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Importance of food-demand management for climate mitigation

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Recent studies show that current trends in yield improvement will not be sufficient to meet projected global food demand in 2050, and suggest that a further expansion of agricultural area will be required. However, agriculture is the main driver of losses of biodiversity and a major contributor to climate change and pollution, and so further expansion is undesirable. The usual proposed alternative—intensification with increased resource use—also has negative effects. It is therefore imperative to find ways to achieve global food security without expanding crop or pastureland and without increasing greenhouse gas emissions. Some authors have emphasized a role for sustainable intensification in closing global 'yield gaps' between the currently realized and potentially achievable yields. However, in this paper we use a transparent, data-driven model, to show that even if yield gaps are closed, the projected demand will drive further agricultural expansion. There are, however, options for reduction on the demand side that are rarely considered. In the second part of this paper we quantify the potential for demand-side mitigation options, and show that improved diets and decreases in food waste are essential to deliver emissions reductions, and to provide global food security in 2050.

Over 35% of the Earth's permanent ice-free land is used for food production and, both historically and at present, this has been the greatest driver of deforestation[1] and associated biodiversity loss. Food demand has increased globally with the increase in global population and its affluence. Globally, the demand for food will undoubtedly increase in the medium-term future. The United Nations' Food and Agriculture Organization (FAO) has projected that cropland and pasture-based food production will see a 60% increase by 2050, calculated in tonnages weighted by crop prices[2]. Another study[3] projected a ~100% increase in cropland-based production, measured in calories, and including both food and livestock feed. The difference between the two studies can be partly explained by shifts towards more cropland-grown livestock feed (as opposed to pasture-based), as countries become richer.

Because agriculture is not on track to meet this demand, according to current trends in yields[4], it has been widely suggested that we should strengthen global efforts in sustainable intensification of agriculture[5–8]. This involves an increase in crop yields while also improving fertilizer, pesticide and irrigation use-efficiency. The existence of yield gaps—the difference between yields achieved in best-practice agriculture and average yields in each agro-climatic zone—suggests that the scope for sustainable intensification is large. Yield gaps are wide in some developing countries, notably in Sub-Saharan Africa, but also exist in developed countries[9,10]. However, to complement these supply-side options, demand-side measures may also be necessary[6–8,11–13].

The objectives of this paper are to estimate the environmental consequences of the increasing food demand by 2050, and to quantify the extent to which sustainable intensification and demand reduction measures could reduce them. Previous quantitative studies have examined future food systems and their impacts on land use[14]. However, few have touched on sustainable intensification[3] or demand-side reductions[12,15,16]. The types of model used in these studies include multiple regression analysis[3], partial equilibrium models (such as the IMPACT (ref. 17) and GLOBIOM (ref. 18) models), and Integrated Assessment models (such as IMAGE; ref. 19). We based our calculations on a transparent, data-based biophysical analysis, which allows us to vary the key drivers of future land use, including those on the demand side. Our scenario based on current trends predicts a higher need for agricultural expansion than previous models[20]. Reasons include using less optimistic projections for future agricultural productivity[4], and not including barriers for land-use conversions. Our methodology is described in more detail in Supplementary Notes 1–2, Figs 1–8, and Tables 1–20. A comparison between our approach and previous studies is detailed in Supplementary Notes.

Analysis of current land use as a baseline

Our approach uses a model of the current global land system, with 2009 as a base year, based on empirical data. Two key components of this model are: an analysis of land distribution, which enables us to allocate land-use change, and determine natural ecosystem losses and GHG emissions; and a map of agricultural biomass flows, which is required to represent the demand-side options. In Fig. 1 we visualize the land system in 2009 with two Sankey diagrams, one for each component: Fig. 1a shows the distribution of land use, which connects to a representation of agricultural biomass flows (Fig. 1b). Sankey diagrams act as a visual accounting system and facilitate communication to a wide array of stakeholders in land use and management, by illustrating magnitudes, flows and efficiencies.

