting.

14
15 The resultant four consumption categories were used pro rata to allocate the net
16 area of land (including the displaced area), to produce the commodity consumed.
17 The bioenergy areas quoted are to produce agricultural commodities used as
18 bioenergy feedstock, and therefore do not include timber or forestry products or the
19 associated areas.

20 21 **2.5 Livestock products**

22 The production of meat, milk and eggs uses land directly, in the form of pasture, and
23 indirectly in the production of feed. The area used to grow each type of feed was
24 determined (Section 2.4), and the pasture area for each country and year is known
25 (FAOSTAT, 2014a). Although the consumption and production data are available by
26 category of animal product (e.g. poultry meat, pig meat, sheep and goat meat, milk
27 and eggs), the quantity of feed and pasture are only available aggregated across all
28 animal products. To map production to land usage there are two potential
29 approaches; either, disaggregate the feed and pasture data (Herrero et al., 2013), or,
30 aggregate the consumption categories. Here we take the approach to aggregate into
31 an animal product index using animal feed conversion ratios.

32 33 **2.5.1 Animal product index**

34 The animal product index for a country c , and time t , is given by:

$$35 \quad \text{Animal product index}_{c,t} = \sum_j cr_j \cdot m_{c,j,t} \quad (1)$$

36 where cr_j is the animal conversion ratio, expressed in kg of feed per kg of production
37 (see Table S2), for animal product category j , and $m_{c,j,t}$ is the quantity of animal
38 product for that category. The conversion ratios are given in Table S2. The animal
39 production index was calculated for each country and year, and used as an
40 aggregated commodity. All areas used in feed production, plus the pasture was then
41 associated with the production of the animal product index. The allocation of land

1 displacement through international trade in animal products was then handled as
2 for the crop commodities.

3
4 The objective of the index is to reduce the impact of variations in the efficiency
5 between animal products, such that substitution between animal products does not
6 result in an increase in yields. Therefore it should still be possible to distinguish
7 between changes in diet, e.g. a switch between beef and chicken, and changes in the
8 productivity or yield in the supplying these commodities.
9

10 **2.5.2 Simplified example of animal product index**

11 To illustrate this with a simplified example, assume there is a country with a
12 constant population of 1000. At time t, there are just two animal products
13 consumed, 18 kg/year of chicken, and 30 kg/year of beef, per capita. The empirical
14 data shows that the total area for feed production and pasture was 330ha. At
15 another time point t+1, we have 30kg/year of chicken and 20kg/year of beef,
16 produced using 250ha of land. We could express yields in three ways; in mass terms,
17 in food nutritional energy terms, and based on feed inputs (i.e. the animal product
18 index). Calculating the yield changes between the time periods in this example
19 suggest yield increases of 37.5% in mass terms, 33.4% in nutritional energy
20 (assuming 9.16 MJ/kg for chicken and 10.47 MJ/kg for beef), and 0.9% for the
21 animal product index. The example values were in fact constructed assuming a
22 constant yield of production of 0.6 t/ha for chicken and 0.1 t/ha for beef, i.e. there
23 was no productivity improvements, only a shift in diet. The change in the animal
24 product index yield is not zero as the ratio of assumed production yields differs from
25 the ratio of feed conversions.
26

27 **2.5.3 Potential impacts from animal product index approach**

28 Globally there has been an increase in the proportion of chicken produced,
29 compared to other meats (Godfray et al., 2010), which without such an approach
30 would result in apparent yield improvements. Although such a shift would produce
31 more calories per area of land, this is based on dietary shifts, rather than an
32 improvement in production yields. The absolute value of the feed conversion ratio
33 do not impact the results presented, only their relative values. The assumption is
34 that the efficiency of each commodity alters at the same rate, i.e. that the
35 proportional relationship between them is preserved. The animal feed conversion
36 ratios are difficult to estimate, and have been the subject of misrepresentation by
37 both sides of the sustainability - meat consumption debate (Fairlie, 2010). The index
38 is used to assign the areas of pasture and feed production, but is not involved in
39 deriving the areas themselves. Therefore changes in the values of the feed ratios do
40 not change the total land areas allocated to the production of animal products,
41 however it does impact the association between the change in areas and shifts in
42 dietary patterns and yields.
43

2.6 Decomposition of land use change drivers

To gain insights into the reasons for the changes in land use a decomposition of the relative importance of each factor was conducted (Kastner et al., 2012). The agricultural area to produce a commodity can be represented as a function of population, average yield, and consumption per capita (Lambin and Meyfroidt, 2011). The mean yields accounting for the land use displacement associated with imports and exports were inferred for each country and commodity. To decompose the changes in net area, we assume that the net agricultural area a , for country c , and commodity i , has the following relationship:

$$a_{c,i} = p_c * k_{c,i} / y_{c,i} \quad (2)$$

where k is consumption per capita (kg/person/year), p is the population, and y is the mean yield (kg/ha).

The decomposition used a Log Mean Divisia Index (LMDI) approach was used to distribute the change in area into dietary, yield or population factors. This approach was selected as it produces a perfect additive decomposition, i.e. the sum of the decomposed values over all elements is equal to the total change (Ang, 2004). Using this decomposition approach, the change in net area between a reference year, t_1 , and another time period, t_2 , can be found by:

$$\begin{aligned} & \text{Net area change due to diet}_c \\ & = \sum_i \left(\left(\frac{a_{c,i,t_2} - a_{c,i,t_1}}{\ln(a_{c,i,t_2}) - \ln(a_{c,i,t_1})} \right) \ln \left(k_{c,i,t_2} / k_{c,i,t_1} \right) \right) \end{aligned} \quad (3)$$

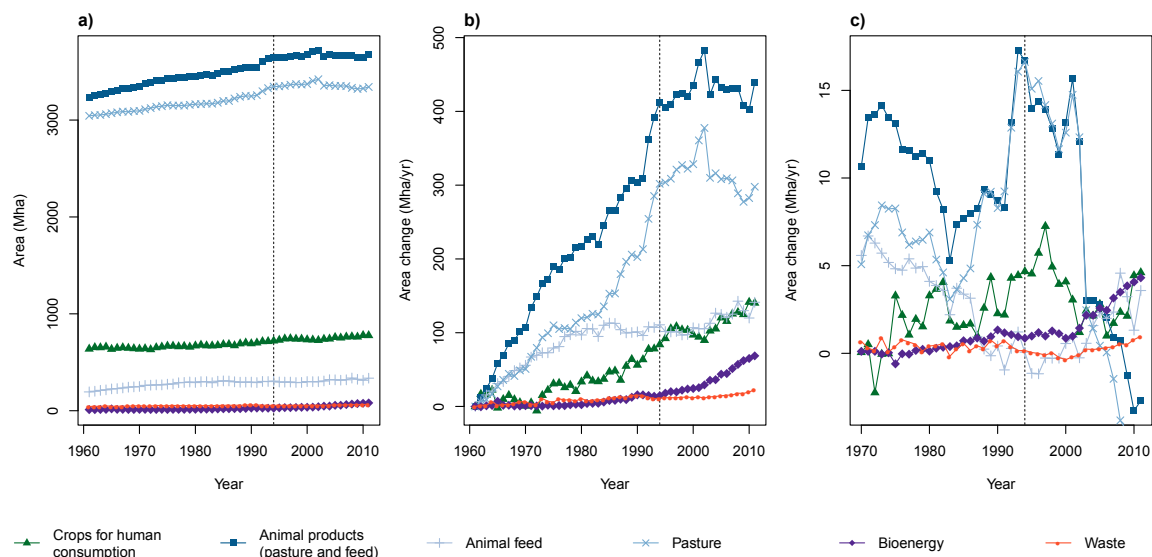
where $a_{c,i,t}$ is the net agricultural area for country c , to produce commodity i , at time t , and $k_{c,i,t}$ is the consumption per capita for that commodity, country and time. With analogous equations used to determine the effect on the net area from changes in populations and yields.

3 Results

3.1 Agricultural land consumption

The production of animal products was found to dominate total agricultural land use, and was responsible for 65% of land use change, nearly twice that attributable to other consumption types combined, in the 50 years since 1961, see Figure 1 a & b. Feed used in the production of animal products alone accounts for around 139 Mha of additional land use, only marginally less than the 140 Mha additional land used in the production of vegetal crops for human consumption (Figure 1b). Furthermore, global pasture area has increased by 298 Mha (FAOSTAT, 2014a), resulting in a total area increase in land use for animal production of 439 Mha (Figure 1b). Around the mid-1990s, the cumulative change in animal products area moves from consistently

1 increasing to varying around a more stable level, with a suggestion of a more recent
 2 decline. The changes on an annual basis show a large inter-annual variation, and
 3 therefore were plotted using a trailing 10-year moving average (Figure 1c). The
 4 areas for vegetal crops for human consumption and biofuels both increased
 5 throughout the 50-year period. The area used to produce feed rose until the mid-
 6 1980s, but thereafter showed a small decline, before increasing again from the late
 7 1990s.



9
 10 *Figure 1. Allocation of land to type of consumption from 1961 to 2011; a) shows the*
 11 *absolute area, b) cumulative area change since 1961, and c) annual area change using*
 12 *a 10-year moving average. The dashed vertical line at 1994 shows the division*
 13 *between the two periods used in subsequent figures.*

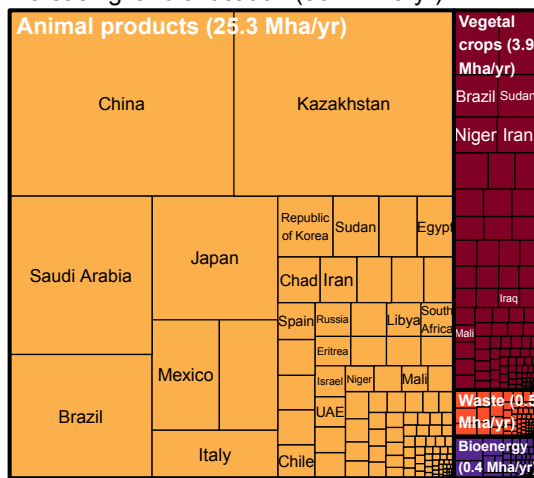
14
 15 Bioenergy from agricultural commodities (i.e. primarily bioethanol and biodiesel) is
 16 associated with a relatively small area in absolute terms, in 2011 the area was 81
 17 Mha or 1.8% of the land (Figure 1a). However, the majority of this has occurred over
 18 the past 10 years, with an average annual rise of 4.4 Mha or 0.1% of the agricultural
 19 land area over that period. The area associated with the production of commodities
 20 that are wasted, prior to reaching consumers, has also been rising slowly but
 21 steadily, increasing by 22 Mha or 0.5% of agricultural land since 1961.

