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Greedy or needy? Land use and climate impacts of food in 2050 under different livestock futures

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ABSTRACT

Both supply and demand side changes are necessary to achieve a sustainable food system. However, the weight accorded to these depends on one's view of what the priority goals are for the food system and the extent to which production systems *versus* consumption patterns are open to change. Some stakeholders see the problem as one of 'not enough food' and focus on the need to sustainably increase supply, while others consider the resource demanding and 'greedy' consumption patterns of the Western world as the main problem and emphasize the need to shift diets. In this study global land use and greenhouse gas emissions are estimated for a set of scenarios, building on four 'livestock futures' reflecting these different perspectives. These scenarios are: further intensification of livestock systems; a transition to plant-based eating; a move towards artificial meat and dairy; and a future in which livestock production is restricted to the use of 'ecological leftovers' *i.e.* grass from pastures, food waste and food and agricultural byproducts. Two dietary variants for each scenario are modelled: 1) a projected diet following current trends and 2) a healthy diet with more fruits and vegetables and fewer animal products, vegetable oils and sugar. Livestock production in all scenarios (except the baseline scenario) was assumed to intensify to current levels of intensive production in North-Western Europe. For each scenario, several variant assumptions about yield increases and waste reductions were modelled. Results show that without improvements in crop productivity or reductions on today's waste levels available cropland will only suffice if production of all protein currently supplied by animal foods is replaced by (hypothetical) artificial variants not requiring any land. With livestock intensities corresponding to current ones in North-Western Europe and with yield gaps closed by 50% and waste reduced by 50%, available cropland will suffice for all scenarios that include a reduction of animal products and/or a transition to poultry or aquaculture. However, in the scenario based on an extrapolation of current consumption patterns (animal product amounts and types consumed in proportions corresponding to the current average consumption in different world regions) and with livestock production based on feed from cropland, available cropland will not be enough. The scenario that makes use of pastures for ruminant production and food waste for pigs, uses considerably less cropland and could provide 40–56 kg per capita per year of red meat. However, such a livestock future would not reduce GHG emissions from agriculture on current levels. This study confirms previous research that to achieve a sustainable food future, action is needed on all fronts; improved supply and reduced demand and waste.

1. Introduction

The current food system is a major driver of environmental pressures (Foley et al., 2005, 2011). The total environmental impact of food consumption depends on the 1) size of the human population, 2) the per capita consumption of food (eaten and wasted), and 3) the impact per kg (or kcal) of food produced, transport, distributed and ultimately disposed of. The global population is expected to reach 9–11 billion by 2050 (UN, 2012). Tackling population growth is one route to reducing food security pressures and addressing environmental concerns (The

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Royal Society, 2012). However, much of the projected population increase is unavoidable due to the population-lag effect, and the issue has historically been sensitive for political and religious reasons. Consequently efforts to reduce food-related environmental impacts have mainly focused on improving food production and reducing its impacts, with attention more recently turning to altering resource-intensive food consumption patterns (Smith et al., 2013). However, which of these factors, production or consumption that is prioritized depends on one's view on what the most urgent goals are for the food system and the extent to which production systems *versus* consumption patterns are seen to be malleable and open to change (Garnett, 2014).

As regards food *consumption*, a combination of population growth and increased affluence has led to a rapid aggregate and *per capita* increase in the supply and consumption of animal products (Kearney, 2010), which generate high environmental burdens (Westhoek et al., 2014). Some stakeholders, including those from the food and farming industries, research institutes and policymakers, see this increase in demand as inevitable or at least a distinct possibility for which preparation to meet this demand is needed. For these groups, the problem to be addressed is 'not enough food' and as such they focus on the need to increase supply for our growing and increasingly wealthy global population (Garnett, 2015). In order to address environmental pressures, production-side technological advances and efficiency that achieve more with reduced impacts per unit of food output are viewed as key. Sustainable intensification is a term that has been coined to describe this concept (Garnett et al., 2013; Smith, 2013; The Royal Society, 2009).

Other groups, including animal rights and environment NGOs, as well as some academics drawn from environmental, nutrition or social science disciplines, see the increasing demand for animal products and other resource-demanding and unhealthy foods as a focal concern. Their analysis sees the problem as one of 'too much greed' (Garnett, 2015) *i.e.* the consumption patterns of the Western world are catastrophically resource intensive and the priority should thus be to address them. This narrative places emphasis on the high environmental footprint of animal products and the perceived inefficiency of feeding grain and other human edible products to animals.

Following these perspectives, different mitigation options are emphasized. Productionist advocates of the 'not enough food' world view urge increased efforts to close yield gaps in crop production and to intensify livestock production, in order to produce more food using less land, water, energy and fertilizers. Proposed mitigation options include improved manure management with *e.g.* biogas production, breeding, feed additives to reduce methane production in ruminants and bioenergy-fueled buildings and machinery (Smith et al., 2008a,b), as well as technologies capable of extracting as much edible and non-edible value as possible from the slaughtered animal (Newton et al., 2014).

Proponents of demand-side changes on the other hand, focus on dietary shift: specifically on the need to reduce overconsumption, alter, decrease or eliminate consumption of animal products, through transitioning to alternatives with lower impact – variously or including poultry (Hoolohan et al., 2013), aquaculture (Roberts et al., 2015), artificial meat/milk (Post, 2012) or plant-based protein (Popp et al., 2010; Stehfest et al., 2009; Wirsenius et al., 2010.

A third narrative centres on the imbalanced power/socio-economic relations among food system actors (Garnett, 2015) and in our relationship with the natural world. For proponents of this approach, the priority is to 'rebalance' the system which expresses itself in advocacy of more 'balanced' or nature-mimicking farming systems. In this paper we call this perspective 'too imbalanced'. Livestock are seen as integral to this balancing act through their ability to recycle nutrients and utilising marginal land and by-products and turning these inedibles into nutritious food for humans. Livestock-including production systems based on organic principles, often with a strong emphasis on grazing, are seen as an integral part of the solution, with animal numbers limited to what the local resource base can maintain.

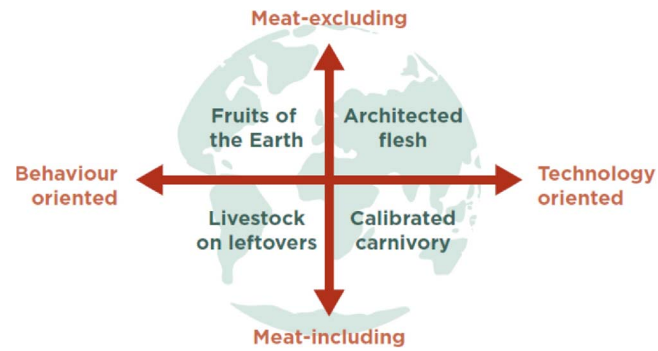

Fig. 1. Four scenarios for livestock futures. From Garnett (2015).

Of course these are overly simplistic representations of different viewpoints, and most people or institutions will span different perspectives. Recent research has begun to blur the dividing line between these narratives. A growing number of often interdisciplinary studies, include and advocate the need for both production-side mitigation options, and demand reductions (Bajželj et al., 2014; Davis et al., 2016; Erb et al., 2016; Godfray et al., 2010; Popp et al., 2010; Smith et al., 2013; The Royal Society, 2009; Tilman and Clark, 2014). For example, Godfray and Garnett (2014) strongly argue that sustainable intensification approaches need to go hand in hand with measures to address diet, tackle population growth and improve equity of access. Whatever perspectives, stakeholders are generally united on the need to reduce the 30–40% of food that is lost or wasted along the food supply chain (FAO, 2011; IMECHE, 2012).

Based on these different viewpoints, *i.e.* on what lies at the root of the food system's problems, and how these problems should be addressed, Garnett (2015) outlined four hypothetical future scenarios for future livestock production and consumption (Fig. 1). These scenarios vary in their inclusion or exclusion of farmed meat, and in the emphasis they place on the mitigation potential of behaviour (changes in demand) versus technology (production improvements) – mirroring the three perspectives of 'not enough food', 'too much greed' and 'too imbalanced'. A brief description is as follows.

'Fruit of the Earth' is a meat-excluding, behaviour-oriented scenario, where global public and policy acceptance of the need to radically alter diets leads to a shift to a mainly plant-based diet. In a second scenario, 'Architected flesh', growing demand for meat is seen as inevitable and met not by conventional animal production but through in-vitro artificial meat production, based on assumed high rapid technological development in this area. In 'Calibrated carnivory', growing demand for animal products is likewise seen as inevitable and is met through widespread adoption of highly intensive poultry, dairy and aquaculture production systems, whose overall efficiency is expected to compensate for the increased demand. Finally, the 'Livestock on leftovers' stems from the third narrative described above of 'too imbalanced'. Here farm animals in the right systems and right scale are seen as an integral part of environmental sustainability by turning biomass from marginal land and food waste into human edible foods. Therefore, this scenario sees a radically different future for livestock farming: animal production is limited to the level supportable from land unsuited to crop production and food and agricultural residues. This avoids competition between food and feed (Garnett, 2009; Röös et al., 2015; Schader et al., 2015). Consumption of animal products is restricted to the levels that these 'leftover' resources can provide.

This study quantifies agricultural land requirements and greenhouse gas (GHG) emissions arising from these different hypothetical livestock future scenarios in 2050 to provide more substance to the discussion on implications from different mitigation options. We model these scenarios for both projected diets and an example 'healthy diet' to show how potential dietary shift would affect land use and emissions. It is assumed that production-side mitigation options and actions to reduce

Table 1
Overview of production scenarios.

