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SUPPLEMENTARY INFORMATION

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Importance of food-demand management for climate mitigation

Bojana BAJŽELJ[*], Keith S. RICHARDS, Julian M. ALLWOOD, Pete SMITH, John S. DENNIS, Elizabeth CURMI and Christopher A. GILLIGAN

Supplementary information

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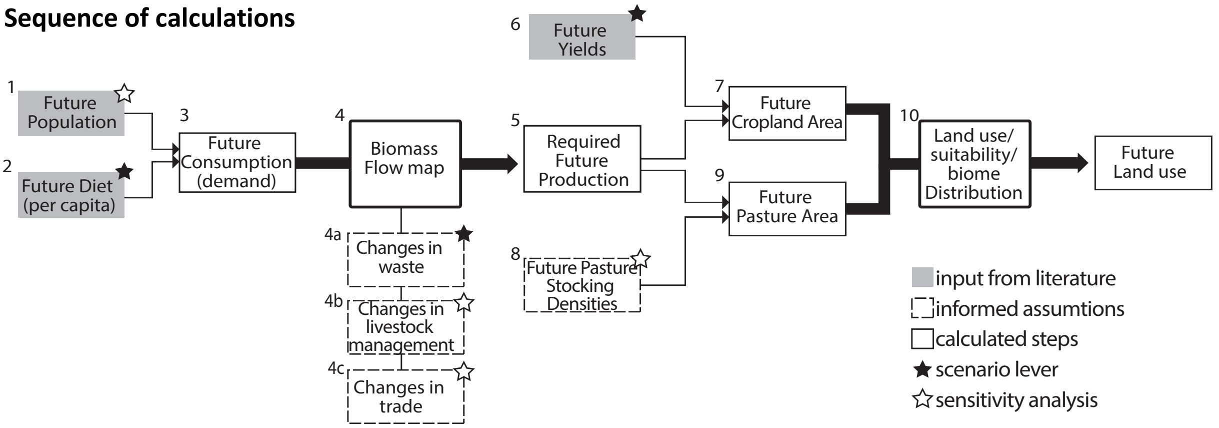
1. Supplementary Methods

We use a data driven method to estimate the future land use based on future population, yields and diets. Calculations for future scenarios are described in steps 1 – 10 as shown on Suppl. Figure 1. Steps 4 (yearly biomass flows) and 10 (land use distribution over suitability classes and global biomes) are key to our method and required significant preparation and parameterisation with current data. The model is constructed with a series of spreadsheets and pre-prepared GIS processing.



Supplementary Figure 1 – A diagram showing how future land-use is calculated based on the changes in demand, and other explicit changes to the land-use system.

1 – Future population. The most recent UN middle projection[1] for population in 2050 (9.6 billion people), by regions, was used for the baseline 2050 scenarios, and UN high and low estimates in the sensitivity analysis.

2 – Future diets. We used two different sets of future diets. The ‘trending’ diets are based on dietary preferences of increasingly affluent and urbanised populations, as predicted by FAO[2], by region and commodity. These underline scenarios CT1, CT2, YG1 and YG2. Scenarios CT3 and YG3 use instead ‘Healthy diets’, where consumption of some foods (sugars, fats and livestock products) are capped at healthy levels[3–5]. (See Suppl. Tables 2-4 for details)

3 – Future consumption. For each commodity in a region, future consumption was calculated as product of the *per capita* dietary preferences and regional population.

4 - Agricultural biomass flows. These were constructed in the manner of a material flow analysis, so that they always add up to the total vegetation growth on cropland and pasture, measured as Net Primary Productivity, in grams of organic Carbon (gC). This is similar to Human Appropriation of Net Primary Productivity (HANPP) analyses[6,7], however HANPP analyses focus on the total NPP diverted away from nature, while here the focus is on the services delivered and their delivery efficiency.

Biomass flows connect 21 distinct crop groups (17 food crop categories, one fibre crop category, one forage category, one for fallow land and one for grass on pasture) to 24 commodities (17 plant food commodities, 5 livestock food commodities, fibre and fuel), and other ‘sinks’, such as soil organic carbon. When calculations are made for future scenarios, the sequence is reversed: the demand for food commodities is the input, from which the crop and grass production are calculated. The map of flows is shown in Supplementary Figure 3, and the parameters are summarised in Supplementary Data 1 (separate spreadsheet file).

The biomass flow map was first parameterised with 2009 data, which was used as a baseline for calculating future production from future consumption demand. Many data points for 2009 were sourced from FAOSTAT statistics[8]. However, we used numerous other sources to fill the gaps in our biomass flow map that FAOSTAT data currently do not cover, namely:

I. the production quantities of agricultural residues and their uses[9–11]

II. losses of crop biomass before harvest[12]; some of the losses along the food supply chain[13]; food losses at retail and consumer level[13]; and

III. animal feed statistics (other than grain feeds and processing co-products, which are covered by FAOSTAT), including pasture productivity and forage crop production[9]. A simple linear system was constructed to calculate the efficiency and feed-mix for each of the 6 livestock commodity categories (explained under the "Agricultural biomass flows" heading below).

The current biomass flow map served as a template for future flows, and a reminder of current inefficiencies in the system. However we can expect some of its characteristics will change in the future. We represented three sets of such changes:

4a – Changes in waste. We tested two options regarding waste flows within the system (consumer and retail waste, processing losses, and agricultural losses). Historically as regions have evolved economically, waste has shifted towards the consumer end of the chain, but remained in about same total proportions. Therefore in the baseline option (CT1 and YG1 scenarios) waste levels remain the same. In the second, waste levels are reduced by 50%. Halving of food and agricultural waste is seen as possible and indeed, desirable, by some experts[14,15].

4b – Changes in livestock management. We assumed that livestock management in most regions will intensify and shift towards more cropland-grown feed, such as soya cake, grains and concentrates. These trends are widely documented[16,17]. They are captured in the study by Tilman[18], which implies that as countries become richer they eat more livestock products, and those livestock products are increasingly rely on cropland-based feed. We also assume livestock production efficiency measured in carbon flows will improve (partially as a result of more easily digestible, cropland-based feeds). These changes are outlined in Supplementary Tables 4 and 5. As a sensitivity test we used an alternative assumption that livestock feed sources and efficiencies remain the same – which results in much larger GHG emissions due to large increases in pasture needed. A recent study by Havlik et al.[19] provides a richer investigation of consequences of different livestock production system transitions or the lack of them.

4c – Changes in Trade. Trade is exogenous in our approach and as a baseline we assume it will remain at 2009 levels. We increased it in sensitivity analysis. However the model results are not very sensitive to assumption about trade.

5- Future production – This is therefore a result of predicted future consumption and changes in the agricultural biomass flows outlined above.

6 – Future yields. Future yields are key parameters for our scenarios. The Current Trends (CT) scenarios assume yields in each region will continue to increase linearly at current rates, which are taken from a recent global yield study[20]. The Yield Gap (YG) scenarios assume that sustainable intensification will achieve yield gap closures in all regions, achieving the current near-optimum for their agro-ecological zone. Yield gaps for each region and crop are taken from the GAEZ study[21].

7 – Future cropland area. Future cropland area is a result of future yields and production. We assume all predicted food demand will be met in each region.

8 – Future stocking densities on pasture These densities are the equivalents of yields on cropland. They determine how much grass biomass livestock can (sustainably) remove from pasture. Unfortunately they are much less well-researched, and there are no statistics collected that can be used to estimate this on global levels. We compared results from a global dynamic vegetation model[22], a previous livestock energy model[9], and livestock products statistics[8], to determine that in some regions, densities can be increased by 12-90% (see Supplementary Table 9 for more details). The pastures in West Europe are an exception, as apparent stocking densities on improved pastures (in W Europe many pastures are improved by fertilisation and active management) already exceed natural productivity potentials. We also do not allow an increase in densities in North America. If the demand for grass biomass increases, we assume that, if possible, future stocking densities will increase first. If the demand for grass biomass is larger than what current pasture at increased stocking density can provide, pasture area expands. The potentials for grass biomass increases are an important assumption, and therefore also the subject of a sensitivity analysis.

9 – Future pasture area is a result of future demand for grazing and assumed future stocking densities. Because of many unknowns (about stocking densities as well as livestock management systems), pasture areas are highly uncertain.

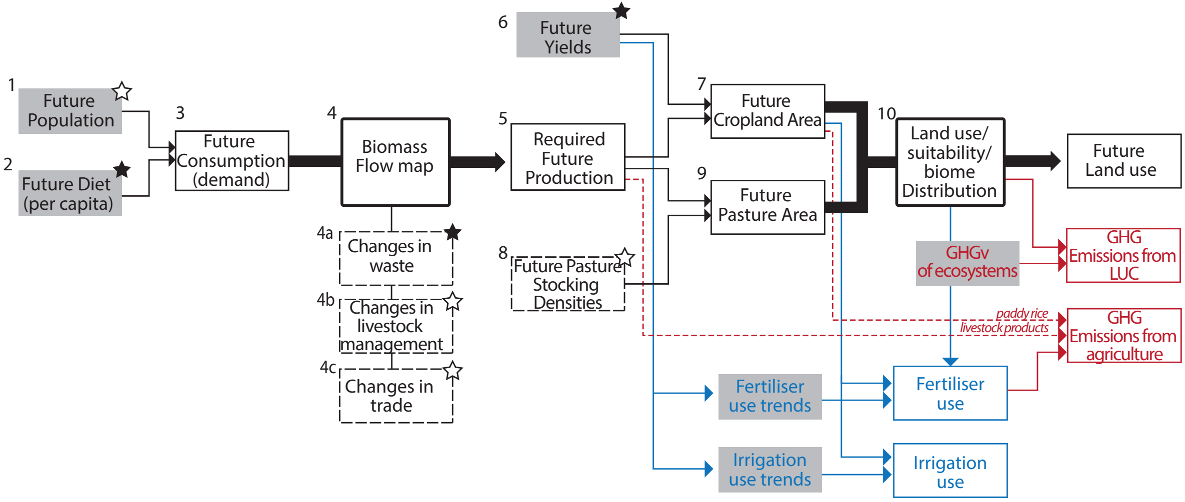
10 - Land-use distribution over suitability classes and global biomes. The location of future cropland and pasture expansions (or retractions) are based on land suitability analysis. Future losses of natural vegetation and GHG emissions are based on the distribution of these changes in land use over current land use and global biomes. In order to allocate future land use, we therefore characterised each unit of land according to three parameters: current land-use, agricultural suitability and biome, by overlaying these three layers in GIS.

Current land-use was derived from several sources. Cropland and pasture are from an expert-reviewed dataset based on several satellite-based maps [23]. Areas occupied by settlements were based on the urban use dataset[24]. Global spatially-explicit forestry data were derived from a survey of management regimes on a country basis[25] to distinguish between (i) plantations, (ii) pristine forests, and (iii) harvested semi-natural forest, treating the remaining (after urban and agricultural land use) natural forest biomes[26] as a background.

Data for agricultural suitability were sourced from the Global Agro-Ecosystem zones data[21]. We aggregated them for all crops together (choosing maximum suitability between all crops for each cell) for baseline climatic conditions, and re-categorised the dataset into 5 classes depending on suitability and necessity of nutrient inputs. See Supplementary Table 10 for more detail.

Global biomes were adapted from the global potential natural vegetation dataset[26]. Mixed forests were split between boreal and temperate forest based on climatic data[21].

Beyond land use: calculations of fertiliser use, irrigation use and GHG emissions



Supplementary Figure 2 –Showing how calculations of fertiliser use, irrigation use and GHG emissions are estimated from different point in the land use system.

Fertilise use was calculated differently for Current Trend (CT) scenarios and Yield Gap (YG) yield scenarios. For Current trends, fertiliser application per unit of land was linearly extrapolated from the last 10 years' data[27], with exception for some regions where trends have recently changed (E Asia, W Europe, C Asia and S Asia). For yield gap scenarios we assume optimum fertilisation to underpin optimum yields[28]. See Suppl. Figure 5 for more details.

Irrigation use is also different on yield scenarios. For CT scenarios it follows current trends of increasing the proportion of irrigated agriculture within total agriculture (although a continuance of such trends may not be possible due to future water scarcity)[29]. For YG scenarios, water use efficiency is assumed to improve, so that the share of irrigated agriculture remains the same. The total area of irrigated agriculture, and therefore irrigation use, changes together with changes in total area of agriculture. The average use of water per unit area of irrigated agriculture in each region is assumed to remain the same. See Suppl. Figure 6 for more details.