22
 23 The global aggregated data hide a number of country level changes. Figure 2 shows
 24 the change in areas to produce animal products and vegetal crops for human
 25 consumption, as well as the area associated with wasted products and feedstock for
 26 bioenergy. The country allocation is via consumption, including accounting for land
 27 displacement through international trade. Two periods, 1961-1994 and 1994-2011,
 28 are used in the presentation of the results to allow for a comparison of the
 29 differences in land use change drivers through time. These date ranges were chosen
 30 to allow comparison of the earlier period where the total pasture area was
 31 consistently increasing, and the more recent period where pasture area is more

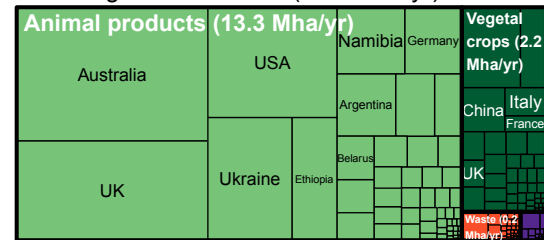
1 stable or declining. The vertical dashed line on the Figure 1 panels indicates this
 2 division (values in Figure 1c lag due to the 10-year trailing average). Figure 2 uses a
 3 'treemap' structure, which combines hierarchical aspects of Venn diagrams and the
 4 area proportionality of pie-charts (Bederson et al., 2002; Bruls et al., 2000),
 5 categorised by direction of area change, allocation type, and country. Each rectangle
 6 is therefore proportional to the area change it represents, and is shown as a nested
 7 structure. For example, in the first period, land allocation in aggregate can be seen
 8 to have increased by 30.2 Mha/year for some countries and uses, while
 9 simultaneously reduced by 15.8 Mha/year in others. Each of the totals is broken
 10 down into the contribution of animal products, vegetal crops, waste and bioenergy,
 11 e.g. 25.3 Mha/year additional land for animal products, with each sub-totals further
 12 divided to the country level contribution. The same data are displayed as a series of
 13 maps in Figure S1.
 14

a) 1961–1994 (Net 14.4 Mha/yr)

Increasing land allocation (30.2 Mha/yr)

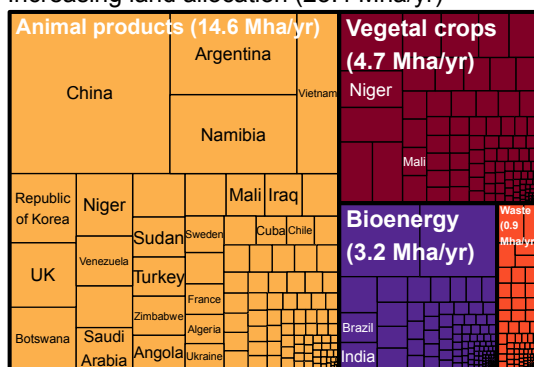


Reducing land allocation (15.8 Mha/yr)

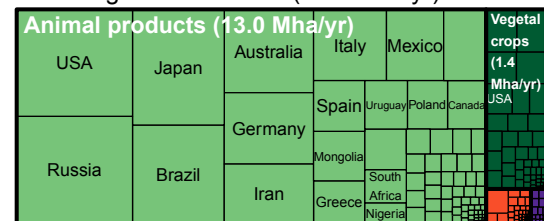


b) 1994–2011 (Net 8.8 Mha/yr)

Increasing land allocation (23.4 Mha/yr)



Reducing land allocation (14.6 Mha/yr)



15
 16 *Figure 2. Mean annual land allocation change to produce animal product and vegetal*
 17 *crops for human consumption, wasted commodities, and bioenergy feedstock, a) 1961*
 18 *to 1994, and b) 1994 to 2011, by country of consumption.*

1 The greatest absolute change in land allocation for both periods is attributed to the
2 supply of animal products consumed in China; in total 222 Mha of additional land
3 (167 Mha and 54 Mha for the respective periods) were used to support a 32 fold
4 increase in consumption. Kazakhstan has the second highest increase from 1961 to
5 1994, however this is in part due to the approach taken to handle the dissolution of
6 the USSR, by pro rata of areas by population. Kazakhstan has a large area of low
7 yielding pasture. Prior to 1992 this was aggregated across the USSR, but
8 subsequently the area is associated solely with the animal products produced in that
9 country, leading to the rise in the resulting area. The areas for other former USSR
10 states tend to offset one another, and data for changes since 1994 are not affected.
11 The third largest increase in land allocation is due to animal products consumed in
12 Saudi Arabia, totalling 96 Mha from 1961 to 2011. A 26-fold increase in
13 consumption of animal products is supported by a 16-fold increase in domestic
14 production, with an additional 85 Mha of pasture, and significant volumes of imports
15 where previously they had been limited.

16
17 The largest reduction in areas also results from changes in the areas used to produce
18 animal products, with Australia having a reduction of 124 Mha, and the United States
19 of America 87 Mha, since 1961. The Australian reduction is explained by higher
20 exports, representing 60 Mha, and a 69 Mha lower pasture area. The same factors
21 underlie the American reduction, but with a greater emphasis on international trade.
22 In aggregate, since 1961, the US moved from a net importer to a net exporter of
23 animal products, representing a 56 Mha shift of production, plus the area of pasture
24 was reduced by 17 Mha.

25
26 Comparing the results from the two periods (Figure 2), there are many similarities,
27 however the principal changes are a reduction in the rate of increase in land used for
28 animal products, and an increase in the rate for bioenergy. The animal product area
29 rise was on average 25.3 Mha/year in the earlier period, but the rate of increase
30 declined to 14.6 Mha/year since 1994. Concerning net land use change, animal
31 products accounted for 83% in the first period and 18% in the second period. The
32 reasons behind this shift will be analysed and discussed using the decomposition
33 results presented below. The net land use change for bioenergy feedstock rose from
34 an average of 0.3 Mha/year to 3.2 Mha/year. Since 1994, bioenergy is a substantial
35 factor in net land use change, accounting for 36% of the total net change, while in the
36 previous period it only accounted for 2%. This is in part due to the reduced rate of
37 increase of the area used for the production of animal products.

38 39 **3.2 Diet, population and yield**

40 The area used for food production for one country depends on the rate of
41 consumption (based on diet and population size), and agricultural yields. Evidence
42 for a change in dietary patterns with income (Cole and Mccoskey, 2013; Kearney,
43 2010; Keyzer et al., 2005; Tilman et al., 2011; Weinzettel et al., 2013) can be seen by
44 plotting consumption per capita against the GDP per capita, suggesting rising
45 incomes produce a shift from staples such as potatoes and pulses, to commodities

1 such as meat, milk and sugar, see Figure S2. The rise in global meat consumption per
2 person is particularly significant, with an 83% increase from 1961 to 2011, while the
3 per capita consumption of starchy roots decreased by 17% and pulses by 28%, see
4 Figure S3. In absolute terms, meat consumption more than quadrupled (a 4.12 fold
5 increase), compared to 2.59 for cereals and 1.63 for pulses, given a 2.27 fold increase
6 in the global population.

7
8 Arable yields have increased consistently for most countries (Fischer and Edmeades,
9 2010). We calculated a global mean change in vegetal crop yields, expressed as a
10 percentage change in the mass of the crop produced per hectare of land. Similarly,
11 an average animal product yield change was calculated using the animal product
12 index (see section 2.5). The outcome suggests that animal production yields have
13 been increasing broadly in line with vegetal crop yields for most of the 50-year
14 period. However, in the most recent decade the rate of animal crop yields seems to
15 have increased more rapidly, see Figure S4, perhaps indicating increased
16 intensification in production of animal products. The rise in animal product yields
17 encompasses increases in both animal feed conversion efficiency and in the grass
18 production yield. Over the 50-year period animal product yields have increased by
19 163%, while crop yields have increased by 140%, although there is considerable
20 inter-annual variation. Variations in the rate of yield improvements also exist
21 between countries and are apparent in the decomposition results.

22
23 These yield improvements have enabled a decreasing per capita land area used in
24 the production of food for most countries, and for all regions, see Figure S5.
25 Although the consumption of commodities with high land demand (low efficiency),
26 such as meat, has been increasing (Figure S2 and Figure S3), the improvements in
27 yields (Figure S4) have been sufficient to substantially offset these shifts. Land use
28 per capita can be higher both due to greater consumption rates, particularly of
29 products requiring greater land use, e.g. US meat consumption, but also due to the
30 effect of low yields on agricultural land; e.g. in many countries in Sub-Saharan Africa.
31 However, although per capita areas are falling in most locations, the absolute
32 agricultural area is increasing due to a rising population (Figure 2). The
33 decomposition analysis provides some insights into the interactions of the shifting
34 drivers, and how drivers vary between countries and over time.

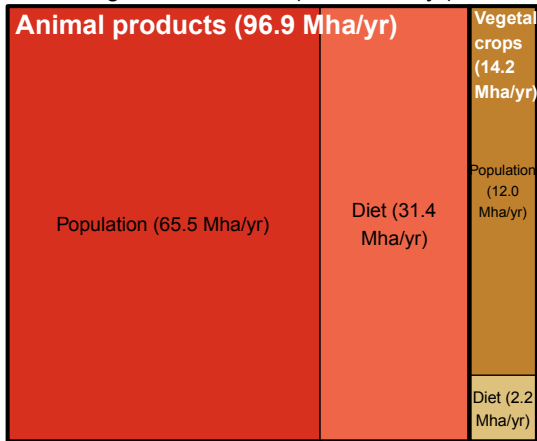
36 **3.3 Drivers for food production area changes**

37 The area for meat and vegetal food production was decomposed into drivers of yield,
38 per capita consumption (or diet) and population. Figure 3 represents the net impact
39 of each driver using a 'treemap' structure. The waste and bioenergy areas are not
40 included, as they are not part of the food area decomposition analysis.