The analysis of land distribution overlays agricultural suitability[10] with global biomes[21] and current land use[22,23] in each region (Fig. 1a). This shows in which biomes cropland and pasture

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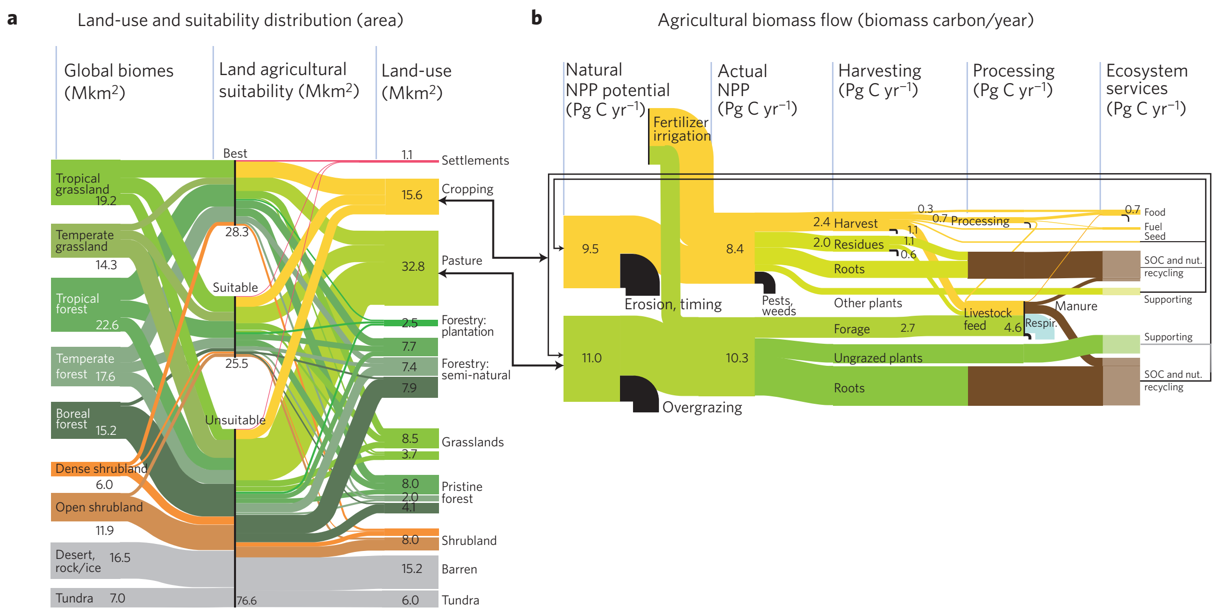

Figure 1 | Distribution of terrestrial biomes, suitability and land use and its connection to the global agricultural annual biomass flows for 2009. a, Major global biomes are traced onto three classes of land for agricultural suitability. 40% of the total ice-free land area is suitable for agriculture, of which about half is already in agricultural use for either pasture or cropping. **b**, Pasture and cropland areas support agricultural biomass growth, which we follow through harvesting and processing stages, to the delivery of final services. In both panels the width of each line is proportional to the magnitude of flow. Black lines show losses.

expansion have happened in the past, and where they are likely to occur in the future. For example, further cropland expansion is likely in tropical forests and savannahs, where approximately 75% of their area is suitable for agriculture.

Where possible, we base the agricultural biomass flow analysis for the base year of 2009 (Fig. 1b) on FAO agricultural statistics[24]. These are supplemented where necessary by other data sources[25–29]: for example on pre-harvest losses, livestock feeds, crop residues and their uses. Given the uncertainty in the data, subsistence farming is likely to be under-represented. Food sourced from forests and aquatic systems is not included. Net primary productivity potential of cropland and pasture is a starting point for biomass flows. Some productivity potential is lost (~5 PgC yr^{-1}) to soil erosion (caused by overgrazing on pasture) and to the use of cropping systems that do not achieve the productivity of all-year natural vegetation. On the other hand, humans artificially improve productivity with irrigation[30,31] and fertilization[32] (adding ~4.3 PgC yr^{-1}).