GHG emissions from Land use change (LUC). We used GHG values of ecosystems[30] to calculate emissions and carbon sequestration associated with agriculture and settlement expansion and contraction. See Suppl. Figures 7 and 8, and Suppl. Tables 17-19 for more details.

GHG emissions from agriculture are associated with fertiliser use and production, rice paddy methane emissions, emissions from enteric fermentation and manure management, as well as energy use in mechanised agriculture. Calculations were based on scaling up today's emissions[31–34] linearly with emission sources (therefore no improvements in terms of manure management, paddy rice management, feed additives to reduce enteric fermentation or similar are included; only fertilser production emission intensity is assumed to improve by 20%. This assumption represents a shift from coal to gas nitrogen production in China). See Suppl. Table 20 for calculations of these emissions by source.

Diets: current, trending and healthy

Supplementary Table 1 - Current diets as calculated on the basis of FAO 2009 statistics - Food Balance Sheets[8]. Food Balance Sheets show the supply of commodities, which are reduced here by food waste at consumer and retail stages[13], to show actual consumption. The table shows a large variation in diets between the regions, many of which are well above recommended daily calorie intakes, while others are still slightly below.

	N America	C Asia	E Asia	E Europe	Latin America	North Africa	Oceania	S Asia	SE Asia	W Europe	W Asia	Sub-Saharan Africa
Kcal/ person / day												
Vegetables	58	87	147	64	33	76	55	38	37	58	72	23
Fruits	89	50	60	53	103	103	93	55	87	91	102	68
Sugar & Sweeteners (HFCS)	315	150	68	308	363	262	373	179	147	318	285	139
Vegetable oils	660	235	295	326	305	234	506	243	269	514	425	290
Red meat	207	176	314	180	145	57	247	16	119	260	63	74
Poultry	160	15	50	70	91	30	122	9	35	67	69	33
Eggs	45	17	63	48	31	12	20	8	20	39	24	8
Dairy	344	267	59	313	149	175	289	159	24	391	197	50
Fish*	38	5	56	40	19	19	42	12	60	56	14	19
Wheat products	432	1049	435	729	277	929	432	506	138	543	1000	241
Rice	63	58	606	31	256	143	93	668	1193	45	142	187
Maize	245	39	56	56	388	253	34	53	145	65	98	451
Other grains	25	38	10	95	11	186	12	79	5	35	59	260
Roots	60	101	111	168	108	68	71	51	87	94	66	321
Pulses	43	7	0	0	0	0	0	0	0	0	0	0
Other crops	218	61	142	170	107	72	185	70	137	208	111	124
TOTAL	2964	2350	2416	2611	2369	2600	2534	2136	2443	2727	2713	2268

* not included in our modelling, but shown here for a complete picture of diets.

Supplementary Table 2 - Projected per capita dietary preferences in 2050. There are as calculated based on the projections by a panel of FAO experts[2]. They are predicted to change from the current diets to become more 'western' including more livestock based products and more calorie rich foods, such as sugar and fats. The predicted changes in dietary preferences are related to socio-economic changes, such as increased affluence and urbanisation. These are the basis (together with population increase) for calculating the 2050 food demand in scenarios CT1, CT2, YG1 and YG2.

	N America	C Asia	E Asia	E Europe	Latin America	North Africa	Oceania	S Asia	SE Asia	W Europe	W Asia	Sub-Saharan Africa
Kcal/ person / day												
Vegetables	36	61	112	42	23	59	34	42	26	45	58	18
Fruits	63	41	52	46	89	108	92	70	66	90	91	69
Sugar & Sweeteners (HFCS)	310	262	138	306	450	335	607	302	245	327	336	220
Vegetable oils	649	266	487	334	256	230	489	428	323	533	361	393
Red meat	233	278	491	203	196	91	278	62	186	294	99	115
Poultry	180	23	78	79	123	47	138	35	54	75	109	50
Eggs	56	31	107	59	45	21	25	33	33	48	42	14
Dairy	348	338	90	332	176	204	262	233	37	389	230	55
Fish*	38	5	56	40	19	19	42	12	60	56	14	19
Wheat products	430	1034	419	725	290	916	449	511	92	540	986	293
Rice	73	52	586	28	261	135	102	676	1399	45	130	214
Maize	402	22	88	60	294	250	25	42	130	63	49	548
Other grains	70	17	11	91	30	156	6	57	3	70	32	283
Roots	43	98	73	158	86	67	52	65	125	78	65	253
Pulses	35	2	13	9	150	36	7	67	28	27	41	63
Other crops	61	8	20	8	85	56	23	15	12	58	114	199
TOTAL	3027	2539	2821	2520	2571	2729	2632	2651	2819	2739	2758	2806

* not included in our modelling, but shown here for a complete picture of diets.

Supplementary Table 3 - Healthy diets in 2050. These are based on dietary preferences, but with some foods that are deemed unhealthy above certain levels[3–5], capped, and daily calorie consumption set at 2500 Kcal. The note below the table explain these in more detail.

	Healthy cap	**N America**	**C Asia**	**E Asia**	**E Europe**	**Latin America**	**North Africa**	**Oceania**	**S Asia**	**SE Asia**	**W Europe**	**W Asia**	**Sub-Saharan Africa**
	kcal/ pers /d note	kcal/ person / day											
Vegetables	min 136 [1]	**136**	**136**	**136**	**136**	**136**	**136**	**136**	**136**	**136**	**136**	**136**	**136**
Fruits	min 119 [2]	**119**	**119**	**119**	**119**	**119**	**119**	**119**	**119**	**119**	**119**	**119**	**119**
Sugar & Sweeteners (HFCS)	max 150 [3]	**150**	**150**	82	**150**	82	138	130	119	88	**150**	**150**	135
Vegetable oils	max 360 [4]	**360**	266	**360**	334	256	230	**360**	**360**	323	**360**	**360**	**360**
Red meat	max 57 [5]	**57**	**57**	**57**	**57**	**57**	**57**	**57**	**57**	**57**	**57**	**57**	**57**
Poultry	max 161 [6]	**161**	23	78	79	123	47	138	35	54	75	109	50
Eggs	max 50 [7]	**50**	31	**50**	**50**	45	21	25	33	33	48	42	14
Dairy	max 300 [8]	**300**	**300**	90	**300**	176	204	262	233	37	**300**	230	55
Fish*	constant [9]	38	5	56	40	19	19	42	12	60	56	14	19
Wheat products	Distribution of staple crops is based on cultural preferences, (trending diets).	662	1198	531	836	520	854	865	507	85	762	904	210
Rice		113	61	742	33	468	126	196	670	1302	64	120	153
Maize		50	10	53	60	53	250	5	17	47	63	17	548
Other grains		107	20	14	105	55	146	11	56	3	99	29	203
Roots		67	113	93	182	154	62	100	64	116	110	60	181
Pulses		54	2	13	9	150	36	7	67	28	27	41	63
Other crops		75	9	25	9	87	55	45	15	11	73	111	196
TOTAL	2500 [10]	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
Daily protein intake (g/day)	64 [11]	80	67	64	75	64	80	66	72	64	74	85	78

Specific notes:

[1] Representing at least three portions of vegetables per day. Based on FAO/WHO[4] and Harvard Medical School[3] advice.

[2] Representing at least two portions of fruit per day. Based on FAO/WHO[4] and Harvard Medical School[3] advice.

[3] Recommendation by American Heart Association[5].

[4] Recommendation by American Heart Association[5].

[5] Maximum two 85g portion per week, representing sparing use. Source: Harvard Medical School[3]. The allocation between beef, pork and lamb is determined based on cultural preferences in each region. These recommendations are contested in the literature, as some argue that there are no health considerations associated with lean, unprocessed meat (apart from hormone content associated with intensive production). However fatty and processed meat & dairy products tend to follow those healthier cuts, becoming cheaper and therefore more attractive to the population. We therefore decided it was correct to cap livestock products for public health levels, as suggested by Harvard Medical School.

[6] Maximum of one 85g portion a day. Source: Harvard Medical School[3]. See the discussion on red meat.

[7] Representing 5 eggs a week. Source: Harvard Medical School[3].

[8] Maximum of two 200g portions a day. Based on FAO/WHO[4] and Harvard Medical School[3] advice. The discussion on red meat also applies for dairy.

[9] Due to limitations in global fisheries and the risk of over-fishing, these are kept constant.

[10] Based on recommended levels for an adult man. These are conservative given that women, children and elderly require less; however we felt some buffer was necessary, given the variation in population and between years.

[11] If necessary, meat was swapped with pulses as the source of protein, to achieve the minimum of 60g of protein daily intake (however in most regions, baseline diet already provided sufficient protein even if meat was reduced to healthy levels).

General Notes

It is difficult to parameterise an average 'healthy diet' that would represent a range of different individual diets that people in different regions could adopt, as these largely depend of their individual nutritional requirements and context. The main alteration from the projected dietary preferences was a decrease of excessive consumption in sugars and fats, which are the main risk factors to cardiovascular diseases and diabetes. These is especially prevalent in industrialised countries. Not all regions show these trends, and those that to not, were not altered in this regard.

For the Healthy Diets scenario we reshaped regional dietary preferences according to latest nutritional literature, by capping the average daily consumption of refined sugars and sweeteners, and vegetable oils, meat and dairy as sources of saturated fats. Any regions below these levels were allowed to increase them based on current trends – we did not 'prescribe' the exact consumption these foods, just the upper limit. We have however prescribed a minimum level of fruit and vegetable consumption. Total daily calorific consumption was set at 2500 Kcal, which was achieved by varying the consumption of different staple foods. The patterns within the staple food group reflect current cultural dietary preferences, following from the current diets. Bold numbers show values where the trending diets did not meet healthy recommendations and were therefore changed for this scenario.

Not all nutritional issues are captured in these representations of the average ' healthy diets'. For example, the relationship between saturated and unsaturated fats was only partially represented in the ratio between animal and vegetable fats. Omega-3 (healthy) and Omega-6 fatty acids (unhealthy), or the relationship between glucose and fructose (less healthy) within sweeteners, are not represented as they occur with the same food category, although they are considered important for healthy nutrition[35].

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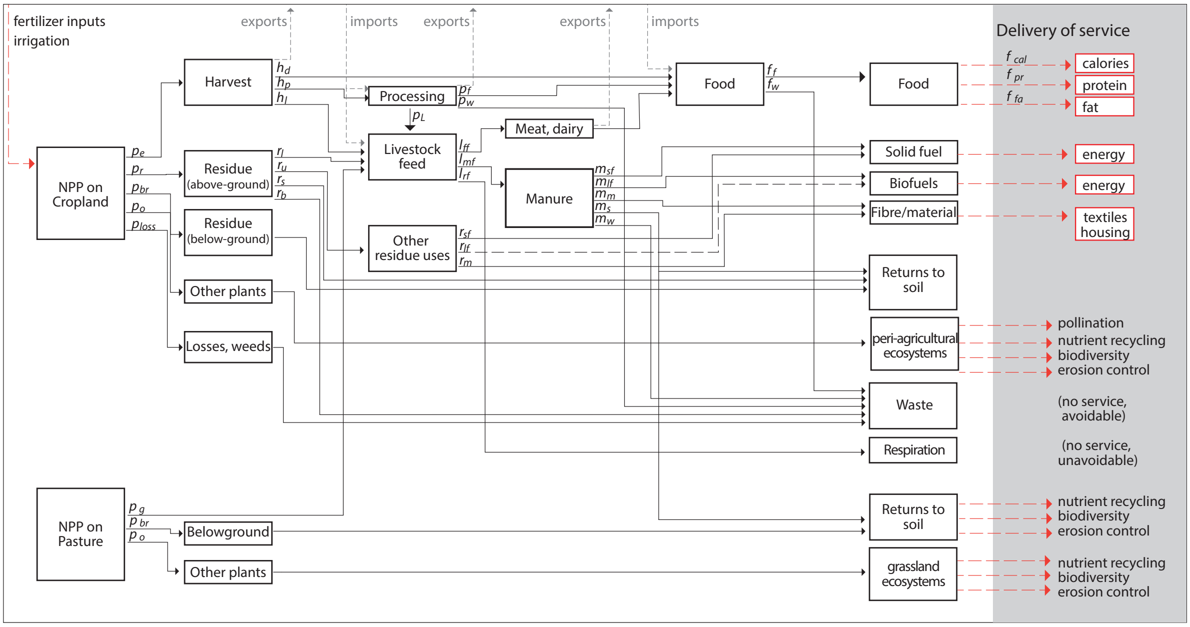
Agricultural biomass flows

Supplementary Figure 3 – A representation of the biomass flow model, and a map to the parameter values presented as the Supplementary Data 1(separate file), and obtained from a number of sources[2,7–13,36–38]. Allocation coefficients are annotated at the exits from each box e.g. *hp* denotes the allocation of harvest to processing and maps onto the column with the matching notation in Supplementary Data 1.