1

a) 1961–1994 (Net 13.7 Mha/yr)

Increasing land allocation (111.1 Mha/yr)

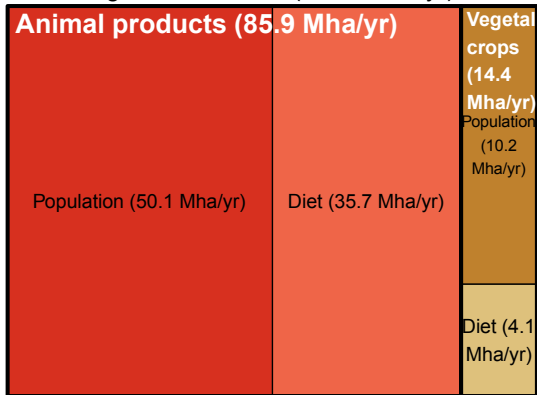


Decreasing land allocation (97.4 Mha/yr)

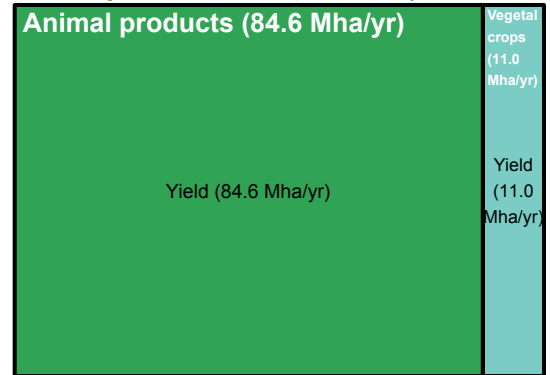


b) 1994–2011 (Net 4.6 Mha/yr)

Increasing land allocation (100.2 Mha/yr)



Reducing land allocation (95.6 Mha/yr)



2

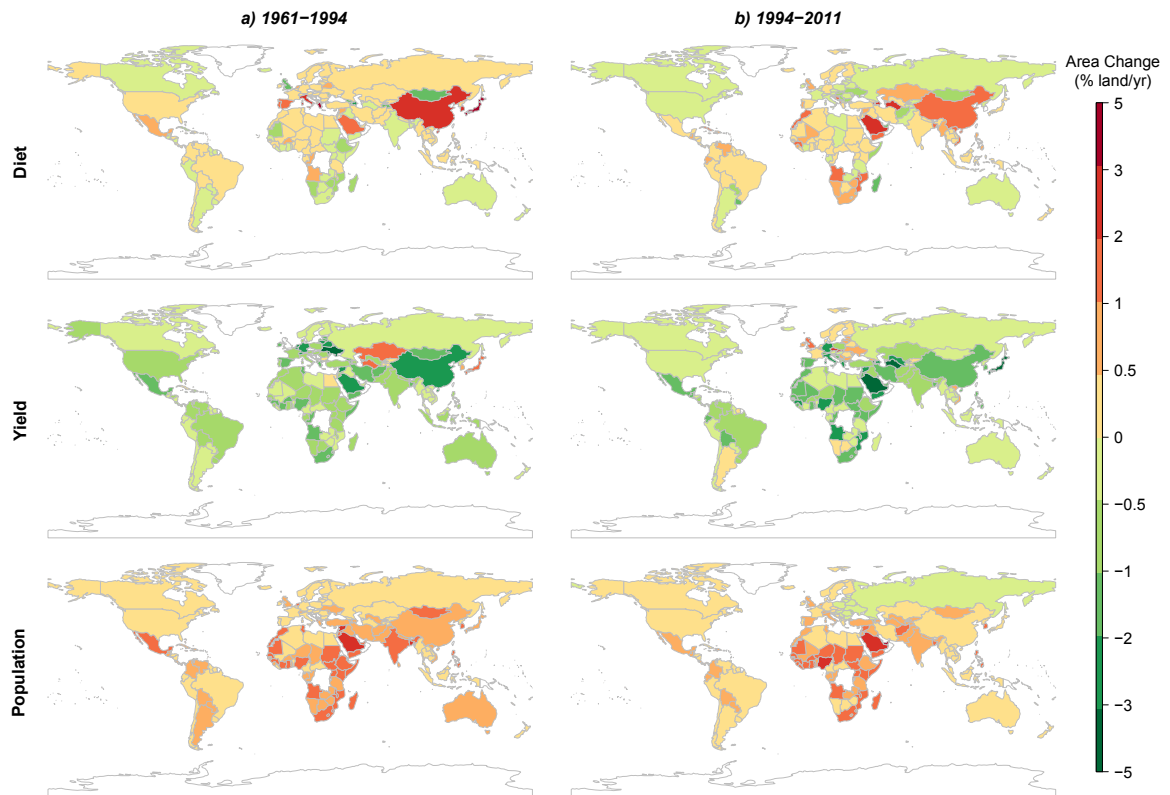
3

4

5

6

Figure 3. Land allocation change to produce food for human consumption decomposed into net diet, yield and population drivers, a) 1961 to 1994, and b) 1994 to 2011.



1
2 *Figure 4. Maps of mean annual land area change for food production, based on*
3 *location of consumption, decomposed into diet, yield and population drivers, expressed*
4 *as a percentage of land area, a) 1961 to 1994, and b) 1994 to 2011.*

5
6 Over the period from 1994 to 2011, animal products accounted for 86% of the
7 additional demand for land. At the same time yield improvements of animal
8 products generated 88% of the reduction in land requirements (Figure 3). The
9 result of this is a net area increase for animal products of 1.6 Mha/year, which is
10 lower than for crops for human consumption, at 3.3 Mha/year (Figure 2).
11 Population and diet both play a significant role as drivers for increased agricultural
12 land use. Globally in the 17 years to 2011, 40% of the need for additional land
13 results from shifts in diet, with 90% of this from changes in consumption of animal
14 products. Shifts in vegetal crop consumption are a driver for increased land use, but
15 at a comparatively lower level. The remaining 60% increase in pressure for
16 agricultural land use globally is from population growth. These globally aggregated
17 changes conceal inter-country variation and potentially opposing changes between
18 countries or over time. Figure 4 shows maps of the resulting drivers, expressed as
19 percentage annual change of land area, divided into the same two periods, countries
20 with largest absolute values are given in Table S3 and Table S4. The changes in of
21 population and yields can be seen to be relatively consistent in increasing and
22 decreasing, respectively, land requirement globally and over time, if at varying
23 levels. Conversely, the impact of diet appears to be more varied between countries
24 and time periods (Figure 4).
25

1 China is a notable exception where the main driver is the change in dietary patterns,
2 rather than population, and less than a quarter of the increase in land use is from
3 population change (Figure 4). This is consistent with the rapid rise in Chinese per
4 capita GDP, and the associated dietary changes (Figure S2). China alone accounted
5 for 43% of the dietary driven increase in agricultural land. For most countries, yield
6 improvements for animal products provide the main driver of reduction in
7 agricultural land use (Table S3 and Table S4). Only India and Mongolia go against
8 this trend in the 1994 to 2011 period. In the case of India, changes for crops
9 dominate due to low levels of animal product consumption. For Mongolia, the
10 existing high levels of animal product consumption have been falling over time,
11 leading to diet being a driver for reduced land requirement in that country.

12
13 The decomposition results of changes from 1961 to 1994 display similarities to
14 those from 1994 to 2011, but with some notable differences. Both time periods are
15 dominated by the changes related to the consumption and production of animal
16 products, with 86-87% of drivers for increase in land use from animal products, and
17 87-88% of the area reducing from yield improvements of animal products in each
18 case (Figure 3). The net land use change from food production is substantially
19 reduced, from 13.7 Mha/year in the period 1961-1994 to 4.6 Mha/year in the period
20 1994-2011. The main reason for this is a reduction in the population driver for
21 meat. Although in absolute terms population has been increasing relatively
22 consistently, averaging 78 million people/year for both periods, the percentage rate
23 of increase has been falling, from around 1.8% in the earlier period to 1.2% per
24 annum in the later period.

25
26 Another difference between the results in the two time periods is a shift in the
27 balance between population and diet as a driver. The pressure on land from animal
28 products related to diet increased from 32% in the period of 1961-1994 to 42% in
29 the period of 1994-2011. The balance for crops also shifts to being more driven by
30 diet, with 15% of the vegetal crop driver coming from diet between 1961 and 1994,
31 rising to 29% since 1994. The increasing importance of diet as a driver can also be
32 seen in Table S1, Table S4 and Figure 4. During the earlier time period, out of the 19
33 countries with the largest shifts in land use, only China has the change in
34 consumption of animal products being the largest driver. However, in the more
35 recent period, 6 of the 21 countries now have dietary changes in animal product
36 being identified as the most significant driver for increased land use for food
37 production.

38 39 **4 Discussion**

40 **4.1 Animal products**

41 Animals can produce food by grazing land that would be unsuitable for producing
42 other crops, and therefore do not always compete with other food production
43 systems (Foley et al., 2011). Areas of low intensity, such as low yielding pasture, can
44 provide important biodiversity and other ecosystem services, as well as grazing.

1 Conversion of these areas to crop production, may create negative environmental
2 outcomes, and potentially not sustainably provide viable crop yields (Fairlie, 2010;
3 Godfray et al., 2010). As all pasture areas are allocated to animal products in the
4 analysis, the absolute level of land used could be potentially misleading.
5 Consequently, the focus has been on the change in land use, which largely removes
6 the potential for this bias, as any additional pasture must be converted from a
7 previous land use, e.g. natural vegetation or forestry, with potentially negative
8 outcomes. Similarly, the broad definition of pasture is less of concern due to the
9 focus on change in area. The use of crops for animal feed, is even more clear-cut, as
10 it always reduces the quantity of food potentially available for human consumption.