It is striking how small the amount of food actually delivered is (0.7 PgC yr^{-1}, or 2,490 kcal person^{-1} d^{-1}), compared with overall cropland productivity (8.3 PgC yr^{-1}), or compared to harvest (2.4 PgC yr^{-1}). The discrepancies are mainly due to the inefficiency of supplying food calories as livestock products, and to losses in every step in the system (shown in Fig. 1b as black curved lines).

Livestock globally consume 4.6 PgC yr^{-1} as feed (1.2 PgC yr^{-1} of crop products, 0.7 PgC yr^{-1} of crop residues and 2.7 PgC yr^{-1} of pasture forage). The main outputs, meat and dairy, contain only about 0.12 PgC yr^{-1} or 2.6% of that carbon mass, before losses (contributing 410 kcal person^{-1} d^{-1}). These results are confirmation of both the trophic energy inefficiency and the land-intensiveness of animal-based food products. We estimate that grazing on pasture unsuitable for cropping, whose natural climax vegetation is grass or shrubs, contributes approximately 14% of total livestock feed measured in carbon mass (0.6 PgC yr^{-1}). Such land use has no opportunity cost in cropping and does not cause deforestation, but can still have negative consequences for carbon storage and biodiversity. The latter is particularly true for 'improved' pastures, which, as opposed to semi-natural pastures, are sown and require artificial inputs. If we also add the crop residue feeds and processing co-products as efficient contributions to the livestock production system, together these support about 30% of current livestock production; the remaining 70% has to be seen as a very inefficient use of land to produce food.

Losses due to pests and weeds account for 1.0 PgC yr^{-1}, or 13% of plant growth on cropland (Fig. 1). This calculation is based on a single study[29] and is highly uncertain, highlighting the need for new world-wide studies of preventable pre-harvest losses. Losses further down the chain are smaller in mass, but nevertheless represent significant fractions of their representative flows (agricultural losses 0.18 PgC yr^{-1} (12%), processing losses 0.06 PgC yr^{-1} (8%) and food waste losses 0.08 PgC yr^{-1} (12%); these are calculated on the basis of a previous top-down study of losses in agriculture[26]). Importantly, the later in the chain the loss of biomass occurs, the more wasteful is the loss, as the biomass has already undergone previous transformation stages that required inputs of resources and energy.

From our analysis shown on Fig. 1, it is clear that if the demand for inefficient pathways of food supply (that is, livestock products) disproportionally increases, the whole system becomes not only larger, but also less efficient. Previous studies[3,17,33] directly link the demand for food commodities to agricultural production without considering possible changes in the supply chain that connect the two, and put most emphasis on yields. Our biomass flow map highlights that opportunities to reduce waste and improve efficiency are equally important.

Future scenarios

The interplay between intensification, waste reduction and dietary preferences, informed our choice for six parameter combinations for scenarios in 2050 (Table 1). The probabilities of these key variables are unknown. We examine sustainable intensification to the point of yield-gap closures as the scenario that best represents the collection of supply-side management changes that improve food supply and reduce environmental impact. It includes improved irrigation efficiency and eliminates over-fertilization. Food waste

Table 1 | Main parameters for the six core scenarios, split into two groups.