Livestock feed model within agricultural biomass flow

A livestock feed model was devised to estimate the mix of animal feeds from different sources. Four sources are distinguished: (i) cropland-grown feeds, which are the most energy and nutrient rich, for example maize grain and soybean cake; (ii) cropland-grown forage crops, which are less energy dense, such as whole maize and alfalfa; (iii) crop residues (such as straw) and (iv) pasture grass. For simplicity we assume that crop residues and pasture grass have similar energy density. Energy densities for feeds are adapted from Wirsenius[9]. The model includes six animal production systems: pork, beef and bovine meat, poultry, sheep and goat meat, eggs and dairy. The overall production in each of these categories is documented by FAOSTAT, however there are several unknowns in this model, notably how much of each of the feed categories is consumed by each of the production systems, and the efficiencies of converting the feed into animal biomass. To solve for these the model is assembled as a linear system (described in more detailed in SI3), and takes the information about energy densities, quantities of forage and grazed biomass, from a more detailed model of livestock biomass flows of Wirsenius[9].

System of linear equations to calculate efficiency of converting feed to livestock products:
For each livestock category, in each region:

$$LP = (Dg * lg\% * G + Dfo * lfo\% * FO + Dfe * lfe\% * FE + Dr * lr\% * R) * Elp$$

LP is Livestock production of each category (known from FAO statistics)
Dg, Dfo, Dfe and Dr are relative digestibility of grazed grass, forage, feed and residuals (known)
$lg\%$, $lfo\%$, $Lfe\%$, and $lr\%$ are shares of the total available grazed grass, forage, feed and residuals consumed by each livestock category (sum to 1)
G, FO, FE, R are total biomass of grazed grass, forage, feed and residuals in the region.
Elp is efficiency of converting the total digestible feed to livestock product (unknown)

Then to calculate livestock food production for each livestock feed category sum:

$$LSOf = \sum Elp * lf\%$$

LSO_f is livestock output (food, manure, etc.) for each feed category
$lf\%$ is a share of the livestock system consumption of the feed category

Changes in livestock management

Supplementary Table 4 - Changes in livestock management. Assumptions about the changes in livestock feeding systems for each region, based on C mass content in the feed.

	2009		2050	
	Cropland-grown feed*	Pasture & roughage	Cropland-grown feed*	Pasture & roughage
Sub-Saharan Africa				
Ruminants	1%	99%	1%	99%
Poultry & pigs	10%	90%	20%	80%
N America, Oceania, Latin America				
Ruminants	1%	99%	1%	99%
Poultry & pigs	30%	70%	35%	65%
C Asia, W Asia, E Europe, N Africa				
Ruminants	1%	99%	2%	98%
Poultry & pigs	40%	60%	50%	50%
W Europe				
Ruminants	2%	98%	2%	98%
Poultry & pigs	50%	50%	50%	50%
E Asia				
Ruminants	4%	96%	8%	92%
Poultry & pigs	60%	40%	70%	30%
SE Asia				
Ruminants	4%	96%	8%	92%
Poultry & pigs	70%	30%	80%	20%

* grains, soya cake, and co-product concentrates such as molasses. Excluding hay and crop residues.

Supplementary Table 5 - Changes in the efficiency of livestock products in gC of products per gC of feed. These depend on the composition and digestibility of feed, and livestock products. They are estimated based on the feed composition changes assumed (see Supplementary Table 4).

	2009	2050
N America	6.1%	6.6%
W Europe	9.8%	10.0%
E Europe	4.0%	5.0%
N Africa	5.3%	5.8%
Sub-Saharan Africa	3.6%	4.6%
E Asia	14.4%	14.9%
C Asia	2.5%	3.5%
S Asia	10.3%	10.8%
SE Asia	9.3%	9.8%
W Asia	5.1%	6.1%
Latin America	4.4%	5.4%
Oceania	3.3%	4.3%

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Changes in future yields

Supplementary Table 6 – Current yields [t/ha]. An overview of current (2009) yields by regions, as reported by FAOSTAT[36].

	N America	C Asia	E Asia	E Europe	Latin America	North Africa	Oceania	S Asia	SE Asia	W Europe	W Asia	Sub-Saharan Africa
Wheat	2.9	1.7	4.7	2.7	2.7	2.7	1.6	2.7	1.8	6.1	2.5	2.0
Rice (Milled Equivalent)	7.9	3.5	6.5	5.3	4.6	9.5	5.9	3.5	4.1	6.9	6.1	2.0
Barley	3.5	1.6	3.5	2.6	2.4	1.7	1.8	2.1	1.8	4.7	1.9	1.7
Maize	10.3	5.6	5.2	4.5	3.5	6.4	6.9	2.3	3.7	8.1	5.6	1.8
Rye	2.1	1.5	3.0	2.3	1.2	1.9	0.6	0.0	0.0	4.6	2.5	0.6
Oats	2.8	1.4	2.8	2.0	2.0	1.1	1.4	1.0	0.0	3.2	2.3	1.5
Millet	1.9	1.1	1.6	1.1	1.5	0.3	1.0	0.8	0.9	2.9	0.7	0.8
Sorghum	4.4	5.4	2.9	1.8	3.1	0.7	3.5	1.0	1.1	5.5	1.3	1.0
Cereals, Other	3.6	2.3	3.6	2.5	2.5	2.6	2.3	1.6	1.4	4.8	2.5	1.4
Starchy Roots + (Total)	41.2	16.9	17.4	15.2	12.8	22.7	12.9	18.9	17.6	35.0	22.9	8.8
Sugar Cane	78.1	0.0	68.1	1.0	77.9	110.5	72.9	60.7	68.0	85.8	23.8	51.1
Sugar Beet	58.2	13.2	43.2	37.0	69.7	50.1	0.0	35.6	0.0	74.3	52.2	14.2
Pulses + (Total)	2.0	1.5	1.5	1.8	0.9	1.1	1.3	0.7	1.2	2.6	1.4	0.6
Treenuts + (Total)	3.8	1.8	3.9	2.6	0.7	0.7	1.3	1.4	1.3	0.8	1.6	0.6
Oilcrops, other than soya	2.0	0.6	1.9	2.1	1.7	1.9	1.1	1.1	0.9	3.6	3.5	1.2
Soyabeans	2.9	1.8	1.6	1.4	2.2	2.9	1.9	1.0	1.4	2.8	3.4	1.4
Vegetables + (Total)	31.4	26.0	23.1	18.8	15.4	22.2	22.4	13.9	9.8	26.8	21.6	6.1
Fruits - Excluding Wine + (Total)	22.9	7.0	10.6	6.8	14.8	12.0	11.3	10.7	12.5	10.1	10.5	7.0
Cotton and fibre crops	0.9	0.7	1.3	1.1	1.0	0.6	2.0	0.6	0.6	1.0	1.4	0.3
Forage crops (alfalfa, wholemaize)	22.6	28.0	40.9	29.1	28.0	14.1	28.1	28.0	40.9	28.0	28.2	14.1

Supplementary Table 7 – Trending future yields [t/ha]. Yields in 2050 following a linear extrapolation of the current yield trends, as analysed by Ray et al.[20] Yield trends for the main crops, such as wheat, maize, soybean and rice were available in the literature. Therefore these were taken as proxies for changes in yields of other crops (maize is a proxy for other C4 crops, soybean for oilcrops and pulses, and wheat for other grains, and roots). The yield of sugar cane was capped at 120 t/ha. These yields are inputs into the CT scenarios.

	N America	C Asia	E Asia	E Europe	Latin America	North Africa	Oceania	S Asia	SE Asia	W Europe	W Asia	Sub-Saharan Africa
Wheat	4.1	3.1	7.9	2.3	4.3	3.9	1.2	4.1	3.2	7.6	3.5	3.3
Rice (Milled Equivalent)	11.8	1.6	8.4	8.2	8.6	16.6	6.6	5.3	6.0	9.0	7.9	1.9
Barley	4.8	2.9	6.0	2.1	3.7	2.4	1.3	3.2	3.3	5.9	2.5	2.7
Maize	17.2	7.7	7.1	6.2	7.0	11.2	9.9	4.3	7.8	12.1	10.1	2.8
Rye	2.9	2.8	5.0	2.0	1.8	2.8	0.4	0.0	0.0	5.7	3.4	1.0
Oats	3.9	2.6	4.8	1.6	3.1	1.6	1.0	1.5	0.0	3.9	3.1	2.4
Millet	2.6	2.0	2.7	0.9	2.3	0.4	0.7	1.2	1.6	3.7	1.0	1.3
Sorghum	6.1	10.2	4.9	1.5	4.8	1.0	2.6	1.5	1.9	6.8	1.8	1.6
Cereals, Other	5.1	4.3	6.0	2.1	3.9	3.6	1.6	2.4	2.5	6.0	3.4	2.2
Starchy Roots + (Total)	57.6	31.7	29.2	12.7	20.2	32.3	9.4	28.9	32.0	43.6	31.3	14.5
Sugar Cane	120.0	0.0	92.2	1.4	120.0	120.0	104.3	111.4	120.0	120.0	32.5	78.3
Sugar Beet	81.3	24.7	72.5	31.0	109.8	71.3	0.0	54.6	0.0	92.5	71.3	23.3
Pulses + (Total)	2.8	2.4	2.0	2.7	1.5	1.6	1.9	1.0	2.1	3.3	1.8	1.2
Treenuts + (Total)	4.1	2.8	5.3	4.0	1.1	1.0	1.9	1.8	1.8	0.8	1.6	1.2
Oilcrops, other than soya	2.2	0.9	2.5	3.2	2.8	2.8	1.7	1.4	1.2	3.7	3.5	2.1
Soyabeans	3.2	2.8	2.2	2.2	3.7	4.3	2.8	1.3	1.9	2.8	3.5	2.7
Vegetables + (Total)	43.9	48.7	38.8	15.8	24.3	31.7	16.3	21.3	17.8	33.4	29.5	10.1
Fruits - Excluding Wine + (Total)	32.0	13.2	17.8	5.7	23.3	17.1	8.2	16.3	22.7	12.6	14.4	11.5
Cotton and fibre crops	1.2	1.3	2.2	0.9	1.5	0.9	1.4	1.0	1.0	1.2	1.9	0.5
Forage crops (alfalfa, wholemaize)	31.6	52.5	68.7	24.3	44.1	20.1	20.4	43.0	74.4	34.9	38.5	23.2

Supplementary Table 8 – Future yields with yield gaps closed. Existing yield gaps are taken from the GAEZ database[21]. For those few crops that GAEZ does not report the yield gaps (vegetables, fruits, forage crops), we have assumed the same improvement as in current trends extrapolation. These yields are inputs into the YG scenarios.