	Type of animal product	Type of livestock/meat production system	Use of by-products
Livestock-as-usual (LAU)	Mix of beef, pork, poultry, egg, dairy and seafood production as for current consumption patterns[a]	Slight efficiency increase from today's system as assumed in Bajželj et al. (2014)	As projected by Bajželj et al. (2014) – current levels of by-product is are slightly reduced – replaced by a slightly higher use of grain feeds.
Intensive livestock (INT)	As in LAU	Intensive systems corresponding to current levels of intensive production in North-Western Europe[b]Milk yield 8800 kg per cow and year.	Fibre-rich by-products used as ruminant feed, oil cake used for dairy and monogastrics. Fishmeal for monogastrics. No use of food waste as feed.
Intensive dairy and poultry (IDP)	Milk and beef meat from dairy cows and their off-spring. Remaining animal product calories supplied by chicken.	As in INT	As in INT
Intensive dairy and aquaculture (IDA)	Milk and beef meat from dairy cows and their off-spring. Remaining animal products supplied by aquaculture products.	As in INT	As in INT
Artificial meat (ART)	Artificial meat and milk, and other novel protein sources.	Highly industrialized. Uses no agricultural land.	Not used for food.
Plant based eating (PBE)	None. Livestock products are replaced by pulses and cereals on an iso-caloric basis.	NA	Not used for food.
Ecological leftovers (EL)	Milk and beef meat from dairy cows and their off-spring and pig meat, but only as much as can be produced on 'ecological leftovers' globally (for healthy diet capped to 'healthy' levels)	Dairy herds raised on pasture and fibre-rich by-products. Milk yield 5–6000 kg per cow and year. Pigs raised on food waste, oilseed cake and cereals.	Fibre-rich by-products and oilseed cake used as ruminant feed, oil cake used for pig production in combination of food waste and some cereals.

[a] According to FAOSTAT Food Balance Sheet for the different regions.
[b] Represented by current average systems in Sweden; Supplementary material S3.

waste, are implemented to approximately half of their known technical potential and compared to a baseline (*i.e.* productivity and waste levels in 2009), and that livestock efficiencies globally increase to levels corresponding to those in North-Western Europe. Hence, the purpose of this study was to estimate the theoretical agricultural land needed and GHG emissions generated from supplying the projected global population with food in 2050 under a range of different livestock futures. We then summarize and discuss the implications of these different futures for wider environmental concerns, for humans and for farm animal welfare.

2. Method

For seven possible production scenarios (Section 2.1), each under four distinct sets of assumptions about future yield increases and food waste levels (Section 2.3), and under two dietary variants (Section 2.2) – in total 56 scenarios – we calculated land requirements and GHG emissions using a regionalized global agricultural biomass flow model built in Excel and populated with region specific data from mainly FAO (2015) and Bajželj et al. (2014). Twelve regions were modelled separately: Eastern Europe, Western Europe, Central Asia, East Asia, South Asia, South-east Asia, Western Asia, Latin America, North America, Sub-Saharan Africa, North Africa and Oceania. This study explicitly adopts a bioregional approach — we do not include any trade between regions in order to give insights into the potential of different regions to produce enough food for their populations under different livestock futures (see Supplementary material S1 for regional results). The modelling is explained in brief here and in more detail in the Supplementary material S2.

Land use requirements were calculated by transforming the *per capita* dietary energy values (kcal) of food (for a projected diet in 2050 and a 'healthy' diet; Section 2.2), into food quantities (kg) using data on energy content in food (kcal/kg) from FAO (2015). Yearly quantities of food required in a specific region were calculated by multiplying daily *per capita* consumption with the projected population in 2050 for that region (UN, 2012) and by allowing for region-specific food losses at all stages of the food chain (FAO, 2011). The quantity of agricultural commodities and feed needed to produce this quantity of food was then calculated. For plant based foods, this was the quantity of edible yield obtained once crop residues, husks *etc.* were excluded (FAO, 2011). (For yield levels refer to Section 2.3). For animal products, an additional step was needed: the feed requirements for each animal species were multiplied by the overall number of animals needed to produce the specified quantity of milk, meat, fish and egg. Finally, the land area needed to produce plant foods for human consumption and livestock feeds was calculated for each crop type using the yield per land area. Depending on the sub scenario, either current yields (FAO, 2015) or higher yields (halfway between current yields and optimum yields; Section 2.3), were assumed.

GHG emissions from fertilizers and from rice cultivation were calculated following the methodology in Bajželj et al. (2014); emissions in 2009 for each emission category were scaled up in linear proportion to production. That is, the nitrous oxide emissions from fertilizer use were scaled based on the amount of fertilizer used and methane emissions from rice based on land area used for rice cultivation (FAO, 2015). To calculate emissions from enteric fermentation in ruminants and pigs, emissions factors from for yearly methane emissions per animal (Supplementary material S3.4) were multiplied by the number of animals needed in each scenario. Emissions from manure handling were calculated using the IPCC Tier 2 methodology (IPCC, 2006) taking into consideration the amount of cropland located in cool, temperate and warm areas in each region. Smith et al. (2008) estimate a technical reduction potential of approximately 20% for these emissions sources and here, in keeping with the study's other assumptions about technological improvements, we assume that half of this potential can be realized in 2050 *i.e.* emission factors for N_2O and CH_4 emissions are reduced by 10%. Emissions from energy use, including the production of mineral fertilizers, on farm energy use, the cultivation of artificial meat and food processing, were not included as these are accounted for under the United Nations Framework Convention on Climate Change in the energy sector.

2.1. Livestock production scenarios

Garnett's (2015) livestock future scenarios (Fig. 1) were further refined and elaborated on as follows, leading to the construction of seven production scenarios (Table 1). As a baseline, a Livestock-As-Usual (LAU) scenario was included; results for this was taken from Bajželj et al. (2014) with some modification (Supplementary material 2.1).

Three scenarios were based on the 'Calibrated carnivory' future. Intensive Livestock (INT) is an extrapolation of consumption patterns today: all animal product types are consumed in proportions corresponding to the current average consumption in different world regions and then projected forward following assumptions by FAO (Alexandratos and Bruinsma, 2012). In the Intensive Dairy and Poultry (IDP) and the Intensive Dairy and Aquaculture (IDA) scenarios, some beef and all pork meat is replaced by poultry and aquaculture products (80% finfish from high yielding closed recirculating systems and 20% mussels, oysters and other filter feeders) respectively, on the basis of its greater feed conversion efficiency. In the INT, IDP and IDA scenarios intensive dairy production continues to provide milk, and beef meat from culled dairy cows and their offspring. The offspring are reared in intensive confined systems to achieve maximum growth rates and feed is produced entirely on cropland (silage and grazed ley). Byproducts from production of plant based foods (mostly cereal bran and oil cake) complement feed grown on cropland in all scenarios. For details see Supplementary material S3.1.

In the Artificial Meat (ART) scenario (corresponding to the 'Architected flesh' future), farmed meat and dairy are replaced by artificially grown meat and milk and by other novel protein sources that can be produced mainly on waste streams and so do not require agricultural land. For example, the feedstock to produce artificial meat is assumed to be cyanobacteria grown in ponds placed on non-agricultural land (Tuomisto and Teixeira de Mattos, 2011). This is evidently a highly speculative scenario based on optimistic assumptions about the pace of technological advance and its commercial application, especially as it involves two novel technologies – large-scale production of cyanobacteria biomass and cell culturing (Alexander et al., 2017) – but worth including given the interest that the possibility attracts.

In the Plant Based Eating (PBE) scenario (equivalent to 'Fruits of the Earth' future), legumes and cereals isocalorically replace all animal products. An effect of this is that the PBE diets contain less protein than diets in the other scenarios (between 51 and 76 g per person per day compared with 64–131 g; Supplementary material S6).

In the Ecological Leftover (EL) scenario, dairy cows and other cattle are reared on grass from pastures and byproducts derived from food produced for direct human consumption. Food waste is fed to pigs together with oilseed cake and cereals to achieve a balanced ration. Pigs were chosen over poultry since they can digest most of the byproducts not suitable for ruminants; poultry depend more on cereals and can only digest a limited quantity of byproducts (McDonald et al., 2011). Hence, the use of cropland to produce feed is minimized.

Detailed assumptions about the expected rates of livestock intensification at a global level are not available, although FAO 2013 suggests that a 30% increase in FCE may be possible (Gerber et al., 2013) and several studies have modelled outcomes of different assumed efficiency gains (Bennetzen et al., 2016; Havlík et al., 2014; Hedenus et al., 2014). Therefore, for all scenarios and regions, it was assumed that the feed conversion efficiency (FCE) of livestock production increases by 2050 to correspond to current levels of intensive production systems in North-Western Europe which can be defined as 'medium intensity' and hence consistent with the study's assumption about technological improvements by 50% (Supplementary material S3). To achieve this level of FCE globally requires developments in breeds, feed formulations and management systems appropriate to different regions and contexts (see discussion in Section 4.2).