Scenarios	Yields		Demand-side reductions	
	Current trends in yields	Yield gap closures (sustainable intensification)	50% food waste reduction	Healthy diets
CT1	×			
CT2	×		×	
CT3	×		×	×
YG1		×		
YG2		×	×	
YG3		×	×	×

The Current Trends (CT) scenarios assume yields in each region will continue to increase at current rates[4]. The Yield Gap (YG) scenarios assume that sustainable intensification will achieve yield gap closures[10] in all regions. Both yield scenarios are set against three different options on the demand-side: no changes to the system; a 50% reduction in food and agricultural waste; and waste reduction as above plus a move towards healthy diets, meaning the average consumption of sugar, oil, meat and dairy is limited according to expert health recommendations[37–40].

and dietary change are the two most prominent demand-side measures proposed in previous studies[12,34,35] and have been shown to have a large potential, so we have selected these two for closer examination in our study. Changes in agricultural biomass flows and land distributions in the six scenarios are shown in Supplementary Fig. 9. For each scenario we estimated four indicators: forest losses, carbon emissions (from land-use change and agricultural production), fertilizer use and irrigation use (Table 2).

Baseline scenarios assume that global population increases to 9.6 billion by 2050 (ref. 36), and that dietary preferences change with socio-economic transitions[2]. The average per capita consumption increases to 2,710 kcal d^{-1} (including 470 kcal of livestock products). Large conversion (+42%) to cropland will be necessary if yield improvements at current rates, combined with livestock intensification, are the only changes to the agricultural system (CT1 scenario, see Table 2). A predicted increase in food demand would result in an overall ~77% increase in agriculture-related GHG emissions, due to increased deforestation rates (a 78% increase to 7.1 $GtCO_2e\ yr^{-1}$; mostly in Sub-Saharan Africa and South-East Asia) and increased emissions from livestock, fertilizer and higher agricultural energy use associated with mechanized agriculture (a 76% increase to 13.0 $GtCO_2e\ yr^{-1}$). There would also be large losses of tropical forests (3 Mkm^2) and other valuable ecosystems. This scenario, which represents 'business-as-usual', would, therefore, have a number of very detrimental consequences.

The YG1 scenario ('yield gap closure') fares a lot better (Table 2). Previous studies[3,33] have already established that decreased deforestation more than offsets any increase in emissions associated with sustainable intensification. Here we confirm this, while also including some relevant emission sources omitted in previous studies (fertilizer production and agricultural energy use). However, without demand reductions, cropland would still need to expand by ~5%, pasture by ~15%, and GHG emissions would increase by ~42% compared with current levels, even with currently-attainable yields being achieved world-wide. Our results indicate that yield-gap closures achieved with sustainable intensification would not meet projected future demands without an increase in agricultural area and in GHG emissions. Sustainable intensification is crucial; however, it is unlikely to be sufficient.

Demand-side reductions show further promise. Here we quantify potential savings from cutting food and agricultural waste by half, which has previously been suggested as a promising mitigation strategy[26,34,35]. These scenarios (CT2 and YG2) reduce the area of cropland by ~14% and GHG emissions by 22–28% (~4.5 $GtCO_2e\ yr^{-1}$) compared with their respective baseline scenarios for 2050 (CT1 and YG1; Table 2). Along with the reduced cropping area, reducing waste would also reduce fertilizer and irrigation water demand and associated environmental impacts. Improvement potentials are similar in scale in all regions; improving crop storage in developing countries while raising awareness and setting policy targets for food-waste reduction worldwide could be viable climate mitigation strategies.

We also tested dietary adaptation as a demand-side measure, by assuming average diets that are considered to be 'healthy' on the basis of nutritional evidence[37–40]. Their parameterization is described in detail in the notes to Supplementary Table 3. The main alteration from the projected dietary preferences is a reduction in the consumption of energy-rich food commodities (sugars and saturated fats, including livestock products) in regions where diets projected for 2050 exceed established health recommendations. The necessary alterations vary by regions. For example, in industrialized regions, the average consumption of livestock products (which are high in saturated fats) largely exceeds healthy levels[37], and a reduction, or no further increase, could be desirable on health grounds. However, we recognize that livestock can play a critical nutritional role in many regions, societies and agricultural systems. The model ensures that adjusted diets still provide enough protein[37], and a daily calorie intake of 2,500 kcal, through an increase in pulses and staples. These levels are conservative to avoid potential deficiency at an individual level. Regional cultural preferences and crop suitability are retained where possible within these guidelines. Such altered average diets can hardly capture the complexities of nutritional requirements across regional populations; but for brevity we hereafter refer to them as 'Healthy Diets'.