	N America	C Asia	E Asia	E Europe	Latin America	North Africa	Oceania	S Asia	SE Asia	W Europe	W Asia	Sub-Saharan Africa
Wheat	4.9	3.2	8.7	6.9	5.0	8.8	2.2	5.1	5.4	8.0	6.3	4.5
Rice (Milled Equivalent)	11.3	14.6	6.5	9.4	8.4	12.4	6.2	6.5	7.4	8.1	11.8	5.9
Barley	4.9	4.0	7.8	9.5	6.0	7.1	2.6	4.5	3.8	6.7	4.7	4.9
Maize	13.8	19.4	9.6	10.9	9.3	43.1	10.3	8.1	8.0	9.9	12.7	7.9
Rye	3.0	3.8	6.5	8.7	2.9	8.3	0.8	0.0	0.0	6.5	6.3	1.7
Oats	3.9	3.5	6.2	7.3	5.0	4.9	1.9	2.2	0.0	4.5	5.7	4.3
Millet	2.6	2.8	3.5	4.2	3.7	1.2	1.3	1.7	1.9	4.2	1.9	2.3
Sorghum	6.1	13.8	6.4	6.8	7.8	3.2	4.9	2.1	2.2	7.8	3.4	2.8
Cereals, Other	5.1	5.9	7.8	9.4	6.3	11.0	3.1	3.4	2.9	6.9	6.3	4.0
Starchy Roots + (Total)	51.1	44.7	30.4	38.2	27.6	70.4	18.0	31.4	51.0	45.0	39.1	30.1
Sugar Cane	111.5	0.0	80.8	1.0	95.4	125.6	86.0	91.7	95.7	85.8	95.2	87.5
Sugar Beet	58.2	13.2	43.2	37.0	126.7	50.1	0.0	35.6	0.0	74.3	95.3	14.2
Pulses + (Total)	2.8	3.8	2.7	3.4	2.3	2.7	2.0	2.1	2.5	3.7	2.8	2.1
Treenuts + (Total)	5.2	6.5	4.3	4.9	1.4	2.0	3.2	3.2	2.3	0.8	2.1	1.9
Oilcrops, other than soya	2.8	1.4	2.9	5.0	2.8	4.8	2.0	2.2	2.2	5.2	5.8	3.0
Soyabeans	4.2	4.5	2.9	3.5	3.3	5.0	2.2	2.3	2.7	3.8	13.6	3.5
Vegetables + (Total)	43.9	48.7	38.8	15.8	24.3	31.7	16.3	21.3	17.8	33.4	29.5	10.1
Fruits - Excluding Wine + (Total)	32.0	13.2	17.8	5.7	23.3	17.1	8.2	16.3	22.7	12.6	14.4	11.5
Cotton and fibre crops	1.6	1.6	1.3	2.7	1.3	2.2	2.0	1.9	1.3	1.2	2.2	0.9
Forage crops (alfalfa, wholemaize)	31.6	52.5	68.7	24.3	44.1	20.1	20.4	43.0	74.4	34.9	38.5	23.2

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Future stocking densities on pasture

Supplementary Table 9 - Allowed increases in pasture grazing densities. Assumptions about the changes in livestock feeding systems for each region, based on C mass content in feed. Estimated on the basis of a global dynamic vegetation model[22], a previous livestock energy model[9], and livestock products statistic[8], to determine that in most regions, densities can be increased somewhat.

	Estimated available carbon biomass 2009 [9] tC/ha	Estimated grazed carbon biomass 2009 [9] tC/ha	Grazed biomass in 2050 tC/ha
Central Asia	1.06	.49	.58
East Asia	.57	.27	.34
Eastern Europe	4.18	2.16	2.43
Latin America	3.68	1.71	2.02
North Africa	1.20	.59	.96
Northern America	2.43	1.66	1.66
Oceania	1.01	.69	.86
South-eastern Asia	1.39	.42	.80
Southern Asia	1.06	.49	.85
West Europe	3.65	2.88	2.88
Western Asia	1.20	.59	.83
Sub-Saharan Africa	.71	.35	.57

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Land-use distribution over suitability classes and global biomes

Supplementary Table 10 – Current global land-use distribution on suitability classes and biomes (Mkm^2). Obtained by overlaying current land-use, global biomes and agricultural suitability.

	Prime Land (at Low Inputs)						Prime Land (at High Inputs)					
km2	Cropland	Pasture	Forestry	Built-up	Natural	**Total**	Cropland	Pasture	Forestry	Built-up	Natural	**Total**
Tropical	0.29	0.37	0.59	0.03	0.49	**1.8**	1.59	0.77	2.68	0.03	2.59	**7.7**
Temperate	0.98	0.34	1.19	0.10	0.36	**3.0**	1.12	0.34	1.83	0.10	0.36	**3.8**
Boreal	0.03	0.01	0.07	0.02	0.03	**0.2**	0.01	0.01	0.17	0.02	0.07	**0.3**
Savanna	0.88	0.75		0.03	1.03	**2.7**	0.74	1.70		0.03	2.26	**4.7**
Grassland	1.02	0.61		0.03	0.43	**2.1**	0.19	0.28		0.03	0.19	**0.7**
Dense Shrubland	0.19	0.13		0.02	0.29	**0.6**	0.17	0.09		0.02	0.22	**0.5**
Open Shrubland	0.05	0.03		0.01	0.04	**0.1**	0.09	0.03		0.02	0.07	**0.2**
Desert	0.00	0.00		0.01	0.00	**0.0**	0.00	0.00		0.01	0.02	**0.0**
Tundra	0.00	0.00		0.00	0.00	**0.0**	0.00	0.00		0.00	0.00	**0.0**
Ice	0.00	0.00		0.00	0.00	**0.0**	0.00	0.00		0.00	0.00	**0.0**
TOTAL	3.4	2.2	1.9	0.2	2.7	**10.4**	3.9	3.2	4.7	0.3	5.8	**17.9**

	Good Land (at Low Inputs)						Good Land (at High Inputs)					
	Cropland	Pasture	Forestry	Built-up	Natural	**Total**	Cropland	Pasture	Forestry	Built-up	Natural	**Total**
Tropical	0.54	0.67	1.37	0.03	1.43	**4.0**	0.50	0.34	1.12	0.01	1.30	**3.3**
Temperate	0.62	0.38	1.47	0.08	0.28	**2.8**	0.25	0.10	0.84	0.04	0.17	**1.4**
Boreal	0.01	0.02	0.17	0.02	0.08	**0.3**	0.01	0.01	0.41	0.01	0.20	**0.6**
Savanna	0.61	1.33		0.03	2.11	**4.1**	0.39	0.91		0.01	1.33	**2.6**
Grassland	0.98	1.49		0.02	0.61	**3.1**	0.16	0.27		0.01	0.19	**0.6**
Dense Shrubland	0.26	0.26		0.01	0.50	**1.0**	0.14	0.11		0.01	0.16	**0.4**
Open Shrubland	0.16	0.28		0.01	0.20	**0.6**	0.07	0.09		0.01	0.12	**0.3**
Desert	0.00	0.01		0.01	0.01	**0.0**	0.00	0.00		0.00	0.01	**0.0**
Tundra	0.00	0.01		0.00	0.03	**0.0**	0.00	0.04		0.00	0.04	**0.1**
Ice	0.00	0.00		0.00	0.00	**0.0**	0.00	0.00		0.00	0.00	**0.0**
TOTAL	3.2	4.5	3.0	0.2	5.2	**16.1**	1.5	1.9	2.4	0.1	3.5	**9.4**

	Other (Unsuitable)						Total					
	Cropland	Pasture	Forestry	Built-up	Natural	**Total**	Cropland	Pasture	Forestry	Built-up	Natural	**Total**
Tropical	0.69	0.75	2.40	0.04	2.03	**5.9**	3.60	2.89	8.15	0.15	7.84	**22.6**
Temperate	0.27	0.62	4.45	0.12	1.16	**6.6**	3.23	1.78	9.78	0.44	2.33	**17.6**
Boreal	0.58	0.46	8.58	0.02	4.18	**13.8**	0.65	0.51	9.39	0.08	4.55	**15.2**
Savanna	0.55	1.80		0.04	2.64	**5.0**	3.18	6.49		0.13	9.38	**19.2**
Grassland	0.50	4.60		0.03	2.65	**7.8**	2.86	7.25		0.12	4.07	**14.3**
Dense Shrubland	0.33	1.29		0.02	1.78	**3.4**	1.10	1.87		0.07	2.95	**6.0**
Open Shrubland	0.49	4.73		0.02	5.44	**10.7**	0.85	5.15		0.06	5.87	**11.9**
Desert	0.11	1.20		0.01	13.94	**15.3**	0.12	1.22		0.03	13.98	**15.3**
Tundra	0.02	0.87		0.00	5.97	**6.9**	0.04	0.92		0.00	6.05	**7.0**
Ice	0.00	0.02		0.00	1.19	**1.2**	0.00	0.02		0.00	1.19	**1.2**
TOTAL	3.6	16.3	15.4	0.3	41.0	**76.6**	15.6	28.1	27.3	1.1	58.2	**130.3**

Notes:

We aggregated the data on suitability from GAEZ v3.0 (IIASA and FAO, 2012) for all crops together for baseline climatic conditions, and re-categorised the dataset into 5 classes, thus:

i. Prime land, where near-optimum yields can be achieved at low inputs (GAEZ suitability index 70 or higher for at least one of the major crops for low inputs)
ii. Prime land, where near-optimum yields can be achieved at high levels of artificial inputs (GAEZ suitability index 70 or higher for at least one of the major crops for high inputs)
iii. Suitable land, where yields of at least half of the optimum can be achieved at low inputs, (GAEZ suitability index between 25-70 at low inputs)
iv. suitable land, where yields of at least half of the optimum can be achieved at high inputs (GAEZ suitability index between 25-70 at high inputs)
v. marginally suitable and unsuitable land

These tables show that the majority of land most suitable for agriculture, but not yet cultivated, is currently under tropical forest , tropical grasslands and temperate forests.

Supplementary Table 11 – Distribution of current cropland over suitability land-classes for each region (Mkm^2) Land suitability is from the GAEZ study. See the Supplementary Table 10 note for a full description.

	Prime LI		Prime HI		Good LI		Good HI		Nonsuitable land		**Total cropland**
Central Asia	.04	12%	.01	2%	.17	51%	.02	6%	.09	29%	**.33**
East Asia	.21	15%	.20	14%	.34	25%	.07	5%	.57	41%	**1.39**
Eastern Europe	1.14	57%	.40	20%	.28	14%	.06	3%	.11	6%	**2.00**
Latin America	.45	25%	.41	23%	.37	21%	.18	10%	.40	22%	**1.81**
North Africa	.05	10%	.10	22%	.12	25%	.05	12%	.15	31%	**.47**
North America	.96	45%	.46	22%	.51	24%	.05	2%	.14	7%	**2.12**
Oceania	.01	2%	.04	8%	.09	18%	.15	29%	.21	42%	**.50**
South-eastern Asia	.02	1%	.45	40%	.13	12%	.19	17%	.34	30%	**1.13**
Southern Asia	.24	10%	.99	43%	.29	13%	.22	9%	.59	25%	**2.32**
West Europe	.10	9%	.24	22%	.29	27%	.16	15%	.30	27%	**1.09**
Western Asia	.07	17%	.03	7%	.11	26%	.02	4%	.20	46%	**.43**
Sub-Saharan Africa	.15	7%	.60	29%	.48	23%	.36	18%	.46	22%	**2.05**
Grand Total	**3.4**	22%	**3.9**	25%	**3.2**	20%	**1.5**	10%	**3.6**	23%	**15.63**

Supplementary Table 12 – Current forests and areas free of major human land-uses over suitability land-classes for each region (Mkm^2). This table shows the suitability of land not yet used for either settlements, cropping or pasture. These are the areas where agriculture could expand, although at large environmental costs. Therefore it shows the suitability of land reserves, from agricultural perspective, in each region. Latin America and Sub-Saharan Africa have most land suitable for agricultural expansion, especially if we assume fertiliser and other high inputs can overcome poorer soil nutrient availability. Cropping can also expand on pasture, but as a consequence pasture in model must expand further in natural vegetation. For that reason, pasture in not counted in 'agricultural land reserves'.

	Prime LI		Prime HI		Good LI		Good HI		Nonsuitable land		**Total nat veg.**
Central Asia	.05	4%	.01	1%	.20	17%	.03	2%	.90	76%	**1.19**
East Asia	.32	5%	.13	2%	.53	8%	.08	1%	5.29	83%	**6.35**
Eastern Europe	1.03	7%	1.09	7%	.66	4%	.92	6%	11.56	76%	**15.26**
Latin America	1.26	9%	3.28	24%	2.42	18%	2.03	15%	4.61	34%	**13.60**
North Africa	.03	0%	.25	4%	.09	1%	.09	1%	5.82	93%	**6.28**
Northern America	.76	5%	1.32	9%	1.00	7%	.58	4%	10.23	74%	**13.89**
Oceania	.06	1%	.42	8%	.47	9%	.45	9%	3.81	73%	**5.23**
South-eastern Asia	.02	1%	.73	23%	.23	7%	.43	14%	1.74	55%	**3.15**
Southern Asia	.15	4%	.42	13%	.24	7%	.15	5%	2.38	71%	**3.34**
West Europe	.06	2%	.18	7%	.32	12%	.21	8%	1.79	70%	**2.55**
Western Asia	.06	2%	.03	1%	.17	5%	.02	1%	3.27	92%	**3.56**
Sub-Saharan Africa	.92	7%	3.20	24%	2.47	18%	1.36	10%	5.68	42%	**13.63**
Grand Total	**4.7**	5%	**11.1**	13%	**8.8**	10%	**6.4**	7%	**57.08**	65%	**88.02**

Supplementary Table 13 - Predicted area of cropland in 2050 for each region and core scenario (Mkm^2), as calculated by our approach. The changes in cropland area vary drastically between regions, from small decreases (C Asia, N America, W Europe), to large increases (S Asia, Sub-Saharan Africa). The influence on assuming the healthy diets is different between regions, while the decrease of food waste universally reduces the area of cropping.