All scenarios were set to supply a human diet of equivalent quantities of energy from either animal products (poultry and dairy in IDP, aquatic products and dairy in IDA, artificial meat in ART); or plant-based protein (pulses and cereals in PBE); or a combination of animal and plant protein (EL limits livestock production to what can be produced from pastures, by-products and food waste, and so pulses and cereals are added to reach the same caloric values). In all scenarios, consumption of six grams of wild seafood per person per day was included. This was based on the FAO's projected volumes for capture fisheries in 2022 (96 million tonnes) but reduced by 25% to account for the large uncertainties in these projections and so as not to overestimate the amount of protein that sustainably could be supplied from wild seafood stocks (FAO, 2014).

2.2. Dietary variants

Each production scenario was modelled for two dietary variants: a projected diet and an example of a healthy diet. In the projected diet variant, dietary patterns are assumed to follow current trends based on FAO assumptions (Alexandratos and Bruinsma, 2012): energy intakes are projected to increase to between 2585 and 3131 kcal/capita/day for different regions in 2050; vegetable oil and sugar intakes exceed nutritional recommendations, and animal protein intakes (or their protein equivalents, according to scenario) will rise in most regions. The healthy diet is based on a composite of recommendations from WHO, Harvard Medical School and American Heart Association and gives 2500 kcal/person/day in all regions. For the healthy diets, vegetable and fruit consumption was set to 123 and 119 kcal per person per day respectively in all regions. Sugar content was capped at 150 kcal per person and day, and vegetable oil at 360 kcal for regions which had projections that exceeded that level. Consumption of red meat was capped at 57 kcal per person per day in all regions, poultry at 161 kcal (only North America had projected levels exceeding this cap), egg at 50 kcal and dairy at 300 kcal (three regions reached the cap for egg and four regions for dairy). Consumption of staples such as wheat, rice, maize, roots and pulses was distributed based on regional cultural preferences in the different regions (diets for the different regions are presented in detail in Supplementary material S6).

In the EL scenario, livestock output is determined by what is supportable from pasture biomass (mainly through grazing but also potentially from harvesting of grass from pastures for winter feed), food waste and agricultural byproducts. Consumption of animal products in this scenario is therefore limited to their regional availability. For the healthy diet in the EL scenario, consumption of meat was capped to healthy levels as described above.

2.3. Yield and waste levels

The seven livestock production scenarios, each in two dietary variants, were also examined under four disctinct sets of assumptions about crop yields and waste reductions. In the first set, crop yields (assuming single cropping) and waste levels are set to the current (2009) average yields in each region (FAO, 2011, FAO, 2015). In the next set, current crop yields are as now but waste is assumed to be reduced by 50%. In the third set, the yield gaps are assumed to be closed by 50% but current levels of waste persist. The final set of results is based on yield gap closures and waste reductions of 50% each. The feasibility and challenges associated with achieving these goals are discussed in Section 4.1.

As results are very sensitive to assumptions on crop productivity, two sensitivity analyses coupled to this are provided. In the first, grass biomass from pasture land (not only grass biomass from cropland; see Section 2.1) is used in all scenarios (not just the EL scenarios), and in the second, potentials with multi-cropping were studied. Details are provided in the Supplementary material S5.1 and S5.2.

3. Results

Results for global land use is presented in Section 3.1 and for global greenhouse gas emissions in Section 3.2. Regional results are presented in Supplementary material S1.

3.1. Land use

The currently used cropland does not suffice for any of the scenarios

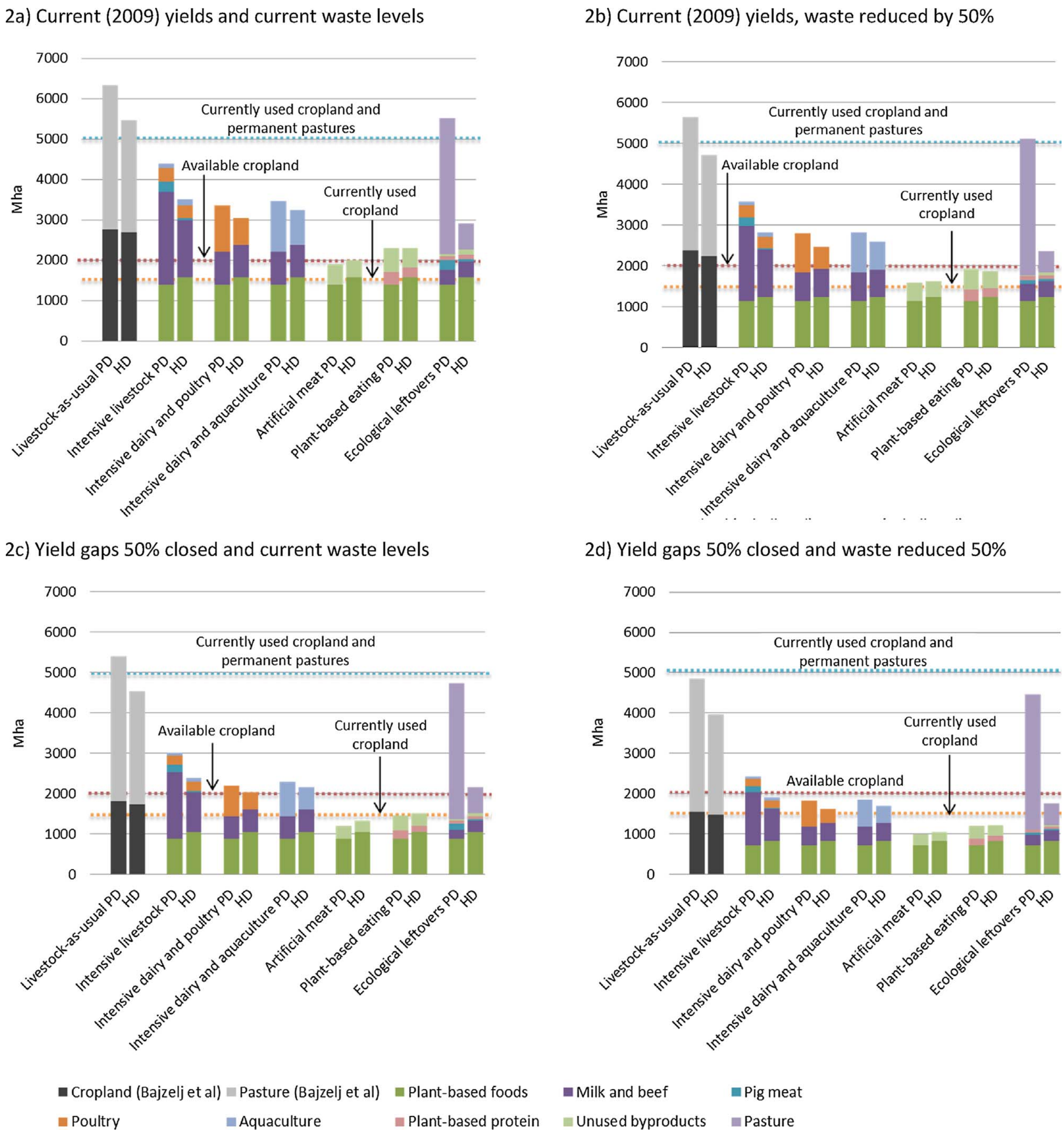

Fig. 2. Land use for the production of food for the global population in 2050 for Projected Diets (PD) and Healthy Diets (HD) for the different livestock production scenarios and under different assumptions for yield gaps closures and waste reductions. The categories 'Milk and beef', 'Pig meat', 'Poultry' and 'Aquaculture' includes feed for these species grown on cropland, including by-products from plant-based foods (allocated based on mass). 'Unused by-products' are by-products from plant-based foods not utilized as feed (could be used for bioenergy production or refined to human edible products). See text in Section 3.1 for explanation of available cropland.

if no improvements are made on current yields (2009) (Fig. 2a), not even when waste levels are reduced by 50% (Fig. 2b). If yield gaps are closed by 50% but today's waste levels persist (Fig. 2c), the currently used cropland would be enough for both dietary variants of the ART, PBE and EL scenarios, but for the healthy variants only just as the vegetable-heavy healthy diet requires more cropland than the sugar-heavy projected diet.

With regards to theoretically 'available' cropland, approximately 1.4 billion ha of currently unused land has been classified as prime or good cropland based on soil, terrain and climate characteristics. However, there are several constraints on its use; for example it may be under forest cover or protected; or lack servicing infrastructure. This leaves some 450 Mha potentially available, mostly in Latin America and Sub-Saharan Africa (Alexandratos and Bruinsma, 2012; Lambin and Meyfroidt, 2011). In all, once currently used cropland and practically available uncultivated land are added together, total land available for productive cropland amounts to approximately 2000 Mha.

Only if waste is reduced and yield gaps are closed to 50% (Fig. 2d) is the land requirement below this limit in the INT, IDP and IDA scenarios, and the INT scenario only for a healthy diet as substantial amounts of cropland would be needed for animal feed production. Only scenarios without livestock feed production on cropland (ART, PBE and EL) use less than *currently* used cropland, and so avoid the potential negative effects (for climate or biodiversity) of *any* further cropland expansion.

In the INT, IDP and IDA scenarios it is assumed that all forage for ruminants is produced on cropland i.e. no biomass from permanent pastures was utilised as animal feed. A sensitivity analysis was performed to assess how land requirements would change under the assumption that forage from pastures is used exclusively instead (through grazing or harvesting silage or hay from grasslands). This decreases pressure on cropland for these scenarios by 7–13% for the IDP and IDA scenarios and by 19–36% for the INT scenario (variation depending on dietary variant – PD or HD – and waste and yield levels; see Supplementary material S5.1 for details) but total land use (including cropland and permanent pastures) would increase by 21–66%.