Scenarios involving Healthy Diets (CT3 and YG3 in Table 2) reduce the area necessary for cropping by ~5%, pasture by ~25% and the total GHG emissions by ~45%, compared to the CT2 and YG2 scenarios. Almost all of these large GHG emission savings (5.6 out of ~6 $GtCO_2e\ yr^{-1}$) are associated with livestock reductions. There are two sources of these savings: a decrease in enteric fermentation and manure emissions, and carbon sequestration occurring with a return of some of crop and pasture lands to natural vegetation. Implementation of healthy diets would therefore greatly benefit both the environment and the general health of the population[37] in regions where excessive consumption of energy-rich food occurs, or may develop.

The changes towards healthy diets are greatest in the industrialized world, which, with some exceptions, also produces most of the livestock products. Therefore the greatest reductions in impacts are in temperate zones, rather than the tropics. All scenarios, including the most optimistic one (YG3), incur losses of pristine tropical forests due to the combination of large predicted increases in population and per capita food demand in the tropics, and the suitability of current forest land for conversion to cropland. One of the goals of sustainable agriculture is to avoid further expansion into tropical forests[7], but this appears to be unachievable with changes in the agricultural sector alone.

The results from our model are highly sensitive to some assumptions, especially those about yields, total population and livestock system developments; they are somewhat sensitive to fertilizer assumptions and less sensitive to assumptions about trade (Table 3 and Supplementary Note). If global population is assumed to be 14% higher, then the resulting cropland area increases by 14%, and GHG emissions increase by 26%. Under more pessimistic assumptions, results change even more. For example, if we assume yield stagnation on today's level, we would expect the resulting cropland area to increase by about 27%, (the difference between today's yields and yields in CT1). However, the combination of demand growth and stagnating yields causes expansion into relatively unsuitable land in regions that exhaust their reserves

Table 2 | Main indicator outputs for six 2050 scenarios.

	Units	2009*	CT1	CT2	CT3	YG1	YG2	YG3
Cropland	Mkm^2	15.6	22.2 (+42%)	19.2 (+23%)	18.2 (+17%)	16.4 (+5%)	14.2 (−9%)	13.7 (−12%)
Pasture	Mkm^2	32.8	37.1 (+13%)	33.7 (+3%)	25.4 (−23%)	37.7 (+15%)	33.9 (+3%)	25.8 (−21%)
Net forest cover†	Mkm^2	26.1	22.6 (−14%)	23.9 (−8%)	26.0 (−0%)	24.0 (−8%)	25.9 (−1%)	27.2 (+4%)
Tropical pristine forests	Mkm^2	7.9	7.2 (−10%)	7.3 (−8%)	7.5 (−6%)	7.5 (−6%)	7.7 (−3%)	7.7 (−3%)
Total GHG emissions	$GtCO_2\ yr^{-1}$	11.4	20.2 (+77%)	15.7 (+38%)	9.3 (−19%)	16.2 (+42%)	11.7 (+2%)	5.9 (−48%)
Fertilizer use	$Mt\ yr^{-1}$	106	154 (+45%)	136 (+29%)	125 (+18%)	190 (+79%)	161 (+51%)	145 (+37%)
Irrigation water use	$km^3\ yr^{-1}$	2,890	6,370 (+120%)	5,410 (+87%)	5,270 (+82%)	4,500 (+56%)	3,830 (+33%)	3,790 (+31%)

Percentages in brackets are relative to values in 2009. In the two scenarios with no demand management, cropland area increases for 5–42%, pasture for 13–15%, there is significant deforestation and an increase in GHG emissions. YG scenarios fare better across the indicators, with the exception of fertilizer use. Demand reduction measures on the other hand improve all indicators. *Showing middle values[23,24,31,49], uncertainty ranges are up to ±70%. †Excluding boreal forests.