11
12 Meat, milk and egg production are relatively inefficient uses of land for food
13 production (Smil, 2002), and changes in diet have also increased the consumption of
14 meat and milk faster than other commodities (Figure S3). The result, as
15 demonstrated by the decomposition analysis, is that the consumption of animal
16 products dominates the increased pressure on agricultural land (Figure 3 & 4), even
17 in the period since 1994 where it is not such a major driver for net land use change.
18 The change in area for production of animal products would have been greater but
19 for yield improvements associated with the production of these commodities,
20 mitigating the potential increases. Higher animal product yields can be achieved by
21 increasing animal conversion efficiency or pasture yields through, for example,
22 amended management practices or breeding. Unfortunately, the datasets used do
23 not provide a mechanism to distinguish between these aspects. Future work could
24 attempt to disaggregate the impact of pasture output from the animal conversion
25 efficiency, by including spatial forage quality, grazing system and proportion of feed
26 versus forage.

27
28 The shift in diets seen in the results, globally towards that of developed countries,
29 may negatively influence human health in two ways, firstly by increasing rates of
30 obesity and other non-communicable diseases associated with diet, and secondly
31 through a decline in environmental quality and ecosystem services due to the
32 impacts of changes in the land use system to supply the foods consumed (Tilman and
33 Clark, 2014). The high rates of consumption of (particularly processed red) meat,
34 dairy and refined sugars, typical of many developed nations, can have negative
35 health implications (Kearney, 2010). Diabetes, hyper-tension and cardiovascular
36 disease have emerged as major causes of morbidity and mortality, with links to
37 obesity, and high levels of consumption of meat are associated with obesity (Wang
38 and Beydoun, 2009). Conversely, in some poorer communities meat is a vital source
39 of human nutrition, and further meat consumption would be a benefit to health
40 where malnourishment or lack of certain nutrients is prevalent. However, the
41 incidence of under-nourishment globally is declining (Porkka et al., 2013), while that
42 of obesity is increasing (Popkin, 2006).

4.2 Bioenergy

The trade-off involved between food security, the environment and energy are extremely complex (Hoff, 2011). The results here show that the area used to produce agricultural commodities for bioenergy feedstock have so far been relatively limited in absolute terms, representing 1.8% of the agricultural area in 2011. Nonetheless, the recent rate of increase has been significant when compared to the other agricultural land uses, accounting for 36% of the net agricultural land use change since 1994. Use for bioenergy removes the potential for that area to produce food for human consumption, requiring lower food demand, greater yields e.g. through increased intensification, or a larger agricultural area. Equally, the reverse could be stated, that supplying food for increasing consumption removes potential land for bioenergy feedstock production. Comparing the animal product dietary driver since 1994, of 35.7 Mha/year, to the 3.2 Mha/year for bioenergy, suggests that changes in diet to consume more animal products are having an impact 11 times greater than bioenergy. Further, social benefit may accrue from the use of land for bioenergy, where it displaces fossil fuel usage or other high carbon energy sources. Conversely, increasing the per capita consumption of animal products beyond a moderate level, with attendant potential negative health implications, may have a social cost. Therefore, if bioenergy production can be adopted in conjunction with increasing yields, and moderation in dietary patterns, then both food security and a source low carbon energy may be possible. However, there is the risk that bioenergy may further jeopardise food security for some, in a world where diets continue to shift towards commodities with a high land footprint.

4.3 Waste

The waste area in the analysis only considers losses prior to reaching consumers. Therefore the results understate the overall wastage, and are far less than the 25-40% of total food waste (Godfray et al., 2010; Kummu et al., 2012). Even with this rather limited definition of waste the data suggest a worsening picture, with an increasing proportion of waste. This is not encouraging considering that waste reduction has been suggested as one of the routes to future food security and sustainability (Bajželj et al., 2014; Smith et al., 2013; West et al., 2014).

4.4 Intensification versus extensification

Although total agricultural land has expanded throughout the 50-year period, the results suggest a shift towards intensification in producing animal products, since the late 1990s (Figure 1). There is an expectation that global grassland areas will not expand rapidly, and be accompanied by an increase in feed usage and more intensively managed grassland (Bouwman et al., 2005). The results provide some support for this view, with expansion in pasture areas, prior to the late 1990s, being replaced by a gradual decrease, and an increasing area used for growing feed. The yield improvements for animal products have followed an arithmetically increasing trend over the 50-year period, at a similar rate to vegetal crops (Figure S4). However, in the most recent decade animal products appear to show slight increases

1 in yield improvements above the arithmetic trend, supporting the view of greater
2 intensification over that period. The decomposition analysis (Figure 3) suggests that
3 the pressure for additional meat, milk and eggs from population expansion is
4 reducing. Despite a greater driver from dietary changes, the net effect remains a
5 reduction in the rate of increase in demand for land for animal products. This
6 suggests both an increase in intensification, and a slowing in the rise of demand,
7 producing a reduced rate of agricultural land expansion.
8

9 **4.5 Lessons for the future**

10 The importance of meat and dairy consumption as a driver for land use change has
11 been suggested to increase, as the rate of population growth declines and wealth
12 rises (Godfray et al., 2010). The evidence from the results shown here is that such a
13 shift in drivers has already started. If the rate of population expansion continues to
14 decrease as predicted (Gerland et al., 2014), then the biggest driver will continue to
15 abate. Consequently, diet is likely to overtake population change as providing the
16 greatest driver for increases in agricultural land use. Assuming the rate of
17 population growth continues to slow, and consequentially the population driver for
18 additional land halves in magnitude, while other aspects remained fixed, then a 25
19 Mha/year fall in agricultural land use for food production would be anticipated.
20 However, a moderation in diet, coupled with continued yield improvements may be
21 needed to attain global food security (Bajželj et al., 2014; Davis et al., 2014).
22

23 China is an example where agricultural land use change has already been dominated
24 by increased per capita consumption of animal products (Figure 3 & 4). However,
25 we can expect that countries or regions currently with low incomes and
26 commensurately low per capita meat consumption (e.g. India and sub-Saharan
27 Africa) will see diets shifting towards those of more developed nations. In 1961,
28 meat consumption was 88.6 kg/year in the USA, and just 3.8 kg/year in China. By
29 2011 this had risen to 117.6 kg/year and 57.4 kg/year respectively. The change in
30 Chinese consumption with rising GDP can be seen in Figure S2, for meat and some
31 other food categories. It appears that the rapid rise in average income in China (2.6
32 fold greater increase in GDP than the rest of the world) has supported the expected
33 shift in diets. Consequently, China is now higher up the meat consumption curve,
34 and rising incomes can be expected to stimulate a slower rate of increase in meat
35 consumption, as the plateau in consumption is reached (Cole and Mccoskey, 2013).
36 Per capita consumption of milk and sugar in China has not increased as much as
37 would have been expected, based on the rise in GDP (Figure S2), and has greater
38 scope for significant future expansion to attain the consumption levels seen in many
39 developed nations. As indicated by China, growing incomes in developing countries
40 are likely to increase the pressure on agricultural land from dietary change.
41

42 The results show yield improvements for most countries and commodities, and are
43 also suggestive of an increasing rate of intensification of animal products in the most
44 recent decade (Figure S4). However, the ability to sustain continued improvements
45 in yields is not guaranteed, with suggestions that the rate of improvements is likely

1 to fall (Alexandratos and Bruinsma, 2012; Ray et al., 2012). As well as technical
2 limits to yield increases, there are likely to be sustainability limits to intensification.
3 The increasing costs of fossil fuels for transportation, depletion of rock-phosphate
4 reserves and geopolitical issues affecting access to resources, could also affect yields
5 and production costs (Cordell and White, 2011). The impact of climate change on
6 crop yields may also be increasingly negative from 2030, although adaptation may
7 offset this affect in temperate climates, but with the requirement of additional
8 irrigation (Challinor et al., 2014). Carefully controlling these factors could help the
9 move towards sustainable intensification (Mueller et al., 2012). The combined effect
10 of climate change, nutrient availability, and sustainable intensification methods on
11 yields, both for crops and animal products, is currently unclear.
12

13 **4.6 Validation and validity of results**

14 Global panel data of the type used in the analysis is always going to be of varying
15 quality, with the level of uncertainty being difficult to determine. However, the FAO
16 compiled data used is the best available source of such global data, and as such has
17 previously been widely used for academic purposes. Additionally, validation checks
18 were run to ensure internal consistency of input data and consistency with the
19 results, see supporting information for further details. Another indication of the
20 validity is the broad consistency of results between similar countries, with some
21 outlying cases. These results, including the outlying cases, can be explained through
22 considerations of the changes occurring within those countries, e.g. the rapidly
23 increasing wealth of China. This suggests that country level data artefacts or other
24 biases do not dominate the results.
25

26 **5 Conclusions**

27 The results suggest that there is a potential need for demand-side measures to
28 attempt to influence future dietary patterns. Within developed countries there is
29 likely to be health and also environmental sustainability gains by reducing the
30 quantities of meat, milk and eggs consumed. Similarly, the global consequences of
31 dietary shifts expected or underway in other countries, moving towards diets high in
32 meat, dairy and sugar, typical of developed countries, needs to be anticipated and
33 managed. Success in managing demand for high land use food may provide scope
34 for the continued rapid rate of expansion in the production of bioenergy feedstock,
35 without further increasing the total agricultural land area, supporting
36 decarbonisation of the energy sector, and providing further societal and
37 environmental benefits.
38

39 **6 References**

40 Alexandratos, N., Bruinsma, J., 2012. World Agriculture Towards 2030 / 2050. FAO,
41 Rome, Italy and IIASA, Laxenburg, Austria.