Multi-cropping has been highlighted as an underestimated option to increase yearly yields (Mauser et al., 2015; Ray and Foley, 2013). A sensitivity analysis was therefore performed to investigate how land requirements for the different scenarios would change if multi-cropping would be implemented on all existing cropland where it is deemed feasible (for details see Supplementary material S5.2). Results from this analysis show that need for cropland was reduced between 15 and 19% globally for the different scenarios by accounting for multi-cropping.

3.2. Greenhouse gas emissions

As with land use, GHG emissions fall substantially when livestock production is intensified, yield gaps are closed and waste is reduced. Emission pathways compatible with the 2 °C temperature target allow for total global emissions of 21 Gt of CO_2e in 2050 (Rogelj et al., 2011) from all sectors (energy, transport, waste handling, forestry *etc.*). In the LAU scenario, agricultural emissions take up approximately half of the ‘allowable’ emission space in 2050 (Fig. 3a–d). Since emissions will need to fall further still beyond 2050 (to below emissions of 10 Gt of CO_2 per year in 2100) and since a 1.5 °C rather than 2 °C limit is the ambition of the latest global climate treaty (the Paris agreement; UN, 2015), this scenario is evidently deeply problematic.

For the other scenarios, agriculture’s share of the 21 Gt allowable emissions space in 2050 varies from just 6% and 7% respectively for the healthy ART and PBE sub-scenarios wherein yield gaps are closed to 50% and waste reduced by 50% (Fig. 3d), to 40% for the INT scenario where diets are as projected and without any changes to yields and waste levels (Fig. 3a).

What constitutes a sustainable level of food related GHG emissions, (*i.e.* the share of the total emission space that is taken up by food-related emissions), is a function of the technical and economic potential to reduce GHG emissions from agriculture, compared with other sectors (e.g. energy and transport) and on societal judgements about food’s special status as compared with sectors that provide other goods and services. Note that this study does not include emissions from deforestation or conversion of grasslands to arable land which would be a consequence in all scenarios that use more than currently used cropland (Fig. 2). These emissions can be substantial; the emissions from deforestation in the LAU scenario would amount to approximately 7 Gt CO_2e (Bajželj et al., 2014).

On the other hand, land that is released through more efficient production and/or dietary change in all scenarios (except the LAU scenario) could potentially be used to sequester carbon through reforestation and afforestation or used for nature conservation (Lamb et al., 2016). Röös et al. (2017) previously quantified this potential for Western Europe and results indicate that the carbon sequestration gains are three to 20 times more than the GHGs released from the agricultural activities (nitrous oxide from soil, methane from ruminants and emission from manure management) expressed in terms of GWP100. These benefits are time limited (due to eventual saturation of carbon in soils and live biomass), reversible (if trees are later cut down or if soils lose carbon again due to altered management or changes in climate), associated with a range of economic and practical limitations but nevertheless show the potential of the land that would be freed.

4. Discussion

This study confirms earlier research in that combinations of: 1) yield gap closures, 2) livestock intensification, 3) waste reductions and 4) dietary shifts show great potential to reduce land use and GHG emissions. Table 2 compares the potential of some of the key mitigation options.

These different mitigation options are emphasized to different extents in the different scenarios modelled here based on the underlying perspectives ‘not enough food’, ‘too much greed’ or ‘too imbalanced’. As these mitigation options have additional and differing implications for environment, humans and farm animal welfare we start this section with a brief discussion of these possible effects.

4.1. Increasing yields

This study shows that yield increases and/or waste reductions are necessary mitigation strategies regardless of which livestock future that is envisioned, including an entirely plant based one, *i.e.* it is apparently not only a matter of ‘too much greed’ – plant-based foods from available cropland will not suffice in 2050 under current yield and waste levels and unless agricultural byproducts (e.g. oil cakes) can be refined into human edible foods.

If the negative environmental impacts from the management of pests, diseases, weeds and irrigation water can be overcome using well-designed cropping systems and integrated approaches, an increase in yields could potentially ease environmental pressures (nitrogen and pesticide pollution, water stress *etc.*). On the other hand, approaches focusing on yield increases present legitimate cause for concern since historically yield increases have been achieved by over-applying inputs, with major negative environmental consequences (Foley et al., 2011). When it comes to impacts on biodiversity from closing yield gaps, these are often negative on farmland, but may be positive on spared land (Phalan et al., 2014). However, it may be that productivity increases lead, *via* increased output and associated lower prices, to increased demand over and above current projections; this in turn can drive further land use change (Lambin and Meyfroidt, 2011); an effect known as the Jevons Paradox, and precisely what the yield increase was set out to prevent.

As to feasibility of raising yields, in parts of Africa, Asia, Latin America and East Europe current yields for many crops are only half or less of potential yields (Licker et al., 2010; Neumann et al., 2010; Pradhan et al., 2015) because of factors such as poor soil quality, yield losses due to pests, diseases, weeds and poor access to fertilisers, good quality seed and markets to sell agricultural surplus (Pradhan et al., 2015). Technically, raising yields in low-yielding areas that suffer from soil nutrient deficiencies, poor management *etc*. should be possible, but political will, institutional support and financing form substantial barriers. The impacts of climate change, which are expected to slow increases in agricultural yields at the global level as well as loss of soil fertility (Tittonell and Giller, 2013) also need to be factored in.

4.2. Intensifying livestock production

Current livestock systems are characterized by great diversity and very major differences in feed conversion efficiencies. This study suggests that increases in livestock production efficiency (kg of meat or milk produced per input of feed) holds great potential to reduce pressures on land and achieve GHG emission reductions. To achieve the modelled increases in efficiency, current trends towards concentration and scaling up in the livestock sector would need to be stepped up – as stressed by the ‘not enough food’ proponents. This approach, however, raises serious concerns about point source pollution (Ouyang et al., 2013), the routine use of antibiotics (and associated health risks of

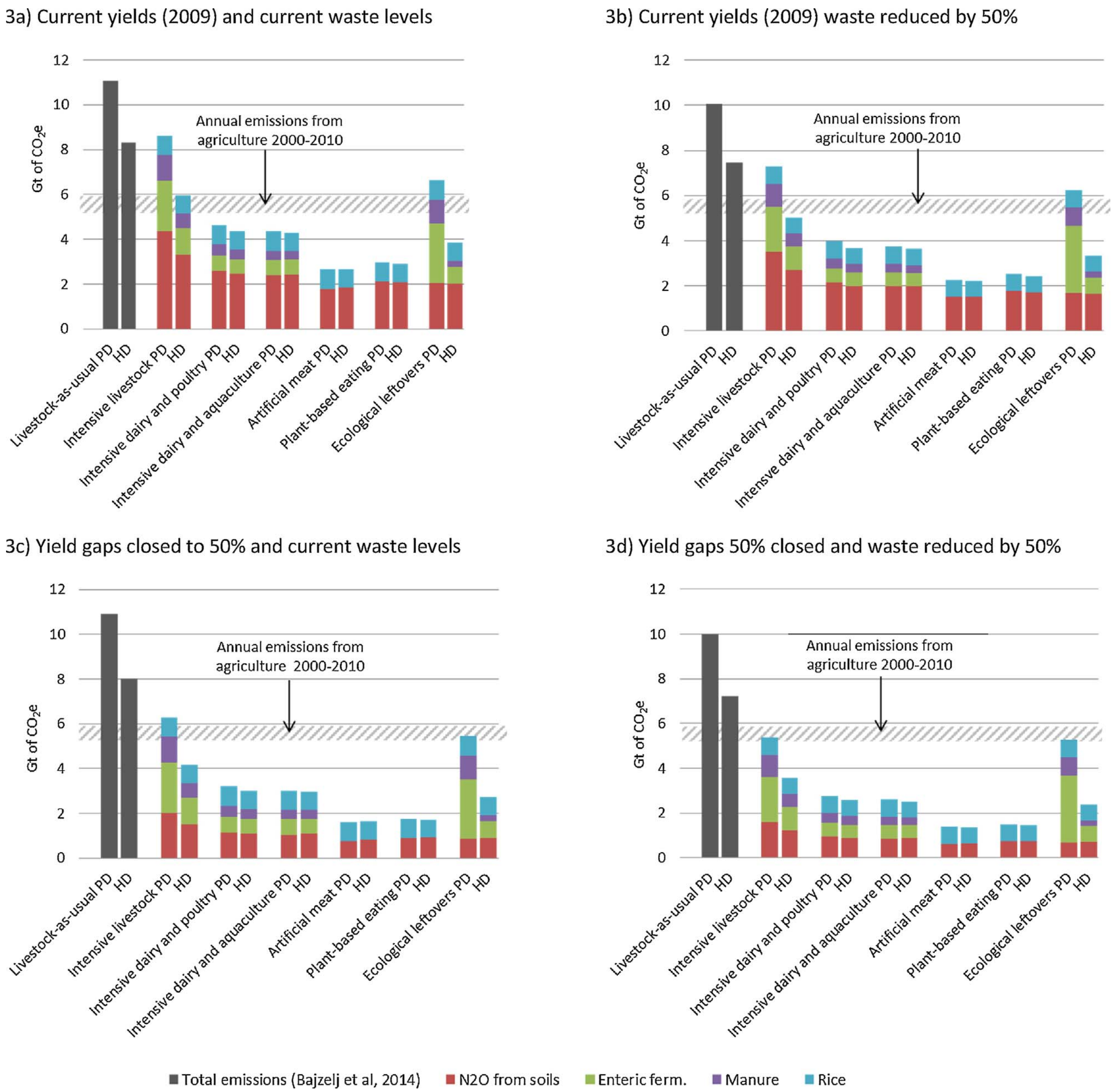

Fig. 3. Emission of greenhouse gases for the production of food for the global population in 2050 for Projected Diets (PD) and Healthy Diets (HD) for the different protein future scenarios and under different assumptions for yield gaps closures and waste reductions. Emission from deforestation and afforestation on spare land not included. Annual GHG emissions from agricultural production in 2000–2010 at 5.0–5.8 Gt of CO_2e pear year from Smith et al. (2014).