	Scenario CT1		Scenario CT2		Scenario CT3		Scenario YG1		Scenario YG2		Scenario YG3	
Central Asia	.31	-4%	.27	-17%	.26	-19%	.25	-22%	.22	-33%	.22	-32%
East Asia	1.87	+35%	1.55	+12%	1.12	-19%	1.67	+20%	1.33	-4%	1.10	-21%
Eastern Europe	1.84	-8%	1.67	-16%	1.57	-21%	1.13	-43%	1.03	-48%	.94	-53%
Latin America	1.96	+8%	1.72	-5%	1.70	-6%	1.93	+6%	1.70	-6%	1.61	-11%
North Africa	.62	+32%	.52	+10%	.50	+5%	.41	-12%	.35	-26%	.34	-28%
Northern America	2.03	-5%	1.85	-13%	1.63	-23%	1.92	-9%	1.73	-19%	1.54	-27%
Oceania	.64	+28%	.59	+18%	.68	+37%	.47	-6%	.43	-14%	.47	-6%
South-eastern Asia	1.71	+51%	1.50	+33%	1.44	+28%	1.16	+3%	1.00	-11%	.97	-14%
Southern Asia	5.08	+119%	4.29	+85%	4.49	+94%	3.11	+34%	2.65	+14%	2.84	+23%
West Europe	1.01	-7%	.88	-19%	.76	-31%	.96	-12%	.81	-26%	.71	-35%
Western Asia	.70	+62%	.55	+27%	.54	+25%	.50	+15%	.42	-2%	.43	-1%
Sub-Saharan Africa	4.40	+115%	3.80	+85%	3.54	+73%	2.93	+43%	2.52	+23%	2.55	+24%
Grand Total	**22.2**	+42%	**19.2**	+23%	**18.2**	+17%	**16.4**	+5%	**14.2**	-9%	**13.7**	-12%

Supplementary Table 14 - Predicted area of pasture in 2050 for each region and core scenario (Mkm^2). In some regions the model does not predict any changes, as all increases in the demand for grass are met by increases in stocking densities. Healthy diets make a large difference in predicted area of pasture.

	Scenario CT1		Scenario CT2		Scenario CT3		Scenario YG1		Scenario YG2		Scenario YG3	
Central Asia	2.48	-1%	2.51	0%	1.43	-43%	2.50	-0%	2.51	0%	1.44	-43%
East Asia	5.06	0%	5.06	0%	2.11	-58%	5.06	0%	5.06	0%	2.08	-59%
Eastern Europe	.55	-53%	.51	-56%	.37	-68%	.55	-52%	.50	-56%	.38	-67%
Latin America	4.41	-7%	3.91	-17%	3.46	-27%	4.42	-7%	3.92	-17%	3.46	-27%
North Africa	2.05	+6%	1.82	-6%	1.62	-17%	2.10	+8%	1.82	-6%	1.66	-15%
Northern America	3.20	+21%	2.87	+9%	1.96	-25%	3.20	+21%	2.77	+5%	1.98	-25%
Oceania	2.76	-26%	2.56	-31%	2.16	-42%	2.77	-26%	2.56	-31%	2.17	-42%
South-eastern Asia	.17	+0%	.17	0%	.12	-30%	.17	-0%	.17	-1%	.12	-29%
Southern Asia	1.57	+102%	1.41	+81%	1.45	+86%	1.62	+108%	1.39	+78%	1.49	+92%
West Europe	.71	+13%	.65	+4%	.40	-36%	.71	+13%	.62	-0%	.40	-36%
Western Asia	2.28	0%	2.28	0%	2.28	0%	2.28	0%	2.28	0%	2.28	0%
Sub-Saharan Africa	11.84	+65%	9.92	+38%	8.03	+12%	12.27	+71%	10.32	+44%	8.32	+16%
Grand Total	**37.1**	+13%	**33.7**	+3%	**25.4**	-23%	**37.7**	+15%	**33.9**	+3%	**25.8**	-21%

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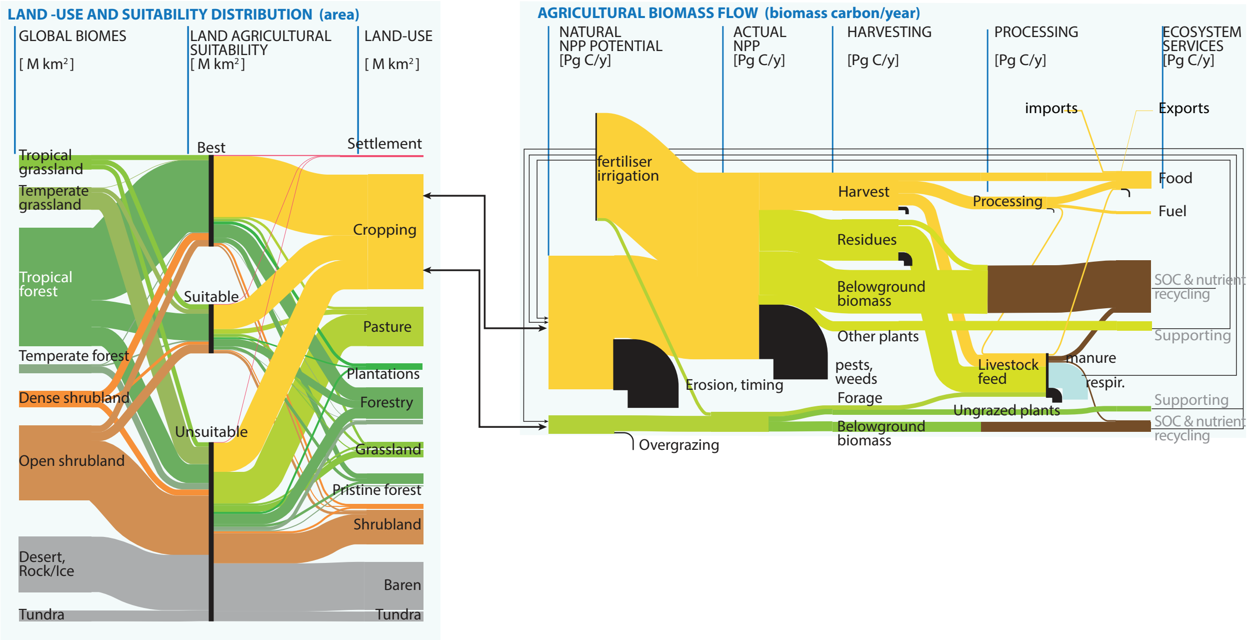
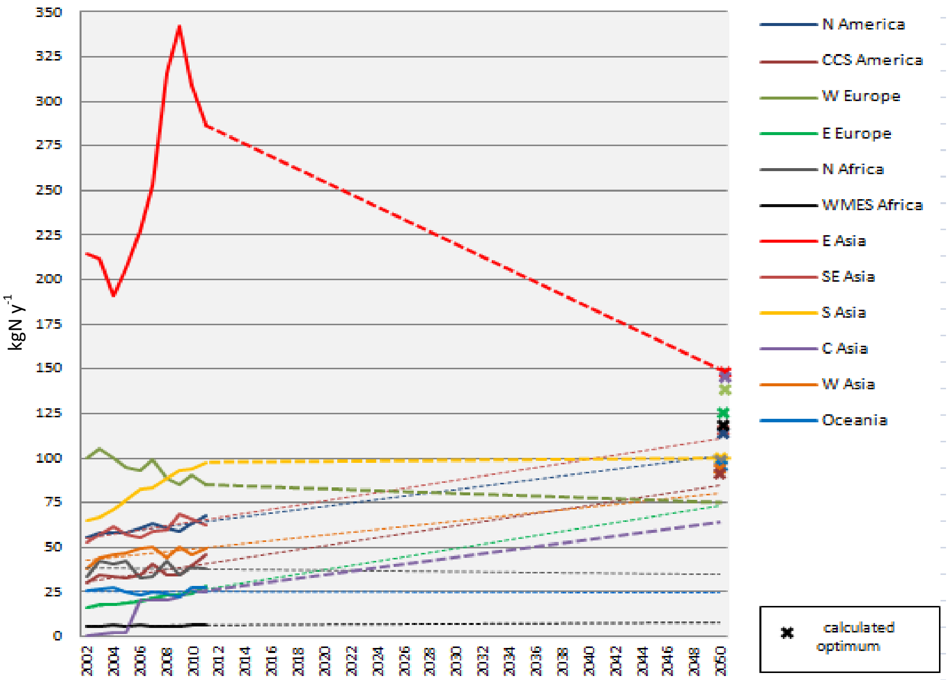
An example of regional land-use distribution and biomass flows in 2009 – South Asia

Supplementary Figure 4 - Current land-use distribution and biomass flows in South Asia. In South Asia cropland makes up a much larger proportion of total area (35%) and NPP flows (42%) compared with the global situation. Pasture on the other hand, is relatively limited. Livestock flows are not as dominant relative to plant food for human consumption and the diet is predominantly vegetarian. Buffalo milk plays a large role in the diets of subsistence farmers, and the buffalo is also used for mechanical work, so that the Figure shows a link from livestock respiration to cropland productivity. Crop residues dominate livestock feed flows, whilst globally, pasture and grain feed dominate as livestock feed mass. The sheer dominance of agricultural land-use over land-covered with natural vegetation and an already large role of irrigation and fertiliser indicates there is even less headroom in the land use system than the global overview would suggest.



Fertiliser use

Supplementary Figure 5 - Fertiliser use trends per unit of arable land (kgN/ha). The consumption of nitrogen fertiliser for the last 10 years (since records began at FAO) was obtained from the FAOSTAT[36] for each macro-region. A trend in fertiliser use per unit area of arable land was calculated on the basis the last 10 years of data, by fitting a linear function.
Linear extrapolation of fertiliser use in South Asia would result in much higher use than optimum; therefore we used the optimum as a cap. In West Europe there has been a steady decline over the last 10 years, which, if continued linearly, would approach zero by 2050; thus, we have just used the last 4 years of data to exclude the large declines earlier in the decade. For Central Asia, a data problem led us to use the last 4 years of reliable data. In East Asia, where nitrogen fertiliser use increased until 2009, but has since sharply declined as China has become more aware of the detrimental effects of over-fertilisation. For East Asia we predicted a decline in fertiliser use until it reaches the optimum fertilisation for each crop.
In CT scenarios we therefore assumed a continuation of current trends, capped by optimum fertilisation for each crop. In YG scenarios, we assumed optimum fertiliser use (to support yield gap closures). The optimum fertiliser levels were derived from a range of literature and case-studies[27] for each crop separately for two suitability classes of soil: nutrient limited and otherwise limited, corresponding to Low input and High input land-suitability classes.



Supplementary Table 15 – Calculated Fertiliser use, by scenario and region (Mt N/y). This Table also shows the ratio of total growth (in tons carbon) per kg nitrogen applied. This ratio is a proxy for the recovery efficiency of nitrogen. Typically this ratio decreases when agriculture moves to high nitrogen, high production systems[34]. In our study, this ratio is however similar across all scenarios, therefore signalling an inherent efficiency improvement. The efficiency improvement is associated with the assumption that over-fertilization (in E Asia, for example) is eliminated, and all regions use the optimum fertilisation levels to achieve optimum yields. The increase in total fertiliser use is therefore associated with higher food production, not higher fertiliser use per product. It matches the findings that today's yields gaps could be closed with only a small increase in fertiliser use, if over-fertilisation was eliminated[36].