Table 3 | One-at-a-time sensitivity analysis for population, yield trends, trade, livestock intensification and fertilizer, using the CT1 or YG1 scenario as a baseline.

Sensitivity scenario	Change in inputs from the baseline scenario	Change in key outputs		Relative sensitivity index*	
		Cropland (Mkm^2)	GHG emissions ($GtCO^2\ yr^{-1}$)	Cropland	GHGs
UN high population	2050 population from 9.6 to 10.9 billion (+14%)	25.3 (+14%)	25.4 (+26%)	1.05	1.90
UN low population	2050 population from 9.6 to 8.3 billion (-14%)	19.0 (−14%)	15.0 (−26%)	1.05	1.89
Stagnating yields	Average yield from 1.8 to 1.3 $tC\ ha^{-1}$ (−27%)	31.2 (+41%)	28.8 (+43%)	−1.44	−1.51
Two-fold increase in yield improvement rates	Average yield from 1.8 to 2.3 $tC\ ha^{-1}$ (+27%)	17.9 (−19%)	16.1 (−20%)	−0.72	−0.76
Increased trade from baseline scenario†	Total trade from 103,300 to 162,800 tC (+58%)	21.6 (−3%)	19.7 (−2%)	0.02	0.04
Fertilizer use efficiency in YG1 improved further	Total fertilizer use from 189,820 to 151,748 ktN (−20%)	16.4 (0%)	15.5 (−4%)	0	0.21
		Pasture (Mkm^2)	GHG emissions ($GtCO^2\ yr^{-1}$)	Pasture	GHGs
Livestock densities and feed as in 2009	Livestock products per area from 44.5 to 21.8 $kgC\ ha^{-1}$ (−51%)	73.3 (+98%)	27.7 (+37%)	−1.91	−0.73
Increased stocking density, but no intensification	Livestock products per area from 44.5 to 33.5 $kgC\ ha^{-1}$ (−25%)	47.9 (+29%)	23.1 (+15%)	−1.18	−0.59
Intensification, but 2009 stocking density	Livestock products per area from 44.5 to 34.4 $kgC\ ha^{-1}$ (−23%)	50.5 (+36%)	24.5 (+22%)	−1.59	−0.95

We varied the inputs based on alternative projections in the literature, or if such explicit projections are missing, by what we consider to be plausible levels. The larger the relative sensitivity index (last two columns, either positive or negative), the more sensitive the model outputs are. *Calculated as the ratio between the change in the input parameter and the relative change in the output. †The increased trade scenario assumes that any surplus cropland in land-rich countries (N. America, W. Europe) will not be abandoned, but used for exports into regions with largest cropland deficits. Without accounting for increased GHG emissions from transport, this incurs a small net emission saving.

of suitable land, resulting in a higher, 41% increase in cropland area required.

Our results show that only when strategies include significant elements of demand reduction is it possible to prevent an increase in agricultural expansion and agriculture-related GHG emissions. As previously suggested, the reduction of meat consumption could be tackled with economic incentives (such as a carbon tax) and the livestock sector should be included into a comprehensive climate mitigation policy[11]. Defining appropriate incentives may require some policy innovation and experimentation, but a strong commitment for devising and monitoring them seems essential[41]. Nutritional experts[40] have called for healthy nutrition to be elevated to the highest priority in national agendas, and that health requirements should dictate agricultural priorities, not vice versa. Our results are consistent with the findings of the recent IPCC report which reported a significant, but uncertain, potential for GHG reduction in agriculture from demand-side measures such as dietary change and waste reduction[42]; at the same time, this delivers better outcomes for food security and environmental impacts.