Table 2
Reductions in global land use and GHG emissions from agriculture in per cent from business as usual (LAU with 2009 yields and waste levels, projected diet) from a selection of mitigation options. Rebound effects are not considered.

Mitigation option:	Reduction in land use (%)	Reduction in GHG emissions (%)
Food waste reduced by 50%	11	9
Yield gaps closed by 50%	15	1
Livestock intensification	31	22
Livestock intensification and dietary shift to a healthy diet	45	46
Dietary shift to plant-based projected diet	64	73

antimicrobial resistance; Marshall and Levy, 2011), spread of zoonotic disease and negative consequences on animal welfare, even while acknowledging that poor welfare (Bergman et al., 2014; Millet et al., 2005) and emergence of zoonotic disease (Lindahl and Grace, 2015) can occur in any system. Today, in countries where animal welfare issues are of great societal concern, and where there is animal welfare legislation, production systems have been forced to improve (Barkema et al., 2015; Velarde et al., 2015); implying that there are limits to what livestock production approaches and productivity improvements are considered morally acceptable. These limits may render some of the livestock production systems in the INT, IDP and IDA scenarios unacceptable and thus politically implausible.

More positively, concentration in the sector also allows for manure to be managed more effectively, one example being biogas production from stored manure, averting methane emissions and substituting for fossil fuels (Smith et al., 2014). However, the issue of concentrated pile ups of nutrient rich digestate, which risk point pollution, remain.

When livestock production is intensified and feed is produced on cropland rather than pasture land, a substantial amount of pasture land is released. The environmental effects will be site specific (Queiroz et al., 2014). In areas such as the North American Prairie and European grasslands, where wild hoofed mammals have historically played an important role in cycling energy and nutrients, managed domestic livestock can and do perform similar functions, and as such (if well managed) potentially contribute positively to natural grassland ecosystems (Lwiwski et al., 2015; Plachter and Hampicke, 2010). The extreme case of removing such herds completely could have damaging effects on grassland biodiversity. However in many areas, livestock are not managed in ways that maintain or enhance biodiversity; high stocking densities and grazing patterns that do not resemble those of wild ungulates and instead undermine biodiversity, pollute water sources and erode soils (White et al., 2000).

Turning from animals to human livelihoods, the intensification of livestock systems would imply a major change to the many current very low intensity pastoralist systems and would affect hundreds of millions of poor people whose livelihoods currently depend on these systems (Thornton, 2010). Positive effects include increased access to nutrition for poor while negative impacts are for example increased competition for scarce resources. These consequences are highly context specific and not well understood (Thornton, 2010). Major developments would also be necessary to make such a transition practically possible; for example developing countries lack the infrastructure and capacity needed for appropriate breeding programmes (Beede, 2013). In addition, production of the high quality feed necessary in these regions is challenging (NRC, 2009; Thornton, 2010). On the other hand, trends suggest that intensification is already underway. The most developed economies (*e.g.* Sweden in which the semi-natural pastures have quickly been afforested or rewilded and are now the most threated eco-system) managed this transition in a 50-year period so it is conceivable that developing economies *could* follow suit in the 30 or so years remaining until 2050. However, much will depend not just on the rate of economic development within individual countries, but also on how climate change affects livestock systems and their infrastructure (including feed crop production and transport networks) as well as changing societal views about livestock, animal welfare, health and environment. For example, people may want livestock systems that are not just 'efficient' defined in terms of feed conversion efficiency, or meat output per unit of GHGs emitted, but that also deliver other 'goods' such as grazing, employment, recreation or landscape aesthetics (Garnett et al., 2015a, 2015b) – aspects highlighted by the 'too imbalanced' proponents.

4.3. Reducing waste

As previous studies have shown (*e.g.* Bajželj et al., 2014; Kummu et al., 2012), our results also highlight the potential to decrease land requirements and GHG emissions from reducing food waste. Food waste reduction comes with few goal conflicts and is therefore uncontroversial – but whether major improvements are realistic is still uncertain. In addition, as food waste reductions mean economic savings for the consumer, rebound effects could offset substantial parts, or even all, GHG savings (Martinez-Sanchez et al., 2016; Salemdeeb et al., 2017).

Initial efforts to curb consumer food waste have been encouraging. The UK, belonging to the group of developed countries in which most food is wasted at the consumer stage (FAO, 2011), was the first country to undertake detailed and systemic measurement of consumer food waste, and between 2008 and 2012 achieved a reduction of 24% (WRAP, 2012). Three factors are likely to have contributed to this reduction: (i) the economic downturn, which affected household budgets, prompting consumers to be more careful; (ii) awareness-raising public campaigns backed by the government and (iii) technical changes such as improved packaging (WRAP, 2014). However, it seems to be challenging to sustain reductions in a context where food remains relatively inexpensive but national food waste campaign efforts are lowered (due to reduced funding for public awareness campaigns); food waste increased again by 2.2% on a per-capita basis (WRAP, 2017).

In developing countries, some initiatives to prevent food losses in the supply chains are underway as most food here is lost at the pre-consumer stage. For example in India, government-backed subsidies for cold chain infrastructure development (refrigerated food transport and storing facilities) have spurred large investments in improved storage (NCCD, 2015).

4.4. Diet shift

Consumer research shows that the main determinants of consumer food purchases are taste and price, followed by the perceived trustworthiness of its origins, health and convenience. Environmental considerations feature to some limited extent (Garnett et al., 2015a, 2015b). Consumer knowledge of food's impact on the environment or other sustainability issues is also poor, which hinders informed food purchases (Bailey et al., 2014; Grunert et al., 2014).

Access to knowledge alone is far from sufficient to change eating habits. Most consumers, at least in Western countries, know what constitutes healthy eating at a basic level (*i.e.* limit sugar, salt and fat and increase consumption of fruits and vegetables) (Grunert et al., 2012), but diets are still poor. Health promotion policy has been dominated by consumer-centred, voluntary approaches such as public awareness raising and labelling, approaches that are more politically acceptable than regulatory or economic measures that target the food industry or the context of consumption, but their impacts have been limited (Garnett et al., 2015a, 2015b). Economic measures that have been tested in a few countries or modelled in research include taxes on sugar, fats and highly processed foodstuffs, and subsidy-oriented interventions to increase consumption of fruits and vegetables. Outcomes are cautiously positive; economic incentives, especially in combination with other regulatory or informative policy, do change consumption, but to what extent, and with what other potentially negative effects, is still highly uncertain since schemes in most countries have only been operating for a short period, and modelling studies have their limitations (Andreyeva et al., 2010; Eyles et al., 2012; Niebylski et al., 2015; Thow et al., 2010). Few interventions aimed at changing habits for environmental reasons have been introduced and even fewer evaluated scientifically (Garnett et al., 2015a, 2015b). Some examples include the recent introduction of new pro-environmental dietary guidelines in Sweden, Brazil and the Netherlands (Fischer and Garnett, 2016) and modelling of the use of GHG taxes to reduce the consumption of meat and dairy foods, which seem to offer some potential (Edjabou and Smed, 2013; Säll and Gren, 2015; Wirsenius et al., 2011). However, wider effects for example on other environmental impacts and nutritional aspects are still to be investigated.

In all cultures, increased wealth leads to increases in the consumption of animal foods, although the link is mediated by cultural and other factors (Rivers Cole and McCoskey, 2013) and the connection is broken above a certain level of income. Urbanisation may also influence meat consumption with increased opportunities for eating out (where meat is commonly consumed) (Bai et al., 2010; Ma et al., 2006), but again the association is complex and mediated by factors such as levels of education. While there are examples of a growing vegetarian/flexitarian (reduced meat consumption) trend among young people in some Western societies (Mintel, 2014; Rousseau, 2015), and meat consumption increases may have levelled off (albeit at high levels) in the EU (OECD, 2016), surveys show that, on the whole, people resist the idea of eating less meat and that meat has strong cultural resonance for many people, particularly men (de Boer et al., 2014; Graça et al., 2014, 2015; Ruby and Heine, 2011; Schösler et al., 2015) – points highlighted by the 'not enough food' advocates to criticise what they see to be unrealistic claims for changing consumption.

Even though the ART and PBE scenarios generate the lowest climate impact of all scenarios, a future entirely devoid of livestock is likely to

Table 3
Overview of possible positive (+) and negative (−) consequences of different mitigation options to reduce climate impacts from the food system, issues are discussed in Section 4.1–4.4.