	2009		Scenario CT1		Scenario CT2		Scenario CT3		Scenario YG1		Scenario YG2		Scenario YG3	
	MtN	tC/kgN	MtN	tC/kgN	MtN	tC/kgN	MtN	tC/kgN	MtN	tC/kgN	MtN	tC/kgN	MtN	tC/kgN
Central Asia	0.7	25	2.0	19	1.7	17	1.7	16	3.7	10	3.2	10	3.1	9
East Asia	38.9	7	27.8	15	23.9	15	17.1	11	24.9	17	20.0	16	15.2	18
Eastern Europe	4.6	27	13.4	11	12.6	10	11.7	9	14.5	10	13.2	10	11.3	10
Latin America	6.2	41	13.8	31	12.2	25	11.6	24	17.5	26	14.5	26	13.4	23
North Africa	1.6	18	1.7	43	1.4	42	1.3	39	4.2	19	3.5	18	3.3	17
Northern America	12.6	34	20.4	17	19.0	15	16.7	13	22.0	17	19.1	16	15.6	16
Oceania	1.1	20	1.1	31	1.0	24	1.2	30	4.7	7	4.3	7	4.5	6
South-eastern Asia	7.4	18	14.6	17	12.9	15	12.2	14	13.2	19	11.4	19	10.5	18
Southern Asia	21.5	15	40.9	12	36.1	11	37.0	11	33.2	15	28.4	15	28.9	15
West Europe	8.1	17	5.9	26	5.3	28	4.3	23	13.6	12	11.5	12	9.1	13
Western Asia	2.2	14	5.3	17	4.2	16	4.1	15	4.7	20	3.8	20	3.7	19
Sub-Saharan Africa	1.2	81	3.3	110	2.8	105	2.6	97	33.7	11	28.0	11	26.6	10
World	**106**	23	**150**	26	**133**	24	**121**	22	**190**	21	**161**	21	**145**	20

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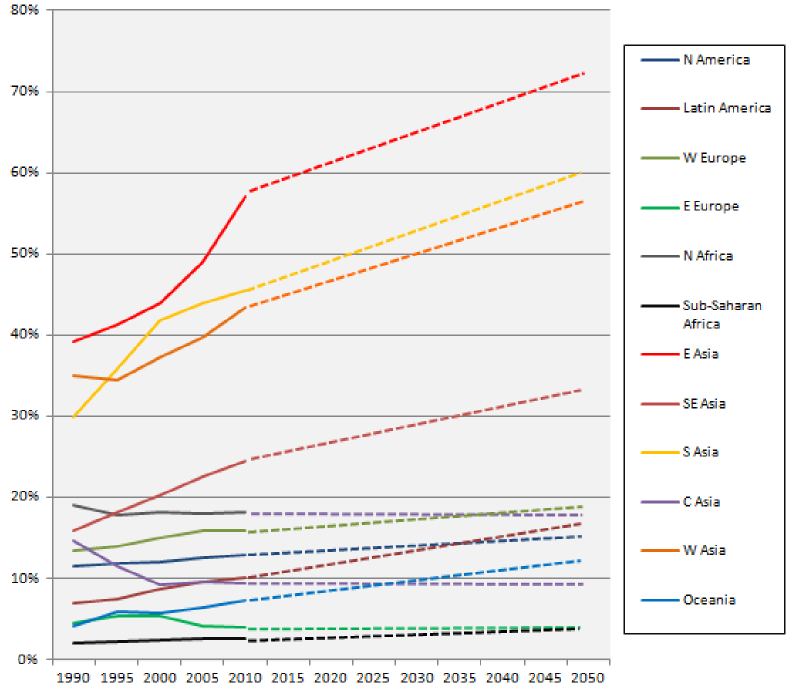
Irrigation use

Supplementary Figure 6 – Trends in irrigated agriculture as a ratio of total agricultural area. We estimated trends in irrigation use *via* a proxy of the area equipped for irrigation, which is the only measure for irrigation with data available over time[29]. The amount of irrigation water applied per unit area of irrigated land in 2009 was calculated separately for each macro-region, based on agricultural withdrawal rates[29]. It was assumed that water application per unit area equipped for irrigation will remain the same in future scenarios (the potential influences of climate change were not included), while the irrigation area continues expanding at current rates (with the exception of E Asia, where we assume the rate will slow down somewhat) . The amount of water needed for irrigation between the scenarios differs due to the different total area needed, while the irrigation intensity remains the same. This implies that YG scenarios represent improved irrigation resource use efficiency.



Supplementary Table 16 – Irrigation use by scenario and region [km^3]

	2009	Scenario CT1		Scenario CT2		Scenario CT3		Scenario YG1		Scenario YG2		Scenario YG3	
116	111	-4%	96	-17%	94	-19%	90	-22%	78	-33%	79	-32%	116
457	811	+77%	672	+47%	487	+6%	723	+58%	577	+26%	474	+4%	457
16	15	-8%	13	-16%	12	-21%	9	-43%	8	-48%	7	-53%	16
236	422	+79%	368	+56%	365	+55%	414	+75%	366	+55%	345	+46%	236
111	146	+32%	122	+10%	117	+5%	97	-12%	82	-26%	80	-28%	111
182	209	+15%	191	+5%	168	-7%	199	+9%	179	-2%	159	-12%	182
10	22	+126%	21	+108%	24	+143%	16	+66%	15	+53%	16	+66%	10
378	780	+106%	686	+81%	660	+75%	529	+40%	456	+21%	444	+17%	378
1,093	3,229	+196%	2,600	+138%	2,780	+154%	1,974	+81%	1,683	+54%	1,804	+65%	1,093
53	69	+29%	60	+12%	51	-4%	65	+22%	55	+3%	48	-10%	53
154	299	+94%	234	+52%	231	+50%	212	+38%	181	+18%	183	+19%	154
83	266	+219%	230	+175%	214	+157%	177	+112%	152	+82%	154	+85%	83
Grand Total	**2,889**	**6,370**	+120%	**5,413**	+87%	**5,271**	+82%	**4,505**	+56%	**3,833**	+33%	**4,035**	+40%

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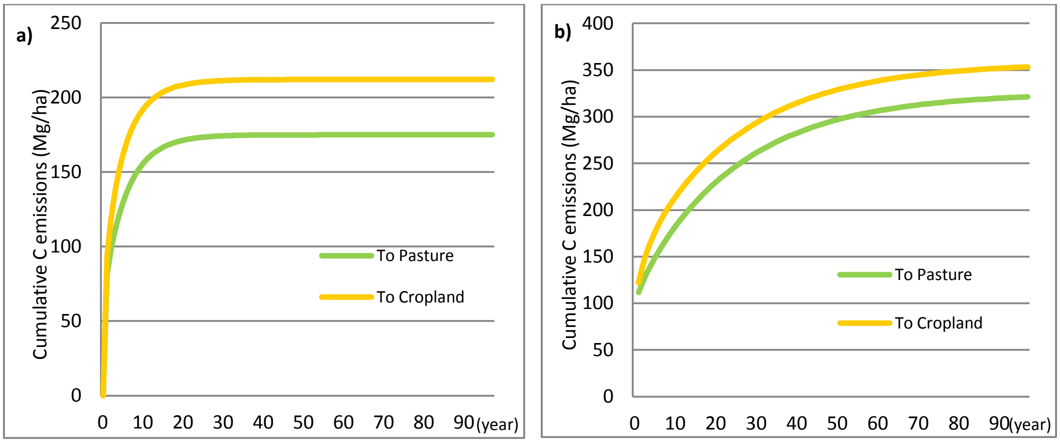
GHG emissions from Land Use Change

Supplementary Table 17 - Deforestation and reforestation carbon exchange parameters. These are adapted from the published greenhouse gas values for ecosystems[30]. We assumed that when land is cleared for cropping and other uses, excess biomass is burned (rather than being used for wood products), but that only a part is combusted immediately (fraction of biomass burned) and the remainder decays over a longer period, as does root and soil organic carbon.

	Carbon pool					Deforestation parameters		
Biome (no land-use)	Aboveground biomass (Mg/ha)	Root biomass (Mg/ha)	Dead wood (Mg/ha)	Litter (Mg/ha)	SOM (Mg/ha)	Fraction biomass burned	Decay constant (combustible)	Decay constant (roots, SOM)
Tropical forest	120	29	10	5	52	.52	.17	.40
Tropical Forest - SE Asia*	129	99	10	4	52	.52	.17	.40
Temperate Forest	194	45	49	25	48	.51	.04	.40
Boreal Forest	73	17	3	29	28	.59	.04	.40
Savanna	11	19		7	40	.75	.20	.40
Grassland	1	7		3	35	.83	.40	.40
Dense Shrubland	24	24		3	27	.75	.13	.40
Open Shrubland	4	9			19	.75	.40	.40
Tundra	6	11		60	43	.50	.40	.40
Desert	2	5			9	.75	.40	.40
Land-uses in different biomes								
Boreal Pasture	1	7		3	48	.50	.40	.40
Temperate Pasture	1	7		3	35	.50	.40	.40
Temperate Cropland	5	1		1	3	.50	.40	.40
Tropical Pasture	2	8			40	.50	.40	.40
Tropical Cropland	5	1		1	3	.50	.40	.40
Built-up					89	.00	.00	.00

* includes 11% tropical peat forest parameters. Peat included as root biomass.

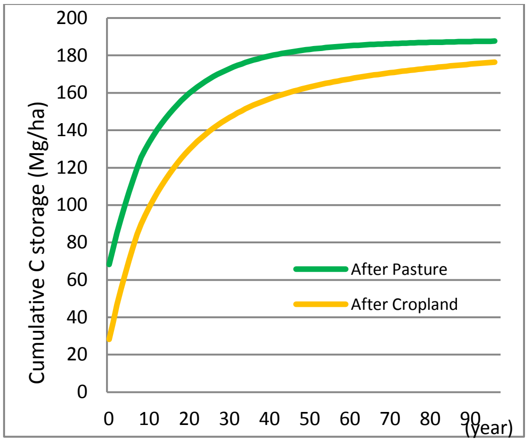
Supplementary Figure 7 – a) Cumulative carbon emission in years after clearing 1 ha of tropical forest; b) Cumulative carbon emission in years after clearing 1 ha of temperate forest. These are calculated with parameters set above.



Supplementary Table 18 - Reforestation carbon exchange parameters. Obtained from GHG values of ecosystems[30] and other sources that have examined reforestation[39]. In the case of reforestation, we model biomass accumulating at a decreasing rate as a function of its NPP, until it reaches the maximum carbon storage in the above and below-ground biomass, which for forests is assumed to be 80% of carbon storage in primary forests, and for grasslands and shrubland 100% of natural vegetation carbon storage.

Biome (no land-use)	NPP	litter half-life (years)	baseline respiration	% of primary carbon attainable (biomass)	% of primary carbon attainable (SOC)
Tropical forest	9.70	1.50	.56	80%	90%
Tropical Forest - SE Asia*	9.70	1.50	.56	60%	90%
Temperate Forest	5.44	7.50	.22	80%	90%
Boreal Forest	4.20	10.00	.41	80%	90%
Savanna	5.50	2.50	1.69	100%	100%
Grassland	2.80	2.50	1.38	100%	100%
Dense Shrubland	3.60	5.00	.30	100%	100%
Open Shrubland	1.50	5.00	.60	100%	100%
Tundra	1.20	60.00	.04	80%	90%
Desert	.60	10.00	.04	100%	100%

Supplementary Figure 8 - Cumulative C biomass storage in years after reforesting 1 ha of tropical forest .



Supplementary Table 19 – Calculated Land-use change emissions (due to cropland, pasture and settlement expansion) by region and scenario [$GtCO_2e$/year]. These follow from the changes in area of cropland and pasture in different regions, biomes and land suitability.

	2009	Scenario CT1	Scenario CT2	Scenario CT3	Scenario YG1	Scenario YG2	Scenario YG3
Central Asia		0.00	-0.01	0.02	-0.02	-0.02	0.01
East Asia		0.56	0.19	-0.80	0.32	-0.04	-0.82
Eastern Europe		-0.37	-0.49	-0.61	-0.81	-0.89	-1.01
Latin America		-0.02	-0.48	-0.72	-0.05	-0.48	-0.79
North Africa		0.07	0.00	-0.04	-0.02	-0.08	-0.11
Northern America		0.07	-0.09	-0.31	0.02	-0.17	-0.36
Oceania		-0.03	-0.08	-0.07	-0.12	-0.17	-0.19
South-eastern Asia		1.21	0.78	0.61	0.06	-0.15	-0.23
Southern Asia		2.03	1.67	1.78	1.06	0.45	0.70
West Europe		0.04	-0.15	-0.47	0.00	-0.24	-0.51
Western Asia		0.17	0.08	0.07	0.04	0.00	0.00
Sub-Saharan Africa		3.39	2.26	1.45	2.27	1.31	0.73
Grand Total	**4.0**[32]	**7.1** +78%	**3.7** -8%	**0.9** -77%	**2.8** -31%	**- 0.5** -112%	**-2.6** -164%

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GHG emissions from agriculture

Supplementary Table 20 - Agriculture emissions by region and scenario [GtCO$_2$e/year]. We calculate emissions associated with fertiliser use and production, rice paddy methane emissions, emissions from enteric fermentation (associated with beef, goat & sheep meat and dairy production) and manure management (associated with all animal food products, to a varying degree), and energy use in mechanisation. Calculations were based on scaling up today's emissions in each of these categories linearly along with emission sources. These are: the total area of rice (for paddy rice emissions); each livestock product quantity (for livestock emissions[33]), fertiliser tonnage (for fertiliser use and production emissions; these are assumed to improve for 20%); and total crop production in carbon for mechanisation.