This study focuses on the overall global picture, but it is important to be aware of the demand differences between regions, and farming systems within regions. The South Asian and Sub-Saharan African regions are predicted to be the most critical in terms of the agricultural land expansion needed to meet the demand, in all scenarios. Water is a local issue, but even on regional levels the estimated amount of irrigation needed to support higher yields is challenging. The irrigation demand in South Asia, for example, is projected to increase by 80% in the YG3 scenario, and up to 200% in the CT1 scenario (Supplementary Table 12). Such large increases in irrigation water supply may not be possible, given that today the use of groundwater is already excessive in many places. For example, the extraction from the Upper Ganges aquifer is already

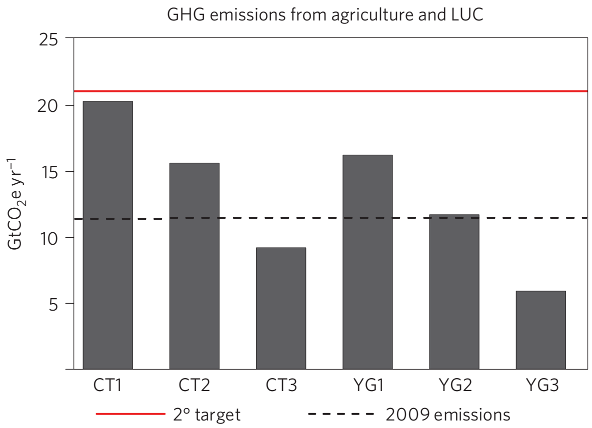

Figure 2 | Diagram showing the total GHG emissions from agriculture and land-use change due to agricultural expansion, for the six scenarios. The 2009 emissions from these sources are shown for comparison, as is the target in 2050 for avoiding dangerous climate change[45] (which should also accommodate energy, industry, and land-use-change emissions from other non-agricultural sources, such as settlement expansion). Agricultural energy use is already included and represents 2–3 $GtCO_2e$.

50 times larger than its estimated recharge rate[43]. Yield increases from increased irrigation may not be fully realized, implying that, to meet the demand, even greater expansion of cropland into natural landscapes would be necessary.

The model presented here would benefit from further developments to include yield as a function of availability of water and fertilizer, and the inclusion of climate change as a driver of yield changes and irrigation demand. This would enable estimation of how shortfalls in irrigation water availability might affect future food production. Bioenergy scenarios also lie outside the scope of this paper; unless food demand patterns change significantly, there seems to be little spare land for bioenergy developments without a reduction of food availability. It is important to note that the model results we present here are conservative in estimating the extent of agricultural land use and its associated emissions in the absence of these model limitations.

Although it is theoretically possible to decarbonize energy supply, such complete reductions are unattainable in the livestock part of the agricultural sector. Although there are many mitigation options in agriculture[44], our study indicates that a decrease in overall agriculture-related emissions can only be achieved by employing demand-side reductions. The agriculture-related emissions in our business-as-usual scenario (CT1) alone almost reach the full 2°C target emissions allowance in 2050 ($21 \pm 3\ GtCO_2e\ yr^{-1}$; ref. 45). Even scenario YG2, with yield-gap closures coupled with halving of food waste, reaches more than a half of the target, leaving only the other half for all other energy and industrial processing emissions (Fig. 2). The share of emissions related to agriculture may therefore increase in the future. However, to date, global food and land-use scenarios have received relatively little consideration in climate change mitigation policies compared with the consideration given to the energy supply and end-use sectors.

Reducing emissions from agriculture is essential to reduce the risks of dangerous climate change. The agricultural industry must strive to improve yields and food distribution, but improved diets and reductions in food waste are also essential to deliver emissions reductions, and to provide enough food for the global population of 2050.