	Affected entity:		
	Environment and resources[a]	Animals	Humans
Yield gaps closed	(-/ +) Increased or reduced nutrient pollution, pesticide use, water stress, biodiversity loss (+) Land sparing (if rebound effects can be avoided)	Not affected	(-/ +) Negative or positive impacts on livelihood of the poor depending on how yields are increased (+) Increased food availability
Livestock efficiencies	(-/ +) Grassland biodiversity when animals are moved off grasslands (−) Point source pollution	(−) More confined environments, risk of more health problems due to breeding for higher yields and growth rates; reduced ability to express natural behaviours	(-/ +) Livelihood of the poor, risk of epidemic zoonotic disease transmission, (−) Risk of antibiotics resistance, negative impacts on aesthetic values of farmlands and tourism if animals are moved indoors
	(+) Potential to produce biogas from manure, grassland biodiversity	(+) Greater scope for animal supervision and veterinary care potentially leading to improvements in animal diets and animal health	(+) Improved aesthetic values in overgrazed areas, reduction of endemic diseases common in extensive systems
Waste	(+) Less nutrient pollution, less resource use etc.	Not affected	(+) Increased food security and improved livelihoods
Diet shift towards healthy diets	(+) Less nutrient pollution, less resource use etc.	Not affected	(+) Health outcomes

[a] Excluding land use and GHG emissions that were calculated in this study.

be unrealistic taking into account the central role of animal products in many cultures, the long history of eating meat and the multitude of additional purposes that farm animals fulfil (Thornton, 2010), as is an upscaling of the consumption of artificial meat to amounts needed to replace all animal protein.

4.5. Perspectives on mitigation options

Demand-side options, including dietary shifts and waste reductions, have the advantage of making more food available without the need to use more resources, and without increasing environmental pressures (Table 3) although rebound effects may temper environmental gains. Hence, proponents of the ‘too much greed’ narrative would describe these as low risk mitigation options that deliver environmental improvements, reduce the number of farm animals (with, by implication welfare gains) and that can also deliver benefits for public health. On the other hand, proponents of the ‘not enough food’ narrative draw attention to the strong historical association between rising animal product consumption and increased wealth (Kearney, 2010) and see dietary shift as highly unlikely and unrealistic; as such, they put little faith in demand-side mitigation options. Instead they highlight the short-term negative impacts such options could have on livestock businesses, producers and consumers in developing countries and economic growth in the agricultural sector.

In contrast, yield gap closures and increased livestock efficiencies are judged to be high risk options by proponents of the ‘too much greed’ and ‘too imbalanced’ narratives, in view of the historical and current environmental impacts caused by (over)use of synthetic fertilisers, pesticides and fossil fuel, all applied with the intention of raising yields (Foley et al., 2005). These stakeholders are sceptical about the potential that ‘sustainable intensification’ holds to be truly ‘sustainable’ – to reduce nutrient losses (both from cropland and intensive livestock production sites), address concerns about animal welfare and animal ethics, tackle zoonoses and antibiotic resistance in intensive systems, and maintain crop and livestock species diversity (Table 3). In addition, the very rationale for closing yield gaps and increasing livestock efficiencies – the ‘need’ to produce more food – is questioned. Critics point out that higher yields may in theory spare land and other resources, but that rebound effects could continue to offset the efficiency gains (Smith et al., 2013).

4.6. Avoiding food-feed competition

The concept of ecological leftovers *i.e.* feeding less or no food-competing feedstock to livestock, (Garnett, 2009; Röös et al., 2015; Schader et al., 2015) in combination with healthy eating recommendations could potentially offer an interesting middle ground between the two perspectives of ‘too much greed’ and ‘too imbalanced’. The ecological leftovers concept rests on the principle of resource efficient use of land and crops, and naturally appeals to the proponents of the ‘too imbalanced’ framing. Combining the principle of ecological leftovers with the healthy eating recommendations caps consumption and satisfies advocates of the ‘too much greed’ narrative. The concept is compatible with agro-ecological principles of efficient use of local resources (Francis et al., 2003) and contributes to food availability (Godfray et al., 2010). It also has potential to bring about increased animal welfare for ruminants, since it enables them to forage, as; one of their strongest biological motivations. This approach could also, if managed properly, ensure biodiversity conservation on those grassland areas that benefit from grazing animals.

In the scenario modelled in this study based on this principle (EL), considerably less cropland is needed than in the other scenarios in which livestock is produced (Fig. 2) since ruminant feed is limited to permanent grassland biomass, and pigs are mainly raised on food waste. However, for the projected diet with no restriction on red meat intake, GHG emissions are still as high as today (Fig. 3). Carbon sequestration in soils could offset some of the GHG emissions; a carbon sequestration rate of approximately 250 kg C per hectare and year on all pasture would be required to offset the emissions associated with the ruminants. Although this is a realistic rate on some pastures (e.g. through improved grassland management; Smith et al., 2008a,b) relying on uptake and offsetting of emission compared to emission avoidance is associated with several complications and uncertainties; carbon sequestration rates will diminish with time as soils become saturated (while methane emissions from livestock continue), soil carbon sequestration is reversible (Smith, 2012), a larger sequestration potential could potentially be achieved with wild and planted forests.

The global per-capita quantity of animal products yielded by these systems amounts to 101 kg of milk, 35 kg of pork and 21 kg of beef meat with 2009 food waste levels and 100 kg of milk, 16 kg of pork and 25 kg of beef meat with food waste decreased by 50% (meat in carcass weight). The regional variation is large, depending on the amount of pasture, by-products and food waste available in the specific region (see Supplementary material S6 for regional results). Amount of red meat is considerably greater than the healthy level specified in this study (13 kg) and more in line with the more liberal recommendation from the World Cancer Research Fund of 500 g of cooked red meat per week (approximately 50 kg carcass weight).

Schader et al. (2015) and van Zanten et al. (2016), who also modelled a global 'ecological leftover' scenario, arrived at a total per capita meat availability of approximately 9 and 35 kg per year respectively. The differences in these estimates (this study, and these other two) lies in the fact that Schader et al. (2015) and van Zanten et al. (2016) modelled livestock efficiencies of grazing animals at lower levels than this study, and in the case of Schader et al. (2015) did not include the use of food waste as feed. Hence, the intensity of grassland management and whether food waste is used as a feed source determines how much meat would be available.

For the proponents of the 'not enough food' narrative (who see steering consumption towards lower-meat diets as improbable) the projected diet variants of the INT, IDP and IDA scenarios may be more appealing or achievable than the EL scenario. Intensifying (INT) or abandoning (IDP and IDA) pure (non-dairy) beef production would save large areas of land, and reduce greenhouse gas emissions greatly, relative to business as usual projections (de Oliveira Silva et al., 2016; Havlík et al., 2014). In these scenarios, corresponding to the 'Calibrated carnivory' future, consumption would not be a policy focus – emphasis would instead be placed on managing the possible negative outcomes of raising livestock in highly intensive systems, including risks of point pollution, animal welfare concerns and zoonotic disease risks.

4.7. Limitations of this study

Our purpose in this study was to test different approaches to their implausible limits − to assess theoretical agricultural land needed and GHG emissions generated from Garnett's (2015) livestock futures representing different perspectives on the food system problem, so as to gather knowledge on approximate limits of different mitigation options and hence enable more substantiated discussions. As such, we present results from extreme scenarios and implementation of mitigation options which means that this study provides a test of the relative importance of different levers for reducing the impact of food system: productivity, reduced waste and different dietary changes rather than providing anything near realistic futures in 2050. For example, an entirely plant based diet, as well as one totally based on artificial meat, is implausible, as is intensification of livestock production in all regions including moving animals completely off pasture land. The EL scenario provides an interesting concept but policy or market mechanisms to steer in this direction are difficult to imagine within current systems. However, these extremes are still valuable to study as advocacy for their implementation is heard in the debate.

Naturally, results are coarse as modelling on a global level is associated with great uncertainties for several reasons. The amount of available pastures and plausible utilization rates are highly uncertain (Chang et al., 2016), the FAO data on food consumption and current yields level has several limitations (FAO, 2016) and the modelling of GHG emissions from biological processes is associated with inherent variation and uncertainty. In addition, climate change effects on future yields were not considered. The assumed pasture utilization rate of 30% used in the EL scenario (Supplementary material S3.3) was set to account for seasonal constraints but was not regionally adjusted (Fetzel et al., 2017). Still, relative differences between scenarios should be illustrative, as where results are comparable, they are in agreement with previous research (for GHG emissions *e.g.* Popp et al., 2010; Hedenus et al., 2014).

The fact that energy use was not included adds uncertainty as regards final total GHG emissions for all scenarios. Intensive meat production in current systems requires approximately from 20 MJ up to over 100 MJ primary energy per kg of product (Röös et al., 2013) while initial estimates of the production of artificial meat are in the same range (26–33 MJ in Tuomisto and Teixeira de Mattos, 2011 and 103.5 MJ electricity in Smetana et al., 2015). Although artificial meat and milk are available on a lab-scale, the consequences of their upscaling are highly uncertain; their production could potentially be energy demanding, which would entail considerable GHG emissions unless energy systems are fossil free in 2050 (Smetana et al., 2015).

It should also be noted that diets are not nutritionally equivalent across scenarios. They differ in protein and fat content (see Supplementary material S6 for details) due to the substitution of animal products based on energy content. Micronutrient content in diets was not assessed − in diets with no meat, fish or dairy, attention has to be paid to some key nutrients including zinc, calcium, iodine, vitamin B12 and riboflavin (Millward and Garnett, 2010).