	2009	Scenario CT1		Scenario CT2		Scenario CT3		Scenario YG1		Scenario YG2		Scenario YG3	
Fertiliser use	1.17 [31]	1.70	+45%	1.45	+24%	1.36	+16%	2.10	+79%	1.77	+51%	1.60	+37%
Fertiliser production (energy)*	0.95 [32]	1.10	+16%	0.94	-1%	0.88	-7%	1.35	+43%	1.15	+21%	1.04	+10%
Livestock enteric fermentation & manure	3.49 [31,33]	7.69	+120%	7.24	+107%	4.04	+16%	7.69	+120%	7.24	+107%	4.04	+16%
Paddy Rice	0.94 [31]	1.21	+29%	1.09	+16%	1.05	+12%	0.93	-1%	0.83	-12%	0.81	-14%
Agriculture energy use	0.84[32]	1.34	+60%	1.16	+38%	0.97	+15%	1.35	+61%	1.15	+36%	0.99	+18%
Grand Total	**7.4**	**13.0**	+77%	**11.9**	+61%	**8.3**	+12%	**13.4**	+82%	**12.1**	+64%	**8.5**	+15%

* Emission intensity of fertiliser production is assumed to improve for 20%.

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Supplementary Note: Comparison with other approaches

By exploring the consequences of current yield trend trajectories for global land-use and its impacts, we obtained bleaker results than most previous studies. For example, by contrast with our study, Nelson et al.[40] predicted, on the basis of IMPACT model results, only a small net change in global cropland area. Furthermore, in some areas where we predict large increases in cropland areas, namely China and India, they predicted significant decreases, with the help of increased trade. The recently published agro-economic model inter-comparison study[41] reported that those types of model project an increase in cropland of 10-25% (+1.5 - +4 Mkm^2)[41], whereas our business-as-usual scenario predicts an increase of 6.5 Mkm^2. The more optimistic results in some previous studies are a consequence of assuming an increase in agricultural productivity at a faster rate than more recently established current yield trends suggest.

Furthermore, our model also has no cost to cropland expansion or any kind of inertia to land conversion. The future food demand predictions, which we use, are based on historical trends, and therefore already include some historical levels of land conversion inertia. It is however possible that land conversion inertia may increase as land becomes scarcer. Some models also constrain agricultural expansion to certain types of current land use only; for example the MagPIE model only allows it on 'frontier forests' and not on the majority of forests that are currently harvested[41]. Lessons from historical and current land-use change, for example in Sumatra, suggest that forestry land-use (or even formal protection of forests) is not a large deterrent for cropland conversion. The immediate necessity for food (in the case of subsistence agriculture) and quick payback (in the case of commercial agriculture) appear to give cropland precedence over other land-uses (with the exception of settlements/urbanisation), even if the conversion is not rational in the long-term economic perspective. We therefore decided against constraining agricultural expansion.

The last significant difference in land-use modelling is in the treatment of trade. Our model is not economic, and can only include trade as an exogenous function. We kept it constant under main scenarios and varied it in the sensitivity analysis. In agro-economic models, trade is an endogenous function, and optimised for best productivity and profitability of suppliers. Increased trade generally results in higher overall efficiency of global food production[42] and inclusion of more liberal trade may affect the model results. We believe different treatments of trade are particularly influential on regional results. For example, agro-economic studies predict a continuous large expansion of agricultural land in Latin America (for exports), while ours predicts a small retraction because of the levelling-off of demand and a potential to increase herding densities.

In addition to the differences in calculating land-use futures, studies also differ in the methodology of calculating GHG emissions. The biggest difference between ours and other models is that we also include agricultural energy emissions from mechanisation and fertiliser production. In IPCC and UNFCC these are counted in energy emissions. However, we include them here, because they also scale up or down with agricultural intensification or food demand reduction. Other differences, such as the use of newer warming potentials for GHGs (e.g. 25 CO_2e as oppose to 21 for methane), also make our emissions higher than those of comparable studies.

Our results are generally most similar to the study by Tilman *et al.*[18]. The findings about the great positive environmental impacts of reduction of meat consumption to healthy levels also match those of Stehfest *et al.*[43], although we predicted a smaller decrease in pasture area. Two very recent studies also arrived at the similar conclusions regarding dietary change and GHG emissions: that a) reducing consumption to the level healthier than current average diets greatly reduces GHG emissions[44], and that b) such reductions are indeed necessary for keeping the total GHG emissions from all human activities under the dangerous, 2°C climate change[45]. Our study is more comprehensive in that it includes the whole agricultural system, not only the livestock production, and in its global coverage. The studies are complementary to ours, as the focus of our study is on land use change and system analysis, whereas the foci of the two other studies are the technological transition in the livestock sector (e.g. manure management improvements)[45] and nitrogen flows[44].

Supplementary Table 21 –Comparison of the modelling approach with other studies

	IMPACT Model [46]	Tilman et al. 2011 [18]	GLOBIOM Model [19,47]	This study
Type	Partial equilibrium economic model.	Multiple regression analysis.	Partial equilibrium economic model.	Statistical data driven scenario analysis.
Agricultural system included	Cropping and pasture	Cropping only	Cropping, pasture (and forestry)	Cropping and pasture
Land-use change location	NI	NI	Grid based	Based on agricultural suitability.
Cropland area	Based on crop price, historical changes and expert judgment.	Total crop area based on demand and yields.	Based on endogenously calculated demand in each region, and yields.	Total crop area based on demand and yields.
Future Yields	Function of commodity price & water availability.	Function of current trends, fertilizer use & technology transfer.	Calculated with EPIC (a process based yield model), depending on management system	Based on current yield trends or Yield gaps.
Environmental impacts included	Required water.	GHG emissions from fertilizer & deforestation. Required fertilizer.	GHG emissions from fertilizer, deforestation & livestock	GHG emissions from fertilizer, deforestation, livestock & energy use in agriculture. Required fertilizer & water. Lost natural vegetation.
Other indicators included	Malnourished children Risk of hunger.	Not Included	Not Included	Not Included
Explicit Changes in agricultural system (scenarios)	NI	Rate of technological transfer to developing countries.	Many over the course of several papers. Changes to livestock management systems, bioenergy scenarios, yield scenarios.	Food waste reduction. Dietary change.

Supplementary Table 22 - Comparison of the results to other studies

		This study		Tilman *et al.* (2001) [48]	IMPACT[40]	Tilman *et al.* (2011)[18]			Agricultural intercomparison study*[41]	GLOBIOM [41,49]
		CT1	YG2		Perfect mitigation baseline	Past trend trajectory	Technology transfer, N-min	Technology transfer, Land-sparing	Medium economic development and population, no climate change	High inputs, complete LUC accounting (including SOC)
Cropland increase	Mkm^2	6.5	-1.4	3.3	0.3	10	4	2	1.5 - 4	1.8
Pasture increase	Mkm^2	4.3	1.1	7.3	NI	NI	NI	NI	-2 - +4	4
GHG emissions	GtCO$_2$/y	20.2	11.7	NI	NI	11.0**	5.1**	3.7**	NI	7.9***
Fertiliser use	Mt/y	154	161	236	NI	250	124	225	NI	NR

*4 partial, and 6 General equilibrium Agro-economic models: AIM, ENVISAGE, EPPA, FARM, GCAM, GLOBIOM, GTEM, IMPACT, MAGNET, MAgPIE

** includes only emissions from clearing for cropland, and fertiliser use; does not include emissions from livestock, rice paddies and agricultural energy use.

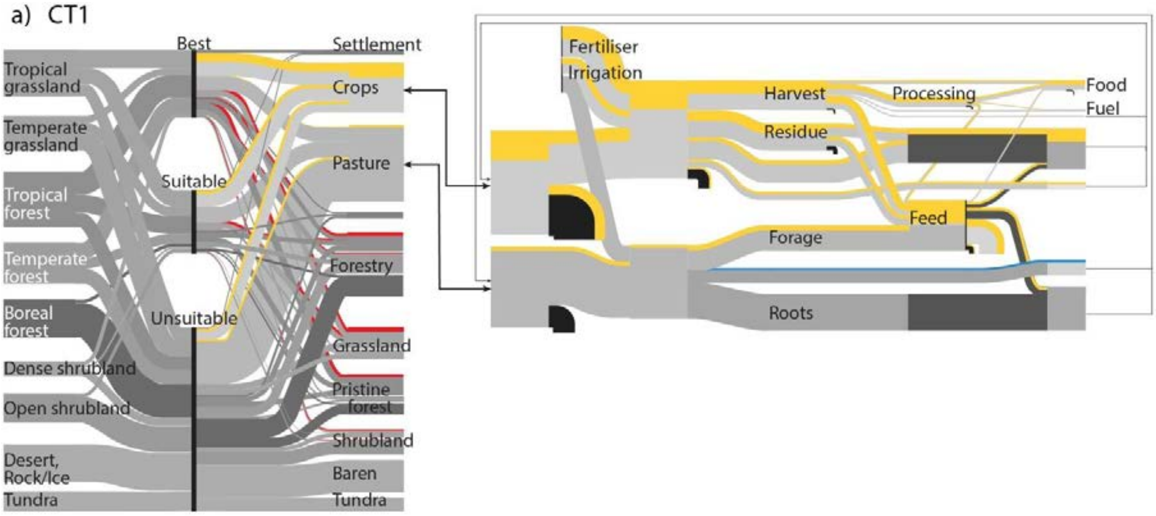
*** does not include emissions from agricultural energy use.

NI = Not Included; NR = Nor Reported

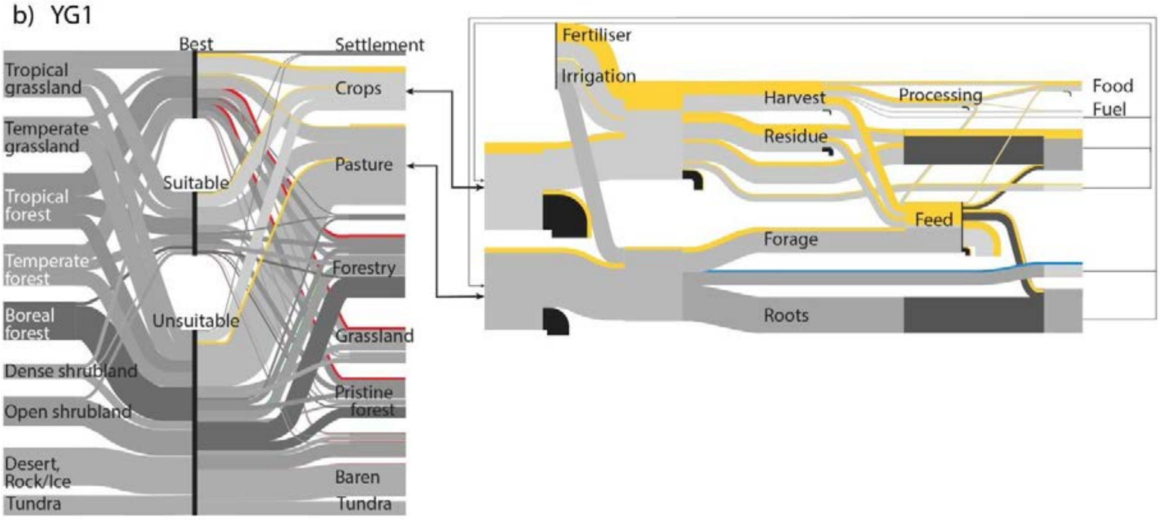
Future scenarios in Sankey diagrams

Supplementary Figure 9 Diagrams for the six 2050 scenarios showing land use distribution by area (left-hand sides of each diagram) and agricultural biomass flows as Net Primary Productivity (right-hand sides, which represent and expand the crop and pasture land uses from the left-hand sides). Colours are used to highlight changes from the situation in 2009: Red - shows a decrease in land areas with natural land cover; Green - shows an increase in natural land areas; Yellow - shows increases in both agricultural land areas and associated biomass flows; Blue - shows decreases in both agricultural land areas and associated biomass flows. CT scenarios (**a,c,e**) and YG scenarios (**b,d,f**) differ in their yields - the YG scenarios involve a greater increase of fertiliser, and some reductions in land degradation, so the YG scenarios require less land to achieve the same harvest. The amount of harvest needed to deliver the same food service decreases from the top to the bottom scenario, as a result of, first, reduced waste (**c,d**) and second, as a result of implementing Healthy diets (**e,f**).