- 1 Ang, B., 2004. Decomposition analysis for policymaking in energy: *Energy Policy* 32,
2 1131–1139. doi:10.1016/S0301-4215(03)00076-4
- 3 Bajželj, B., Richards, K.S., Allwood, J.M., Smith, P., Dennis, J.S., Curmi, E., Gilligan, C. a.,
4 2014. Importance of food-demand management for climate mitigation. *Nat.*
5 *Clim. Chang.* doi:10.1038/nclimate2353
- 6 Bederson, B.B., Shneiderman, B., Wattenberg, M., 2002. Ordered and quantum
7 treemaps: Making effective use of 2D space to display hierarchies. *ACM Trans.*
8 *Graph.* 21, 833–854. doi:10.1145/571647.571649
- 9 Bouwman, A.F., Van der Hoek, K.W., Eickhout, B., Soenario, I., 2005. Exploring
10 changes in world ruminant production systems. *Agric. Syst.* 84, 121–153.
11 doi:10.1016/j.agry.2004.05.006
- 12 Bruls, M., Huizing, K., Wijk, J.J. Van, 2000. Squarified Treemaps, in: *Data Visualization.*
13 *Proceedings of the Joint EUROGRAPHICS and IEEE TCVG Symposium on*
14 *Visualization in Amsterdam, The Netherlands, May 29–30, 2000, pp. 33–42.*
- 15 Cassidy, E.S., West, P.C., Gerber, J.S., Foley, J. a, 2013. Redefining agricultural yields:
16 from tonnes to people nourished per hectare. *Environ. Res. Lett.* 8, 034015.
17 doi:10.1088/1748-9326/8/3/034015
- 18 Cassman, K.G., 1999. Ecological intensification of cereal production systems: yield
19 potential, soil quality, and precision agriculture. *Proc. Natl. Acad. Sci. U. S. A.* 96,
20 5952–5959. doi:DOI 10.1073/pnas.96.11.5952
- 21 Challinor, a. J., Watson, J., Lobell, D.B., Howden, S.M., Smith, D.R., Chhetri, N., 2014. A
22 meta-analysis of crop yield under climate change and adaptation. *Nat. Clim.*
23 *Chang.* 4, 287–291. doi:10.1038/nclimate2153
- 24 Cole, J.R., Mccoskey, S., 2013. Does global meat consumption follow an
25 environmental Kuznets curve ? 9, 26–36.
- 26 Cordell, D., White, S., 2011. Peak Phosphorus: Clarifying the Key Issues of a Vigorous
27 Debate about Long-Term Phosphorus Security. *Sustainability* 3, 2027–2049.
28 doi:10.3390/su3102027
- 29 D’Odorico, P., Carr, J. a., Laio, F., Ridolfi, L., Vandoni, S., 2014. Feeding humanity
30 through global food trade. *Earth’s Futur.* 2, 458–469.
31 doi:10.1002/2014EF000250
- 32 Davis, K.F., Odorico, P.D., Rulli, M.C., 2014. Earth ’ s Future Moderating diets to feed
33 the future Earth ’ s Future. *Earth’s Futur.* 2, 559–565.
34 doi:10.1002/2014EF000254.Received

- 1 Delgado, C.L., Rosegrant, M.W., Steinfeld, H., Ehui, S., Courbois, C., 1999. Livestock to
2 2020: The Next Food Revolution. IFPRI, Washington, DC, USA.
- 3 Eide, A., 2008. The right to food and the impact of liquid biofuels (agrofuels). Food
4 and Agriculture Organization of the United Nations, Rome, Italy.
- 5 Erb, K.-H., Krausmann, F., Lucht, W., Haberl, H., 2009. Embodied HANPP: Mapping
6 the spatial disconnect between global biomass production and consumption.
7 *Ecol. Econ.* 69, 328–334. doi:10.1016/j.ecolecon.2009.06.025
- 8 Fader, M., Gerten, D., Krause, M., Lucht, W., Cramer, W., 2013. Spatial decoupling of
9 agricultural production and consumption: quantifying dependences of countries
10 on food imports due to domestic land and water constraints. *Environ. Res. Lett.*
11 8, 014046. doi:10.1088/1748-9326/8/1/014046
- 12 Fairlie, S., 2010. Meat: A benign extravagance. Permanent Publications, East Meon,
13 Hampshire, UK.
- 14 FAO, 2014. Nutritive Factors. Food and Agriculture Organization of the United
15 Nations, Rome, Italy.
- 16 FAO, 2009. The state of food and agriculture 2009. Food and Agriculture
17 Organization of the United Nations, Rome, Italy.
- 18 FAOSTAT, 2014a. Resources/Land (2014-04-15). Food and Agriculture Organization
19 of the United Nations, Rome, Italy.
- 20 FAOSTAT, 2014b. Commodity Balances/Crops Primary Equivalent (2014-06-04).
21 Food and Agriculture Organization of the United Nations, Rome, Italy.
- 22 FAOSTAT, 2014c. Commodity Balances/Livestock and Fish Primary Equivalent
23 (2014-06-04). Food and Agriculture Organization of the United Nations, Rome,
24 Italy.
- 25 FAOSTAT, 2014d. Population/Annual time series (2014-02-05). Food and
26 Agriculture Organization of the United Nations, Rome, Italy.
- 27 FAOSTAT, 2014e. Production/Livestock Primary (2014-02-10). Food and
28 Agriculture Organization of the United Nations, Rome, Italy.
- 29 FAOSTAT, 2013. Production/Crops (2014-02-06). Food and Agriculture
30 Organization of the United Nations, Rome, Italy.
- 31 FAOSTAT, 2003. Notes to the FAO World Agriculture Trade Matrix Data. Food and
32 Agriculture Organization of the United Nations, Rome, Italy.

- 1 Fischer, R.A., Edmeades, G.O., 2010. Breeding and Cereal Yield Progress. *Crop Sci.* 50,
2 S-85-S-98. doi:10.2135/cropsci2009.10.0564
- 3 Foley, J. a, Ramankutty, N., Brauman, K. a, Cassidy, E.S., Gerber, J.S., Johnston, M.,
4 Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M.,
5 Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J.,
6 Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet.
7 *Nature* 478, 337-42. doi:10.1038/nature10452
- 8 Gerland, P., Raftery, A.E., ev ikova, H., Li, N., Gu, D., Spoorenberg, T., Alkema, L.,
9 Fosdick, B.K., Chunn, J., Lalic, N., Bay, G., Buettner, T., Heilig, G.K., Wilmoth, J.,
10 2014. World population stabilization unlikely this century. *Science* (80-.).
11 doi:10.1126/science.1257469
- 12 Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty,
13 J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of
14 feeding 9 billion people. *Science* 327, 812-8. doi:10.1126/science.1185383
- 15 Haberl, H., Sprinz, D., Bonazountas, M., Cocco, P., Desaubies, Y., Henze, M., Hertel, O.,
16 Johnson, R.K., Kastrop, U., Laconte, P., Lange, E., Novak, P., Paavola, J., Reenberg,
17 A., van den Hove, S., Vermeire, T., Wadhams, P., Searchinger, T., 2012. Correcting
18 a fundamental error in greenhouse gas accounting related to bioenergy. *Energy*
19 *Policy* 45-222, 18-23. doi:10.1016/j.enpol.2012.02.051
- 20 Herrero, M., Havlík, P., Valin, H., Notenbaert, A., Rufino, M.C., Thornton, P.K.,
21 Blümmel, M., Weiss, F., Grace, D., Obersteiner, M., 2013. Biomass use,
22 production, feed efficiencies, and greenhouse gas emissions from global
23 livestock systems. *Proc. Natl. Acad. Sci. U. S. A.* 110, 20888-93.
24 doi:10.1073/pnas.1308149110
- 25 Hoff, H., 2011. Understanding the Nexus. Background Paper for the Bonn2011
26 Conference: The Water, Energy and Food Security Nexus., Stockholm
27 Environment Institute. Stockholm Environment Institute, Stockholm, Sweden.
- 28 Houghton, R. a., House, J.I., Pongratz, J., van der Werf, G.R., DeFries, R.S., Hansen, M.C.,
29 Le Quéré, C., Ramankutty, N., 2012. Carbon emissions from land use and land-
30 cover change. *Biogeosciences* 9, 5125-5142. doi:10.5194/bg-9-5125-2012
- 31 Johnson, J.A., Runge, C.F., Senauer, B., Foley, J., Polasky, S., 2014. Global agriculture
32 and carbon trade-offs. *Proc. Natl. Acad. Sci. U. S. A.* 2014.
33 doi:10.1073/pnas.1412835111
- 34 Kastner, T., Erb, K.-H., Haberl, H., 2014. Rapid growth in agricultural trade: effects on
35 global area efficiency and the role of management. *Environ. Res. Lett.* 9, 034015.
36 doi:10.1088/1748-9326/9/3/034015

- 1 Kastner, T., Rivas, M.J.I., Koch, W., Nonhebel, S., 2012. Global changes in diets and the
2 consequences for land requirements for food. *Proc. Natl. Acad. Sci. U. S. A.* 109,
3 6868–6872. doi:10.1073/pnas.1117054109
- 4 Kearney, J., 2010. Food consumption trends and drivers. *Philos. Trans. R. Soc. Lond.*
5 *B. Biol. Sci.* 365, 2793–807. doi:10.1098/rstb.2010.0149
- 6 Keyzer, M. a., Merbis, M.D., Pavel, I.F.P.W., van Wesenbeeck, C.F. a., 2005. Diet shifts
7 towards meat and the effects on cereal use: can we feed the animals in 2030?
8 *Ecol. Econ.* 55, 187–202. doi:10.1016/j.ecolecon.2004.12.002
- 9 Kummu, M., de Moel, H., Porkka, M., Siebert, S., Varis, O., Ward, P.J., 2012. Lost food,
10 wasted resources: Global food supply chain losses and their impacts on
11 freshwater, cropland, and fertiliser use. *Sci. Total Environ.* 438, 477–489.
12 doi:10.1016/j.scitotenv.2012.08.092
- 13 Lambin, E.F., Meyfroidt, P., 2011. Global land use change , economic globalization ,
14 and the looming land scarcity. *Proc. Natl. Acad. Sci. U. S. A.* 108, 3465–3472.
15 doi:10.1073/pnas.1100480108
- 16 Le Quéré, C., Raupach, M.R., Canadell, J.G., Marland et al., G., Le Quéré et al., C.,
17 Marland, G., Bopp, L., Ciais, P., Conway, T.J., Doney, S.C., Feely, R. a., Foster, P.,
18 Friedlingstein, P., Gurney, K., Houghton, R. a., House, J.I., Huntingford, C., Levy,
19 P.E., Lomas, M.R., Majkut, J., Metzl, N., Ometto, J.P., Peters, G.P., Prentice, I.C.,
20 Randerson, J.T., Running, S.W., Sarmiento, J.L., Schuster, U., Sitch, S., Takahashi,
21 T., Viovy, N., van der Werf, G.R., Woodward, F.I., 2009. Trends in the sources and
22 sinks of carbon dioxide. *Nat. Geosci.* 2, 831–836. doi:10.1038/ngeo689
- 23 Little, S., 2014. Feed Conversion Efficiency: A key measure of feeding system
24 performance on your farm. Dairy Australia, Victoria, Australia.
- 25 Meyfroidt, P., Lambin, E.F., Erb, K.-H., Hertel, T.W., 2013. Globalization of land use:
26 distant drivers of land change and geographic displacement of land use. *Curr.*
27 *Opin. Environ. Sustain.* 5, 438–444. doi:10.1016/j.cosust.2013.04.003
- 28 Mitchell, D., 2008. A Note on Rising Food Prices. The World Bank, Washington, DC,
29 USA.
- 30 Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J. a, 2012.
31 Closing yield gaps through nutrient and water management. *Nature* 490, 254–7.
32 doi:10.1038/nature11420
- 33 Popkin, B.M., 2006. Technology, transport, globalization and the nutrition transition
34 food policy. *Food Policy* 31, 554–569. doi:10.1016/j.foodpol.2006.02.008