One complexity we deliberately avoided was that of trade as we looked at how the scenarios play out in each region separately (see Supplementary material S1 for regional results). Levels of trade range from fully integrated global markets – as often advocated by the 'not enough food' proponents – to more or less local food systems often promoted by the 'too imbalanced' advocates. Establishing an optimal level of trade is complex and needs to consider several outcomes such as the impact on regional and global food prices, environment and climate (Schmitz et al., 2012; Hertel and Baldos, 2016) and the extent to which market integration can improve or undermine resilience in the face of severe climate shocks (Hertel and Baldos, 2016).

5. Conclusions

This study showed that without improvements in crop productivity or reductions on today's waste levels, available cropland will only suffice if the production of all protein currently supplied by animal foods is replaced by artificial variants not requiring any land (ART), a highly implausible future. However, if yield gaps are closed by 50% and waste reduced by 50%, the available cropland will suffice for all those scenarios that include a reduction of animal products and/or a transition to poultry or aquaculture (all scenarios except the INT for projected diets). For scenarios corresponding to an extrapolation of current consumption patterns (animal product amounts and types consumed in proportions corresponding to the current average consumption) and with livestock production based on feed from cropland, available cropland will not be enough (INT for projected diets). A livestock future which make use of pastures for ruminant production and food waste for pigs, uses considerably less cropland and could provide 40–56 kg per capita per year of red meat if livestock production within these restrictions is intensified. However, such a livestock future would not reduce agricultural GHG emissions on current levels, without substantial continuous carbon sequestration in pastures.

Hence, this study confirms previous research that to achieve a sustainable food future, action is needed on all fronts; supply, demand and waste. In other words, more food is needed and less resource-demanding ('less greedy') diets needs to be the norm. Ultimately, stakeholder prioritisation between these strategies will be based on what views stakeholders hold about human nature and on the possibilities for technological, behavioural and institutional change. By providing scientific data connected explicitly to these underpinning perspectives, as we attempted here, it is hoped that future discussion will be more constructive and decisions on future food policy more substantiated.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2017.09.001.

References

Alexander, P., Brown, C., Arneth, A., Dias, C., Finnigan, J., Moran, D., Rounsevell, M.D.A., 2017. Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use? Global Food Secur. http://dx.doi.org/10.1016/j.gfs.2017.04.001.

Alexandratos, N., Bruinsma, J., 2012. World Agriculture Towards 2030/2050. The 2012 Revision. ESA Working Paper No. 12-03. Agricultural Development Economics Division. Food and Agriculture Organization of the United Nations, Rome, Italy.

Andreyeva, T., Long, M.W., Brownell, K.D., 2010. The impact of food prices on consumption: a systematic review of research on the price elasticity of demand for food. Am. J. Public Health 100 (2), 216–222. http://dx.doi.org/10.2105/AJPH.2008.151415.

Bai, J., Wahl, T.I., Lohmar, B.T., Huang, J., 2010. Food away from home in Beijing: effects of wealth, time and free meals. China Econ. Rev. 21 (3), 432–441. http://dx.doi.org/10.1016/j.chieco.2010.04.003.

Bailey, R., Froggatt, A., Wellesley, L., 2014. Livestock ?climate change's forgotten sector. Global public opinion on meat and dairy consumption. The Royal Institute of International Affairs. Chatham House, London, UK.

Bajželj, B., Richards, K.S., Allwood, J.M., Smith, P., Dennis, J.S., Curmi, E., Gilligan, C.A., 2014. Importance of food-demand management for climate mitigation. Nat. Clim. Change 4 (10), 924–929. http://dx.doi.org/10.1038/nclimate2353.

Barkema, H.W., von Keyserlingk, M.A.G., Kastelic, J.P., et al., 2015. Invited review: changes in the dairy industry affecting dairy cattle health and welfare. J. Dairy Sci. 98 (11), 7426–7445. http://dx.doi.org/10.3168/jds.2015-9377.

Beede, D., 2013. Animal agriculture: how can it be sustainable in the future? In: Kebreab, E. (Ed.), Sustainable Animal Agriculture. Cabi, Oxfordshire, UK, pp. 284–311.

Bennetzen, E.H., Smith, P., Porter, J.R., 2016. Decoupling of greenhouse gas emissions from global agricultural production: 1970-2050. Global Change Biol. 22 (2), 763–781. http://dx.doi.org/10.1111/gcb.13120.

Bergman, M.A., Richert, R.M., Cicconi-Hogan, K.M., et al., 2014. Comparison of selected animal observations and management practices used to assess welfare of calves and adult dairy cows on organic and conventional dairy farms. J. Dairy Sci. 97 (7), 4269–4280. http://dx.doi.org/10.3168/jds.2013-7766.

Chang, J., Ciais, P., Herrero, M., et al., 2016. Combining livestock production information in a process-based vegetation model to reconstruct the history of grassland management. Biogeosciences 13, 3757–3776. http://dx.doi.org/10.5194/bg-13-3757-2016.

Davis, K.F., Gephart, J.A., Emery, K.A., et al., 2016. Meeting future food demand with current agricultural resources. Global Environ. Change 39, 125–132. http://dx.doi.org/10.1016/j.gloenvcha.2016.05.004.

Edjabou, L.D., Smed, S., 2013. The effect of using consumption taxes on foods to promote climate friendly diets –The case of Denmark. Food Policy 39 (0), 84–96. http://dx.doi.org/10.1016/j.foodpol.2012.12.004.

Erb, K.-H., Lauk, C., Kastner, T., Mayer, A., Theurl, M.C., Haberl, H., 2016. Exploring the biophysical option space for feeding the world without deforestation. Nat. Commun. 7, 11382. http://dx.doi.org/10.1038/ncomms11382.

Eyles, H., Ni Mhurchu, C., Nghiem, N., Blakely, T., 2012. Food pricing strategies, population diets, and non-Communicable disease: a systematic review of simulation studies. PLoS Med. 9 (12), e1001353. http://dx.doi.org/10.1371/journal.pmed.1001353.

FAO, 2011. Global Food Losses and Food Waste –Extent, Causes and Prevention. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO, 2014. The State of World Fisheries and Aquaculture. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO, 2015. Faostat. Food and Agriculture Organization of the United Nations, Rome, Italy. http://faostat.fao.org/default.aspx.

FAO, 2016. FAOSTAT Food Balance Sheets Metadata. Food and Agriculture Organization of the United Nations, Rome, Italy. http://www.fao.org/faostat/en/#data/FBS.

Fetzel, T., Havlik, P., Herrero, M., Erb, K.-H., 2017. Seasonality constraints to livestock grazing intensity. Global Change Biol. 23, 1636–1647. http://dx.doi.org/10.1111/gcb.13591.

Fischer, C.G., Garnett, T., 2016. Plates, pyramids, planet. Developments in national healthy and sustainable dietary guidelines: a state of play assessment. Food Climate Research Network. University of Oxford, Oxford, UK.

Foley, J.A., DeFries, R., Asner, G.P., et al., 2005. Global consequences of land use. Science 309 (5734), 570–574. http://dx.doi.org/10.1126/science.1111772.

Foley, J.A., Ramankutty, N., Brauman, K.A., et al., 2011. Solutions for a cultivated planet. Nature 478 (7369), 337–342. http://dx.doi.org/10.1038/nature10452.

Francis, C., Lieblein, G., Gliessman, S., et al., 2003. Agroecology: the ecology of food systems. J. Sustainable Agric. 22 (3), 99–118. http://dx.doi.org/10.1300/J064v22n03_10.

Garnett, T., Appleby, M.C., Balmford, A., et al., 2013. Sustainable intensification in agriculture: premises and policies. Science 341 (6141), 33–34. http://dx.doi.org/10.1126/science.1234485.

Garnett, T., Mathewson, S., Angelides, P., Borthwick, F., 2015a. Policies and actions to shift eating patterns: what works? review of the evidence of the effectiveness of interventions aimed at shifting dets in more sustainable and healthy directions. Food Climate Research Network. The University of Oxford and Chatham House, The Royal Institue of International Affairs, London, UK.

Garnett, T., Röös, E., Little, D., 2015b. Lean, green, mean, obscene…? What is efficiency? And is it sustainable? Food Climate Research Network. University of Oxford, Oxford, UK.

Garnett, T., 2009. Livestock-related greenhouse gas emissions: impacts and options for policy makers. Environ. Sci. Policy 12 (4), 491–503. http://dx.doi.org/10.1016/j.envsci.2009.01.006.

Garnett, T., 2014. hree perspectives on sustainable food security: efficiency, demand restraint, food system transformation. What role for life cycle assessment? J. Cleaner Prod. 73, 10–18. http://dx.doi.org/10.1016/j.jclepro.2013.07.045.

Garnett, T., 2015. Gut feelings and possible tomorrows: (where) does animal farming fit? Food Climate Research Network. University of Oxford, Oxford UK.

Gerber, P.J., Steinfeld, H., Henderson, et al., 2013. Tackling Climate Change Through Livestock –A Global Assessment of Emissions and Mitigation Opportunities. Food and Agriculture Organization of the United Nations, Rome, Italy.

Godfray, H.C.J., Garnett, T., 2014. Food security and sustainable intensification. Philos. Trans. R. Soc. B Biol. Sci. 369, 20120273. http://dx.doi.org/10.1098/rstb.2012.0273.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., et al., 2010. Food security: the challenge of feeding 9 billion people. Science 327 (5967), 812–818. http://dx.doi.org/10.1126/science.1185383.