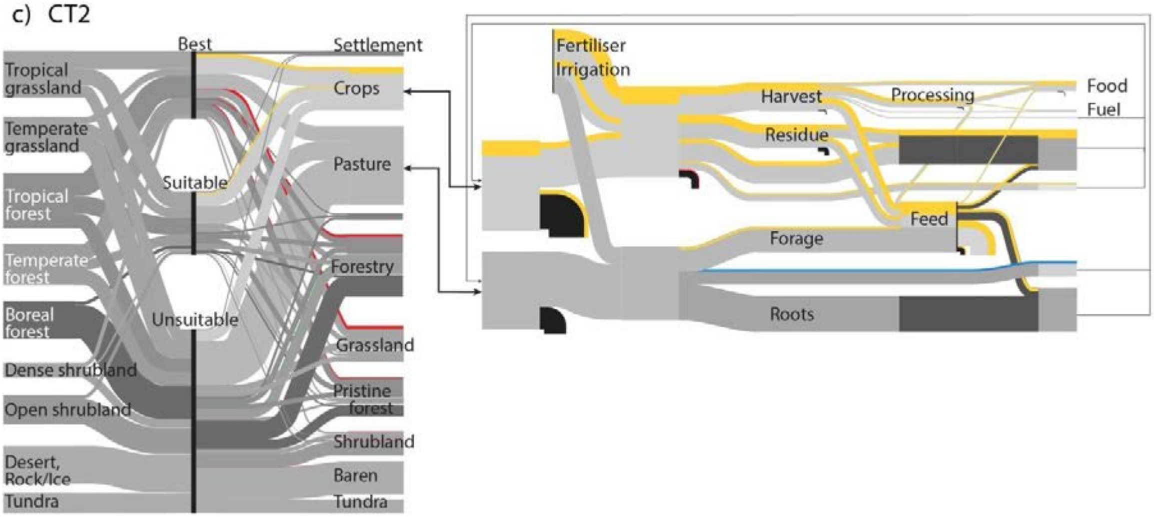
a) CT1



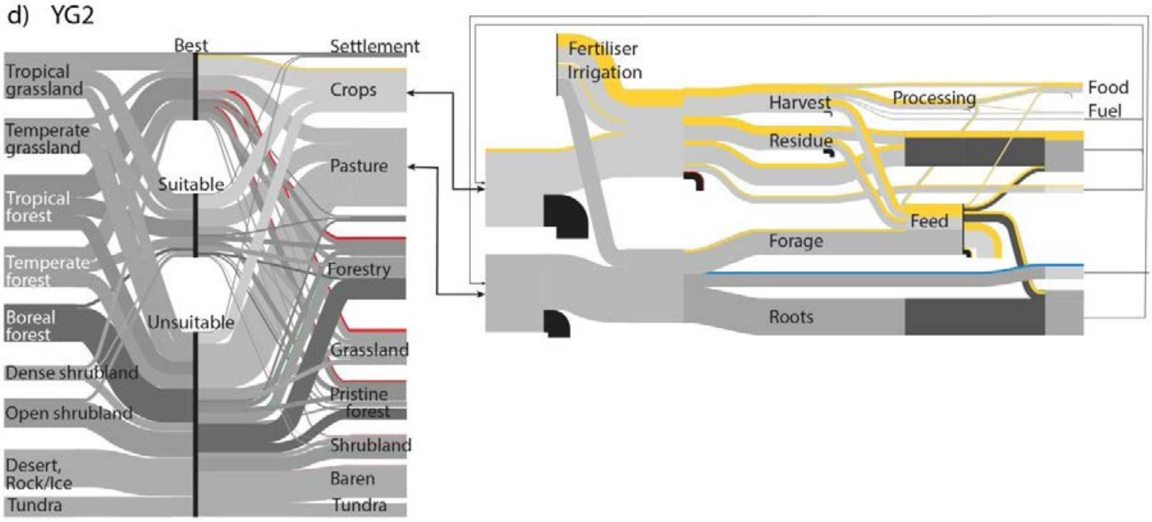
b) YG1



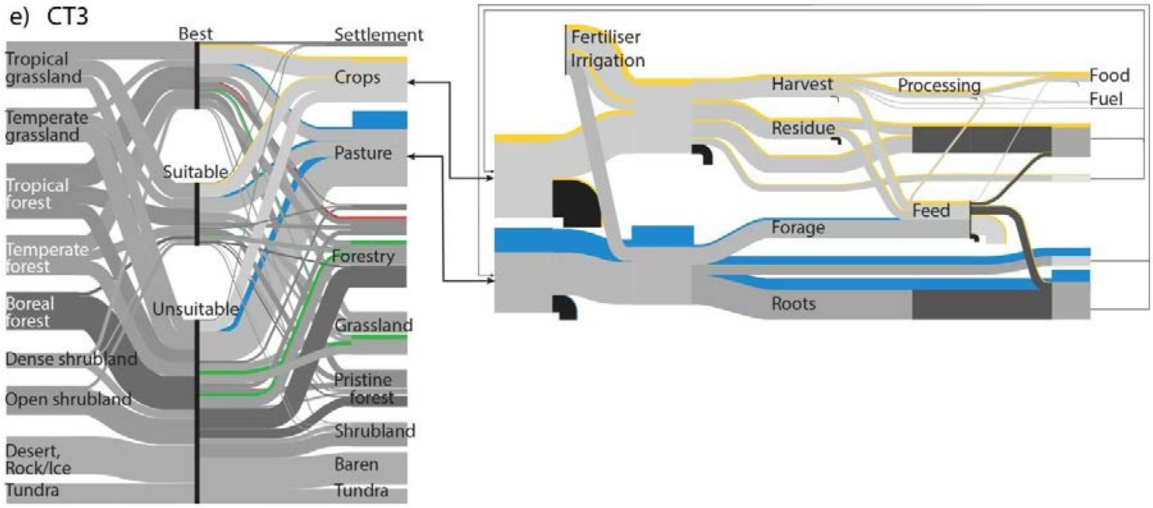
c) CT2

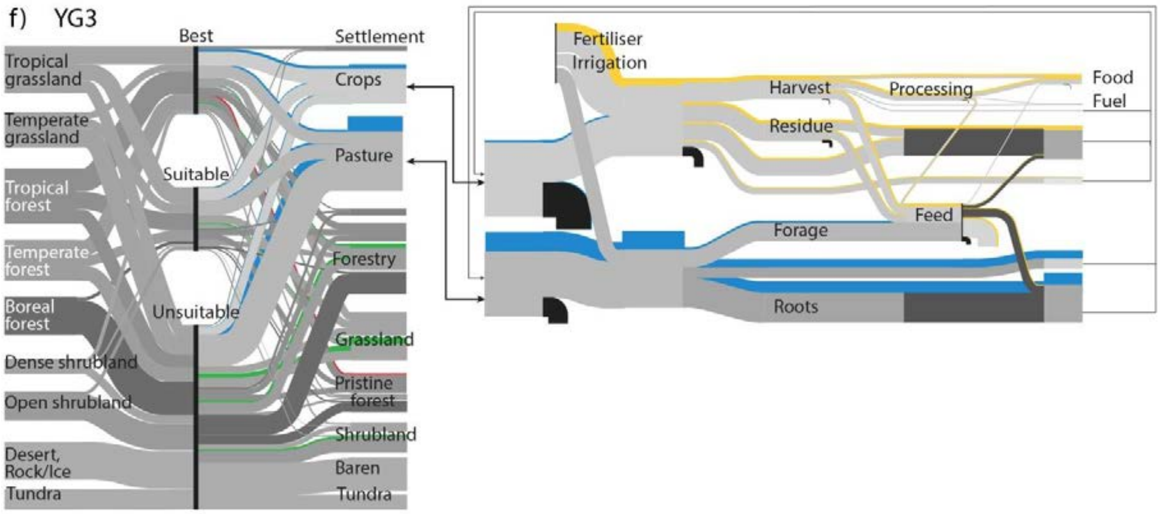


d) YG2



e) CT3




f) YG3
Best
Settlement
Tropical grassland
Crops
Temperate grassland
Pasture
Suitable
Tropical forest
Temperate forest
Forestry
Boreal forest
Unsuitable
Grassland
Dense shrubland
Pristine forest
Open shrubland
Shrubland
Desert, Rock/Ice
Baren
Tundra
Tundra
Fertiliser
Irrigation
Harvest
Processing
Food
Fuel
Residue
Forage
Feed
Roots

Supplementary Note: sensitivity analysis

4.1 Population

Scenarios presented in the results section are based on the mid-range UN population projection for 2050, which has been recently revised up to 9.6 billion[1]. Changing population by +13% (UN high), increases GHG emissions by +10%, while a reduction in population for 13% (UN low) results in a 9% reduction in GHG emissions (Table 4 in the main text).

4.2 Yields

We tested two additional sets of yield assumptions; one involves yields completely stagnating, showing catastrophic results (Table 4). This could happen if, for example, negative impacts of climate change entirely counter-balance any technological improvements (which, according to research by Lobell *et al*.[50] and Ray *et al*.[51] may be happening in some locations in the world). We also tested assumptions that yields could increase at a rate double those in the recent past, for example as a result of a great advance in GMO technology. Doubling these trends would produce results similar to yield gap closures (Table 4), but with larger regional imbalances.

4.3 Livestock production system characteristics

The model is sensitive to the assumptions about the rates of industrialization of livestock systems and the carrying capacity of pastures. In core scenarios we have assumed a move towards more industrialized livestock systems, relying more on grain feed. The total extent of pasture would have to more than double if livestock systems instead scale-up without changes of feeds and stocking densities (Table 4), leading to a great increase in GHG emissions. The model does not capture some negative effects of livestock industrialisation, such as the socio-economic, ethical, and environmental impacts other than GHG emissions. Also not captured is the increased risk of ecological collapse associated with overgrazing when pastures are exploited closer to (or above) their carrying capacity.

4.4 Trade

In the core scenarios, we assumed that food trade between regions remains at the absolute levels of the reference year, and that any surplus cropland in a region (for example in North America), will be abandoned and a converted to natural vegetation. If instead trade increases so that surplus cropland is used for export to regions with cropland deficits, it would help decrease cropland expansion and GHG emissions, albeit not greatly (Table 4). That is because there is either not much surplus land (CT1) or because surplus croplands do not necessarily achieve the yields of newly-converted croplands in deficit regions (YG2). These findings are different to those of Nelson at al.[40], who found trade to be very influential. The increased trade scenario nonetheless saves GHG emissions from deforestation, as the carbon emissions from converting primary forest are larger than the carbon sequestration of the equal area of re-forested secondary forest. We have not considered the increased GHG emissions from transport of food.

4.4 Fertiliser use efficiency

One of the goal that sustainable intensification is trying to achieve is improved fertiliser use efficiency. In our YG scenarios, we already include fertiliser use efficiency improvements, in line with published literatrure[28], by eliminating all over-fertilisation. If we assumed that in addition, near-optimum yields can be achieved with another 20% fertiliser use efficiency (achieved with advance precision fertilisation techniques), the GHG emissions from agriculture would improve for 4%. The model therefore has some sensitivity to fertilisation use efficiency assumptions, but even the most optimistic assumption would not change the main conclusions.

4.5 Other uncertainties

Urbanisation. Although land used for settlements and infrastructure occupies a relatively small area, its predicted 130% increase[52] to 2050 could contribute a further 0.9 GtCO2e of land use change emissions per year. As urban areas encroach on cultivated land, cultivation has to encroach further into natural vegetation, thereby causing a net increase in GHG emissions. We have not included these indirect emission effects as a result of expansion of settlements, as they are highly uncertain. Some estimates of regional increases are provided from global forecasts by Angel[52], who argues that urban land increase is most sensitive to the assumptions about the rate of urban density decrease, which has historically been between 1-2%. For a density decrease of 1% the built-up land expansion is predicted to be 1.9 Mkm^2, while at a constant density it would be 1.2 Mkm^2 , and for a density increase of 2% it would be 3.2 Mkm^2.

However, this is also dependent on the rates of migration of rural populations to cities, and on the changing social mix and housing preferences in urban areas.

Forestry. Increased cropland areas encroaching on forest land may result in biodiversity losses and additional emissions from intensified forestry in the reduced forest areas, which are not included in our results.

Bio-energy. Our model is well suited to calculate alternative scenarios associated with bio-energy; it calculates the amount of agricultural residues and surplus agricultural land for each agricultural scenario. However this is outside the scope of the current paper. Our results suggest that there will be very little spare land for such developments, unless food demand changes significantly.

Sensitivity to other uncertain assumptions, for example in the calculations of fertiliser use, irrigation demand, and GHG emissions were not tested separately.

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