- 1 Porkka, M., Kummu, M., Siebert, S., Varis, O., 2013. From food insufficiency towards
2 trade dependency: A historical analysis of global food availability. PLoS One 8.
3 doi:10.1371/journal.pone.0082714
- 4 R Core Team, 2014. R: A language and environment for statistical computing. R
5 Foundation for Statistical Computing, Vienna, Austria.
- 6 Rathmann, R., Szklo, A., Schaeffer, R., 2010. Land use competition for production of
7 food and liquid biofuels: An analysis of the arguments in the current debate.
8 Renew. Energy 35, 14–22. doi:10.1016/j.renene.2009.02.025
- 9 Ray, D.K., Ramankutty, N., Mueller, N.D., West, P.C., Foley, J. a, 2012. Recent patterns
10 of crop yield growth and stagnation. Nat. Commun. 3, 1293.
11 doi:10.1038/ncomms2296
- 12 SAC Consulting, 2013. Farm Management Handbook 2013/14. SAC Consulting, Rural
13 Business Unit, Bush Estate, Penicuik, UK.
- 14 Schröter, D., Cramer, W., Leemans, R., Prentice, I.C., Araújo, M.B., Arnell, N.W.,
15 Bondeau, A., Bugmann, H., Carter, T.R., Gracia, C. a, de la Vega-Leinert, A.C.,
16 Erhard, M., Ewert, F., Glendining, M., House, J.I., Kankaanpää, S., Klein, R.J.T.,
17 Lavorel, S., Lindner, M., Metzger, M.J., Meyer, J., Mitchell, T.D., Reginster, I.,
18 Rounsevell, M., Sabaté, S., Sitch, S., Smith, B., Smith, J., Smith, P., Sykes, M.T.,
19 Thonicke, K., Thuiller, W., Tuck, G., Zaehle, S., Zierl, B., 2005. Ecosystem service
20 supply and vulnerability to global change in Europe. Science 310, 1333–7.
21 doi:10.1126/science.1115233
- 22 Searchinger, T., Heimlich, R., Houghton, R. a, Dong, F., Elobeid, A., Fabiosa, J., Tokgoz,
23 S., Hayes, D., Yu, T.-H., 2008. Use of U.S. croplands for biofuels increases
24 greenhouse gases through emissions from land-use change. Science 319, 1238–
25 40. doi:10.1126/science.1151861
- 26 Slade, R., Saunders, R., Gross, R., Bauen, A., 2011. Energy from biomass : the size of
27 the global resource. Imp. Coll. Cent. Energy Policy Technol. UK Energy Res. Cent.
- 28 Smil, V., 2002. Worldwide transformation of diets, burdens of meat production and
29 opportunities for novel food proteins. Enzyme Microb. Technol. 30, 305–311.
30 doi:10.1016/S0141-0229(01)00504-X
- 31 Smith, P., Haberl, H., Popp, A., Erb, K.-H., Lauk, C., Harper, R., Tubiello, F.N., de
32 Siqueira Pinto, A., Jafari, M., Sohi, S., Masera, O., Böttcher, H., Berndes, G.,
33 Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E. a, Mbow, C.,
34 Ravindranath, N.H., Rice, C.W., Robledo Abad, C., Romanovskaya, A., Sperling, F.,
35 Herrero, M., House, J.I., Rose, S., 2013. How much land-based greenhouse gas
36 mitigation can be achieved without compromising food security and
37 environmental goals? Glob. Chang. Biol. 19, 2285–302. doi:10.1111/gcb.12160

- 1 South, A., 2011. rworldmap : A New R package for Mapping Global Data. R J. 3, 35–43.
- 2 Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the
3 sustainable intensification of agriculture. Proc. Natl. Acad. Sci. U. S. A. 108,
4 20260–4. doi:10.1073/pnas.1116437108
- 5 Tilman, D., Clark, M., 2014. Global diets link environmental sustainability and human
6 health. Nature. doi:10.1038/nature13959
- 7 Wang, Y., Beydoun, M., 2009. Meat consumption is associated with obesity and
8 central obesity among US adults. Int. J. Obes. 33, 621–628.
9 doi:10.1038/ijo.2009.45.Meat
- 10 Weinzettel, J., Hertwich, E.G., Peters, G.P., Steen-Olsen, K., Galli, A., 2013. Affluence
11 drives the global displacement of land use. Glob. Environ. Chang. 23, 433–438.
12 doi:10.1016/j.gloenvcha.2012.12.010
- 13 West, P.C., Gerber, J.S., Engstrom, P.M., Mueller, N.D., Brauman, K. a., Carlson, K.M.,
14 Cassidy, E.S., Johnston, M., MacDonald, G.K., Ray, D.K., Siebert, S., 2014. Leverage
15 points for improving global food security and the environment. Science (80-.).
16 345, 325–328. doi:10.1126/science.1246067
- 17 Wirsenius, S., Azar, C., Berndes, G., 2010. How much land is needed for global food
18 production under scenarios of dietary changes and livestock productivity
19 increases in 2030? Agric. Syst. 103, 621–638. doi:10.1016/j.agry.2010.07.005
- 20 World Bank, 2014. List of economies. World Bank, Washington, DC, USA.
- 21 Yu, Y., Feng, K., Hubacek, K., 2013. Tele-connecting local consumption to global land
22 use. Glob. Environ. Chang. 23, 1178–1186. doi:10.1016/j.gloenvcha.2013.04.006
- 23

1 **Supplementary Information**

2 **S1 SI Materials and Method**

3 **S1.1 Crop consumption types**

4 *Table S1. Commodities with non food or feed consumption > 20 Mt globally in 2011.*

Item	Quantity (Mt)	Percentage of total supply (%)	Assumed use
Sugar cane	295.7	34.0	Bioenergy
Maize and products	186.3	24.1	Bioenergy
Cassava and products	31.3	22.6	Bioenergy
Palm Oil	28.7	66.8	Bioenergy
Cotton lint	25.7	100	Materials
Rice (Paddy Equivalent)	25.0	4.9	Bioenergy
Wheat and products	21.3	4.1	Bioenergy
Soya beans	20.6	9.1	Bioenergy

5
6

1 S1.1 Animal product index

2 Table S2. Feed conversion ratio for animal product categories.

Animal product type	Conversion ratio by mass (kg feed/kg product)	Conversion ratio by energy ^c (MJ feed/MJ product)
Bovine meat	25 ^{a1}	48
Eggs	2 ²	4
Milk	0.6 ^{b3}	4
Pig meat	9 ^{a1}	12
Poultry meat	4.5 ^{a1}	10
Sheep and goat meat	12 ^a	22
Other meat	12	22

Notes:
a: Accounts for only 25-55% of animal being edible, dependent on the species.
b. Assuming 4% milk solids.
c. Using nutritive factors (FAO, 2014) to convert from mass feed conversion ratio, and feed moisture contents (SAC Consulting, 2013).

Sources:
1: (Smil, 2002)
2: (FAO, 2009)
3: (Little, 2014)

3

4 S1.4 Technical implementation

5 The analysis was primarily conducted in R (R Core Team, 2014). The R code used for
6 the analysis and generation of figures can be found in the data repository
7 <https://bitbucket.org/alexanpe/landalloc>, with the input data available as specified
8 in the main text, but principally from FAOSTAT.

9

10 S1.5 Data issues and validation

11 S1.5.1 Harvested area bias

12 Harvested areas are used for crop commodities. As a result, in systems with multiple
13 harvests per year, the total land area used will be overstated, while where fallow
14 periods are part of the crop rotations the land areas will be understated. The
15 harvested area has been found to increase more rapidly than the actual crop area
16 (Foley et al., 2011), and therefore the net impact is likely to be an overstatement of
17 the change in crop areas. Such a bias therefore will tend to understate the true
18 proportion of land for animal products, relative to vegetal crop for human
19 consumption, but it will have a limited impact on the balance of decomposition into
20 diet, population and yield drivers.

21

S1.5.2 Country coverage and issues

Prior to 2010 the country of former Sudan is used in all FAO datasets. The data for 2011 has a mixed situation with consumption data still based on former Sudan, but country resource data split into Sudan and South Sudan. To resolve this, the consumption data has been disaggregated based on the population ratio of the newer countries. All data for the USSR years before 1992 is disaggregated into its 15 states based on the 1992 population. Similarly, data for Ethiopia PDR pre-1993 is associated with the states of Ethiopia and Eritrea, based on the 1993 population.

No commodity usage data are available for the Democratic Republic of the Congo, Greenland, Oman or Papua New Guinea. Therefore the analysis does not include these countries. In total 197 countries have been included.