Methods

Future land-use predictions are based on a model that describes the physical characteristics of global land-use and agricultural systems. This model was composed by collecting and fitting together the empirical data from many global datasets. It has two crucial components: the land-use distribution analysis and the agricultural biomass flow map. The analysis of land-use distribution was achieved by overlaying data on global biomes[21], current land use[22,23,46] and agricultural suitability[10] in a Geographical Information System.

The agricultural biomass flow map allows us to model changes in food supply chains explicitly, together with livestock management systems, agricultural waste, food waste and dietary preferences. It is constructed in the manner of a material flow analysis, so that the flows always add up to the total vegetation growth on cropland and pasture, measured as net primary productivity (NPP) in grams of carbon. It follows the allocation of agricultural vegetation biomass to harvest, residues, losses and ecosystems in the first instance, and then to food, feed, fibre, fuel, soil recycling, losses and intermediate steps. This biomass flow map is first parameterized with 2009 data. FAOSTAT statistics[24] provide most of the data, supplemented by some characterization of livestock feed systems[25], agricultural residue quantification and uses[25,47], and losses at each stage[26,29].

The model with these two major components was used to assess the consequence of future food demands and changes in the agricultural systems in 12 global regions. Calculations can be described conceptually as the following sequence:

Future consumption for each commodity in a region was calculated as a product of the per capita future dietary preferences associated with socio-economic changes as projected by the FAO (ref. 2) and regional population from the UN mid-range projections[36]. Aggregated by carbon mass, these add up to a 57% increase in food consumption, underpinned by a 75% increase in cropland productivity. Healthy dietary preferences[37–40] are taken as an alternative.

Required future production is calculated on the basis of the predicted future consumption and the characterized agricultural biomass flow map. We assume that agricultural systems in 2050 are different from those of today, in terms of the increased share of cropland-grown feed for livestock, and improved livestock efficiency. Trade between regions is assumed to remain the same. Changes in agricultural waste are implemented at this stage.

Future cropland area is a result of the required future production and yields. 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[4]. The Yield Gap (YG) scenarios assume that sustainable intensification will achieve yield gap closures in all regions, achieving the current potentially attainable yields for their agro-ecological zone. Yield gaps for each region and crop are taken from the GAEZ study[10].

Future pasture area is a result of future demand for grazing and the assumed livestock stocking densities. Unfortunately there are no statistics that could be used to estimate possible stocking densities on global levels. We compared results from a global dynamic vegetation model, a previous livestock energy model[25], and livestock product statistics[24], to determine that some regions can significantly increase densities (Latin America, SE Asia), whereas in others they are already very high (W. Europe, N. America). Because of many unknowns (about stocking densities as well as livestock management systems), pasture areas are highly uncertain.

The location of future cropland and pasture expansions (or retractions) is based on the land suitability component of the land distribution analysis, described above. Losses of ecosystems and GHG emissions are also dependant on the distribution of agricultural expansion over current land use and biomes in each region.

Fertilizer and irrigation use is estimated on the basis of current trends in their uses and total cropland area for each scenario. The YG scenarios assume an increase in irrigation use efficiency, whereas fertilizer use is set at high enough levels to support optimum yields.

GHG emissions from land-use change (LUC) are calculated on the basis of the 'before and after' land carbon pools, which depend on the biome and land use. We used the published methodology and parameters to obtain GHG values of ecosystems[48]. Only emissions from agriculture expansion and contraction are included.

GHG emissions from agriculture associated with fertilizer use and production, rice paddy methane emissions, emissions from enteric fermentation and manure management, as well as energy use in mechanization, are also calculated. Calculations are based on scaling up today's emissions[49,50] linearly with emission sources.

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B.B., J.M.A., K.S.R., C.A.G., J.S.D. and E.C. developed the model, B.B., P.S., J.M.A. and K.S.R. designed the study/scenarios, B.B., K.S.R. and C.A.G. analysed the outputs, and all authors wrote the paper with B.B. leading.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to B.B.

Competing financial interests

The authors declare no competing financial interests.