S1.5.3 Production and consumption data

The equality between quantity of consumption and production was checked for all commodities. Overall, there was a small discrepancy, with less consumption than production across all years, for example 2.9% in 2011. These may be due to losses not included in the waste category. There are some individual crops, which appear more anomalous, for example apples, which are consistently consumed more than they are produced, e.g. by 5.0% in 2011 and 3.6% over the 50 year period. Also, there are some issues that are likely to have arisen due to the mapping of production crops to consumption categories. Most extreme of these is the “other pulses” category, which in 2011 had 34.0 M tonnes consumed but only 24.1 M tonnes produced, a shortfall of 29%. On the other side “other fruit” has 185 M tonnes consumed (including waste), but 299 M tonnes produced, suggesting that there is 38% which has not been accounted for. The absolute size of these issues is not particularly significant however, with 1.5% of missing production and 2.9% that is produced but not consumed, with most of the major crops having been mapped with close agreement. To attempt to correct for these discrepancies the supply quantity were used to allocated areas, rather than production quantity, adjusting the effective yields.

Stock variation was not accounted for in the analysis. This is an inter-annual impact, and as such only causes inter-annual impact on the results. The percentage of supply/production used for stock variation is relatively small (annual net stock variation is typical 0.5 to 1% of total supply), and is likely to have little net effect. The consumption and production described above does not primarily arise to due stock variation, as for impacted crops the discrepancy is typically in the relatively constant, and in the same direction, e.g. indicating fractionally more production and consumption for all years.

S1.5.4 Import and export data

Comparisons were undertaken, for each commodity and year, of the total imports and exports globally (FAOSTAT, 2014b, 2014c). For many products and years there were less global imports than exports, with overall difference of approximately 2-

1 3%, due to losses in transport and other reporting issues (FAOSTAT, 2003). These
2 losses were accounted for by adjusting the imported areas, based on the factor of
3 export/imports quantities.
4

5 ***S1.5.5 Production to consumption mapping***

6 Examining crop production data to ensure all areas have been mapped to
7 consumption shows that in 2011 only 4 categories had not been mapped, with either
8 production over 1 million tonnes or using over 1Mha of land globally. These are
9 seed cotton, coir, rubber and tobacco. In total these account for 50 Mha, or 1% of the
10 4910 Mha of agricultural land.
11

12 A check on the consumption that has not been mapped to production highlights the
13 results in categories for beer, beverages fermented, brans, cheese, meat offal and
14 fish. These are all produced from the processing of commodities that have been
15 mapped, e.g. cheese from milk and beer from cereals; or categories that do not
16 require land use, i.e. fish; or by-products e.g. bran and offal.
17

18 ***S1.5.6 By-products***

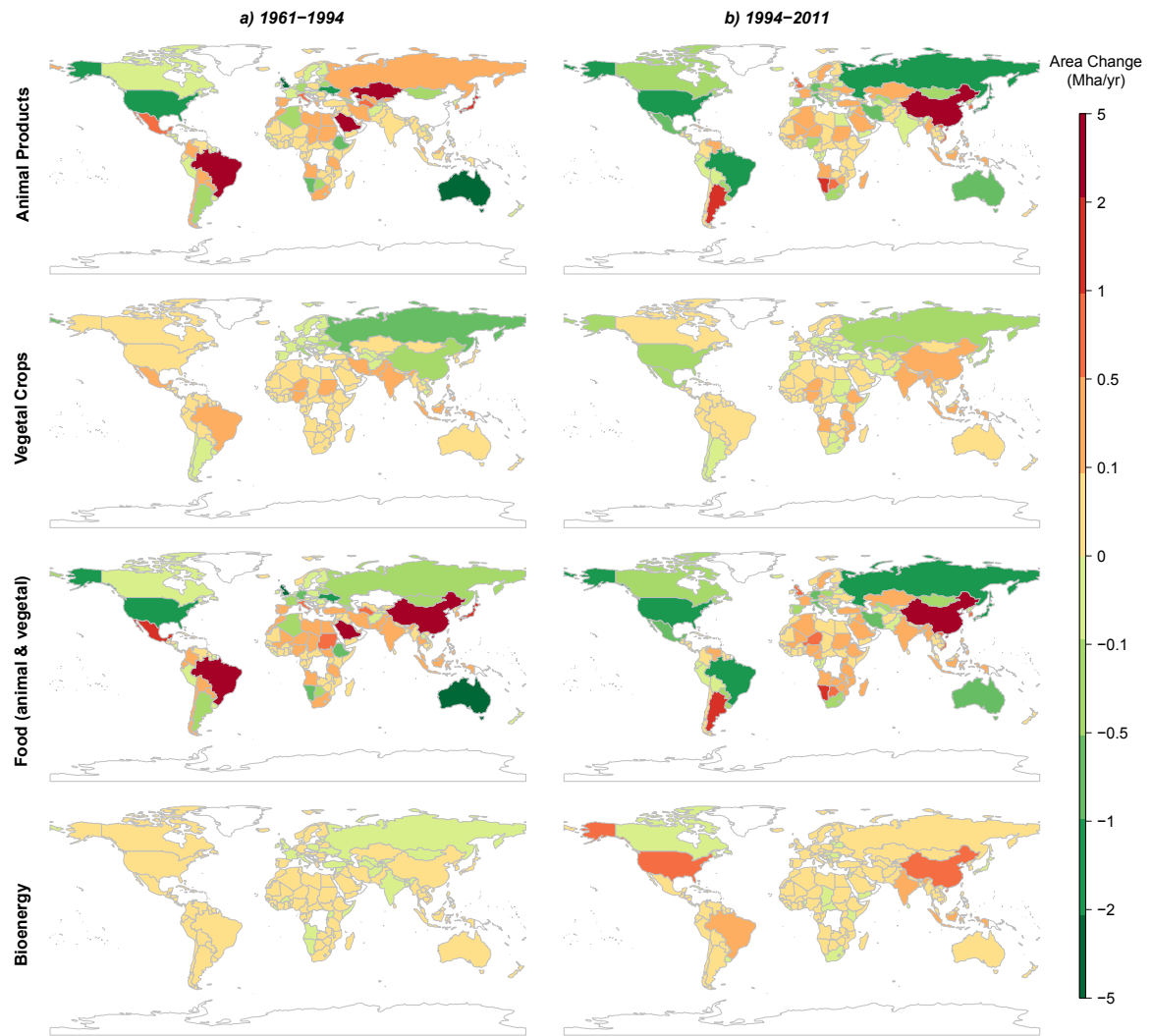
19 However, some cotton seed (comprising ~2/3 of the seed cotton), is used for oil for
20 human consumption and animal feed, this is considered a by-product, and as such
21 not accounted for in the analysis. Other by-products, such as whey from cheese
22 making, and used for animal feed, are similarly not allocated to feed.
23 Consequentially, there will be some overstatement of food allocations and a
24 corresponding understatement for feed.
25

26 ***S1.5.7 Validation overall***

27 There are some inconsistencies within and between the FAO datasets used.
28 However these are relatively small, and steps have been take (as detailed in sections
29 S1.7.2-4) to reduce the impact they have on the overall results.
30

1

S2 SI Results

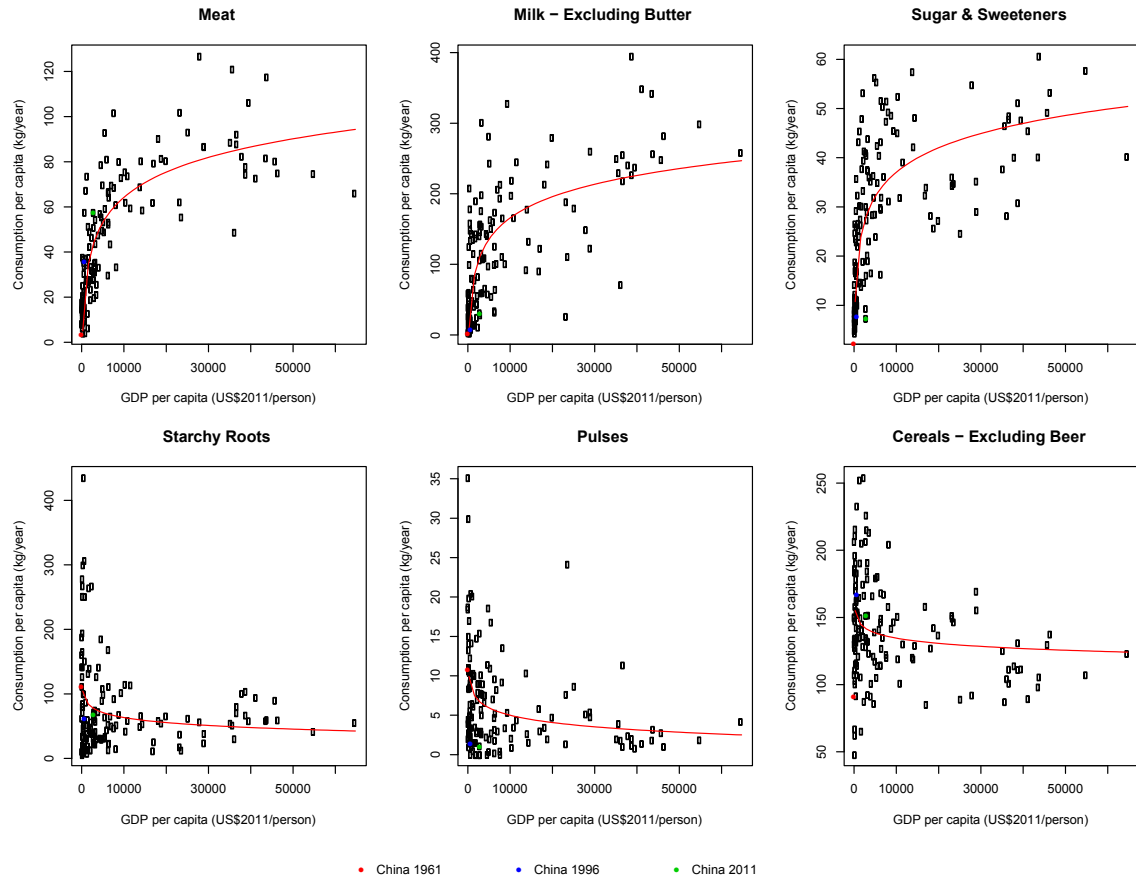


2

3

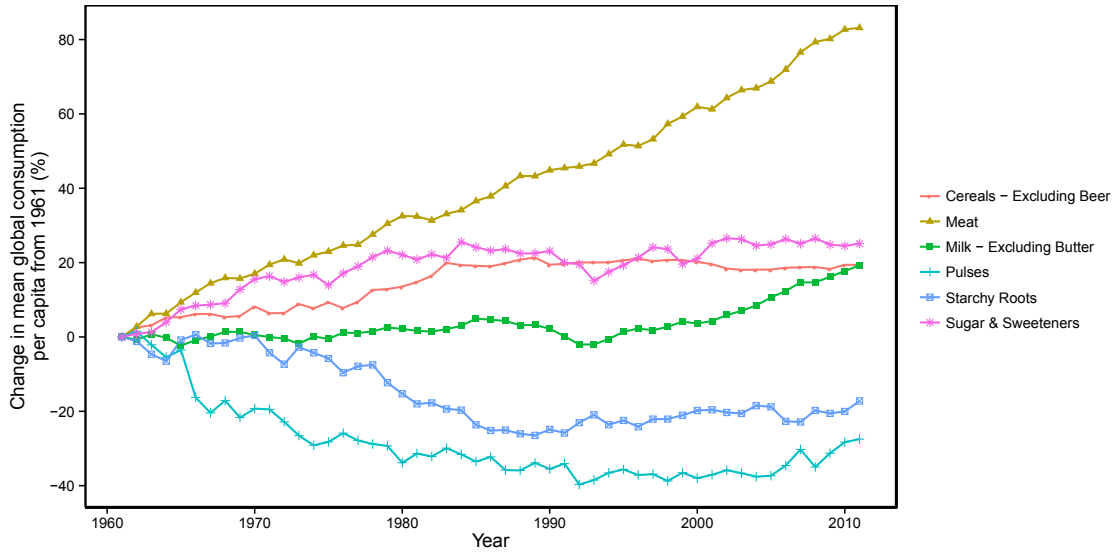
4 *Figure S1. Mean annual change in area (Mha/year) used for animal product and*
5 *vegetal crops for human consumption, and bioenergy feedstock production; a) from*
6 *1961 to 1994, and b) from 1994 to 2011.*

7

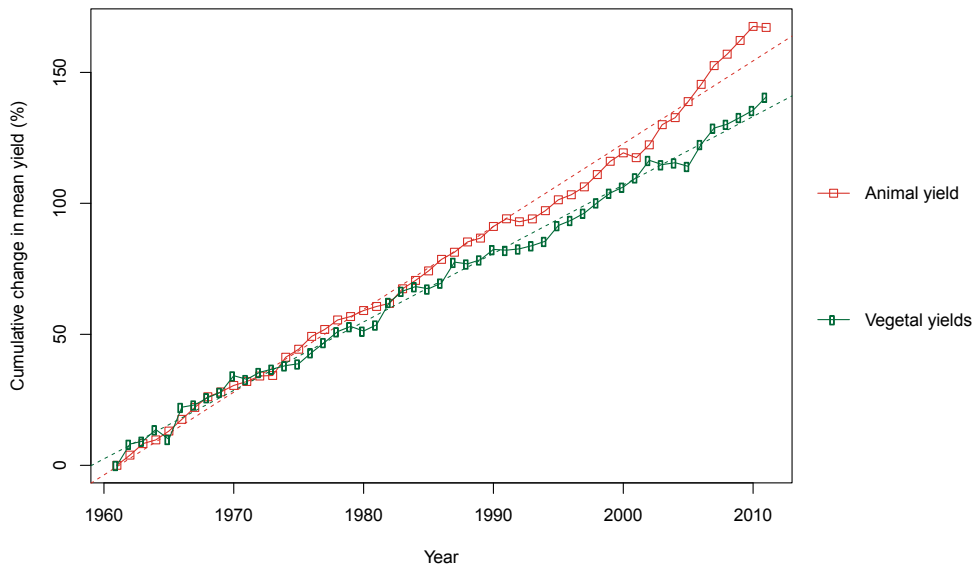


1
2 *Figure S2. Country consumption per capita against the GDP per capita for selected*
3 *aggregate food commodity groups in 2011, showing logarithmic curves fitted. The*
4 *point for China in 2011 is identified, and additional 1961 and 1996 points for China are*
5 *overlaid.*

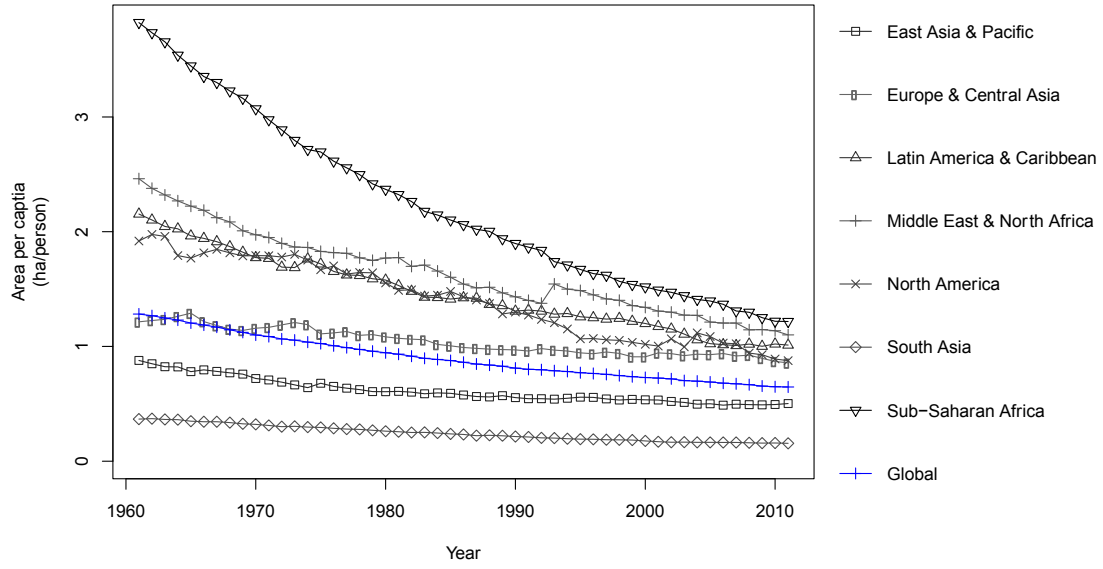
6



1
 2 *Figure S3. Percentage cumulative change in mass of global average per capita*
 3 *consumption for selected aggregate food commodity groups from 1961 baseline.*
 4



5
 6 *Figure S4. Global average yield change since 1961, expressed as a percentage change*
 7 *in the mass of the crop, and the animal product index, produced per hectare. The*
 8 *dashed line shows the best-fit linear regression for each series.*
 9



1
 2 *Figure S5. Total food production area per capita by region from 1961 to 2011, using*
 3 *World Bank (2014) regions.*
 4
 5

1 *Table S3. Decomposition of land use change area in Mha into consumption, yield and*
 2 *population for animal products and vegetal crops, from 1961 to 1994. Countries with*
 3 *any absolute value >40 Mha are separately listed. The largest positive and negative*
 4 *drivers for each location are highlighted.*

Country	Consumption of animal products	Consumption of vegetal crops	Yield of animal products	Yield of vegetal crops	Population on animal product area	Population on vegetal crop area	Total
Algeria	12	1	-54	-4	35	3	-6
Angola	26	0	-64	0	44	1	7
Argentina	-20	-1	-39	-3	44	2	-17
Australia	-33	0	-222	-1	147	1	-108
Brazil	92	0	-139	-5	118	12	78
China	729	52	-769	-121	207	60	159
India	3	-3	-15	-82	14	95	12
Iran (Islamic Republic of)	12	4	-52	-5	47	7	13
Kazakhstan	17	-1	128	2	19	2	168
Mexico	47	1	-91	-6	73	8	32
Mongolia	-58	0	-52	0	100	0	-10
Russian Federation	56	-9	-102	-21	50	10	-15
Saudi Arabia	112	0	-204	0	182	1	91
South Africa	-13	0	-55	-4	73	4	5
Sudan	-8	0	-62	3	81	4	18
Ukraine	8	-1	-61	-11	9	3	-52
United Kingdom	-9	1	-76	-4	5	0	-83
United States of America	30	7	-195	-13	106	8	-58
Rest of the world	35	18	-678	-137	808	174	219
Total	1036	71	-2802	-412	2163	397	452

5
6
7

1 *Table S4. Decomposition of land use change area in Mha into consumption, yield and*
 2 *population for animal products and vegetal crops, from 1994 to 2011. Countries with*
 3 *any absolute value >20 Mha are separately listed. The largest positive and negative*
 4 *drivers for each location are highlighted.*

Country	Consumption of animal products	Consumption of vegetal crops	Yield of animal products	Yield of vegetal crops	Population on animal product area	Population on vegetal crop area	Total
Angola	29	1	-56	-1	31	1	6
Australia	-6	0	-62	0	51	1	-16
Brazil	56	6	-115	-10	39	5	-20
Chad	-2	0	-24	-1	26	1	1
China	267	24	-263	-31	50	11	58
India	1	2	-7	-33	5	39	7
Iran (Islamic Republic of)	7	0	-29	-3	11	2	-12
Japan	1	0	-26	-2	1	0	-25
Kazakhstan	40	-2	-40	-1	4	0	2
Mali	16	0	-30	0	17	2	5
Mauritania	9	0	-28	0	19	0	0
Mexico	13	-1	-46	-4	24	3	-11
Mongolia	-23	0	-3	0	21	0	-6
Mozambique	18	1	-38	-1	21	2	3
Nigeria	3	1	-25	-9	19	12	2
Saudi Arabia	86	0	-156	0	75	1	6
South Africa	10	0	-35	-2	22	1	-3
Sudan	14	-1	-52	-3	43	4	4
Turkmenistan	20	0	-27	0	7	0	0
United States of America	-22	0	-52	-6	47	5	-29
Yemen	9	0	-20	0	11	1	1
Rest of the world	60	39	-306	-81	310	83	105
Total	607	70	-1438	-188	852	174	78

5