Graça, J., Calheiros, M.M., Oliveira, A., 2014. Moral disengagement in harmful but cherished food practices? an exploration into the case of meat. J. Agric. Environ. Ethics 27 (5), 749–765. http://dx.doi.org/10.1007/s10806-014-9488-9.

Graça, J., Oliveira, A., Calheiros, M.M., 2015. Meat, beyond the plate. Data-driven hypotheses for understanding consumer willingness to adopt a more plant-based diet. Appetite 90, 80–90. http://dx.doi.org/10.1016/j.appet.2015.02.037.

Grunert, K.G., Wills, J., Celemín, et al., 2012. Socio-demographic and attitudinal determinants of nutrition knowledge of food shoppers in six European countries. Food Qual. Preference 26 (2), 166–177. http://dx.doi.org/10.1016/j.foodqual.2012.04.007.

Grunert, K.G., Hieke, S., Wills, J., 2014. Sustainability labels on food products: consumer motivation, understanding and use. Food Policy 44, 177–189. http://dx.doi.org/10.1016/j.foodpol.2013.12.001.

Havlík, P., Valin, H., Herrero, M., et al., 2014. Climate change mitigation through livestock system transitions. Proc. Natl. Acad. Sci. 111 (10), 3709–3714. http://dx.doi.org/10.1073/pnas.1308044111.

Hedenus, F., Wirsenius, S., Johansson, D.A., 2014. The importance of reduced meat and dairy consumption for meeting stringent climate change targets. Clim. Change 124 (1-2), 79–91. http://dx.doi.org/10.1007/s10584-014-1104-5.

Hertel, T.W., Baldos, U.L.C., 2016. Attaining food and environmental security in an era of globalization. Global Environ. Change 41, 195–205. http://dx.doi.org/10.1016/j.gloenvcha.2016.10.006.

Hoolohan, C., Berners-Lee, M., McKinstry-West, J., Hewitt, C.N., 2013. Mitigating the greenhouse gas emissions embodied in food through realistic consumer choices. Energy Policy 63 (0), 1065–1074. http://dx.doi.org/10.1016/j.enpol.2013.09.046.

IMECHE, 2012. Global Food Waste Not, Want Not. Institution of Mechanical Engineers, London, UK.

IPCC, 2006. IPCC guidelines for national greenhouse gas inventories. Intergovernmental Panel on Climate Change. Intergovernmental Panel of Climate Change, Geneva, Switzerland.

Kearney, J., 2010. Food consumption trends and drivers. Philos. Trans. R. Soc. B Biol. Sci. 365, 2793–2807. http://dx.doi.org/10.1098/rstb.2010.0149.

Kummu, M., de Moel, H., Porkka, M., Siebert, S., Varis, O., Ward, P.J., 2012. Lost food, wasted resources: global food supply chain losses and their impacts on freshwater cropland, and fertiliser use. Sci. Total Environ. 438, 477–489.

Lamb, A., Green, R., Bateman, I., et al., 2016. The potential for land sparing to offset greenhouse gas emissions from agriculture. Nat. Clim. Change 6, 488–492. http://dx.doi.org/10.1038/nclimate2910.

Lambin, E.F., Meyfroidt, P., 2011. Global land use change, economic globalization, and the looming land scarcity. Proc. Natl. Acad. Sci. 108 (9), 3465–3472. http://dx.doi.org/10.1073/pnas.1100480108.

Licker, R., Johnston, M., Foley, J.A., Barford, C., Kucharik, C.J., Monfreda, C., Ramankutty, N., 2010. Mind the gap: how do climate and agricultural management explain the 'yield gap' of croplands around the world? Global Ecol. Biogeogr. 19 (6), 769–782. http://dx.doi.org/10.1111/j. 1466–8238.2010.00563. x.

Lwiwski, T.C., Koper, N., Henderson, D.C., 2015. Stocking rates and vegetation structure, heterogeneity, and community in a northern mixed-Grass prairie. Rangeland Ecol. Manage. 68 (4), 322–331. http://dx.doi.org/10.1016/j.rama.2015.05.002.

Ma, H., Huang, J., Fuller, F., Rozelle, S., 2006. Getting rich and eating out: consumption of food away from home in urban China. Canadian J. Agri. Econ. Rev. Canadienne D'agroeconomie 54 (1), 101–119. http://dx.doi.org/10.1111/j. 1744–7976.2006.00040. x.

Marshall, B.M., Levy, S.B., 2011. Food animals and antimicrobials: impacts on human health. Clin. Microbiol. Rev. 24 (4), 718–733. http://dx.doi.org/10.1128/cmr.00002-11.

Martinez-Sanchez, V., Tonini, D., Møller, F., Astrup, T.F., 2016. Life-Cycle costing of food waste management in Denmark: importance of indirect effects. Environ. Sci. Technol. 50, 4513–4523. http://dx.doi.org/10.1021/acs.est.5b03536.

Mauser, W., Klepper, G., Zabel, F., Delzeit, R., Hank, T., Putzenlechner, B., Calzadilla, A., 2015. Global biomass production potentials exceed expected future demand without the need for cropland expansion. Nat. Commun. 6, 8946. http://dx.doi.org/10.1038/ncomms9946.

McDonald, P., Edwards, R.A., Greenhalgh, J.F.D., Morgan, C.A., Sinclair, L.A., Wilkinson, R.G., 2011. Animal Nutrition, 7th ed. Pearson Harlow, UK, pp. 156–196 (Chapter 8 Digestion).

Millet, S., Moons, C., Van Oeckel, M.J., Janssens, G., 2005. Welfare, performance and meat quality of fattening pigs in alternative housing and management systems: a review. J. Sci. Food Agric. 85, 709–719. http://dx.doi.org/10.1002/jsfa.2033.
Millward, J.D., Garnett, T., 2010. Plenary Lecture 3 Food and the planet: nutritional dilemmas of greenhouse gas emission reductions through reduced intakes of meat and dairy foods. Proc. Nutr. Soc. 69 (01), 103–118. http://dx.doi.org/10.1017/S0029665109991868.
Mintel, 2014. Number of Global Vegetarian Food and Drink Product Launches Doubles Between 2009 and 2013. (Retrieved from). http://www.mintel.com/press-centre/food-and-drink/number-of-global-vegetarian-food-and-drink-product-launches-doubles-between-2009-and-2013.
NCCD, 2015. Overview on Cold-chain Development. National Centre for Cold-chain Development, New Delhi, India.
NRC, 2009. Emerging Technologies to Benefit Farmers in Sub-Saharan Africa and South Asia. National Academies Press, Washington DC, USA.
Neumann, K., Verburg, P.H., Stehfest, E., Müller, C., 2010. The yield gap of global grain production: a spatial analysis. Agric. Syst. 103 (5), 316–326. http://dx.doi.org/10.1016/j.agsy.2010.02.004.
Newton, R., Telfer, T., Little, D., 2014. Perspectives on the utilization of aquaculture coproduct in europe and asia: prospects for value addition and improved resource efficiency. Crit. Rev. Food Sci. Nutr. 54 (4), 495–510. http://dx.doi.org/10.1080/10408398.2011.588349.
Niebylski, M.L., Redburn, K.A., Duhaney, T., Campbell, N.R., 2015. Healthy food subsidies and unhealthy food taxation: a systematic review of the evidence. Nutrition 31 (6), 787–795. http://dx.doi.org/10.1016/j.nut.2014.12.010.
OECD, 2016. Meat Consumption (indicator). http://dx.doi.org/10.1787/fa290fd0-en.
Ouyang, W., Hao, F., Wei, X., Huang, H., 2013. Spatial and temporal trend of Chinese manure nutrient pollution and assimilation capacity of cropland and grassland. Environ. Sci. Pollut. Res. 20 (7), 5036–5046. http://dx.doi.org/10.1007/s11356-013-1481-8.
Phalan, B., Green, R., Balmford, A., 2014. Closing yield gaps: perils and possibilities for biodiversity conservation. Philos. Trans. R. Soc. B Biol. Sci. 369, 20120285. http://dx.doi.org/10.1098/rstb.2012.0285.
Plachter, H., Hampicke, U., 2010. Large-scale livestock grazing. a management tool for nature conservation. Livestock Grazing and Nature Conservation Objectives in Europe. Springer-Verlag Berlin, Heidelberg, Germany, pp. 3–25 (Chapter: 1).
Popp, A., Lotze-Campen, H., Bodirsky, B., 2010. Food consumption, diet shifts and associated non-CO2 greenhouse gases from agricultural production. Global Environ. Change 20 (3), 451–462. http://dx.doi.org/10.1016/j.gloenvcha.2010.02.001.
Post, M.J., 2012. Cultured meat from stem cells: challenges and prospects. Meat Sci. 92 (3), 297–301. http://dx.doi.org/10.1016/j.meatsci.2012.04.008.
Pradhan, P., Fischer, G., van Velthuizen, H., Reusser, D.E., Kropp, J.P., 2015. Closing yield gaps: how sustainable can we Be? PLoS One 10 (6), e0129487. http://dx.doi.org/10.1371/journal.pone.0129487.
Queiroz, C., Beilin, R., Folke, C., Lindborg, R., 2014. Farmland abandonment: threat or opportunity for biodiversity conservation? A global review. Front. Ecol. Environ. 12 (5), 288–296. http://dx.doi.org/10.1890/120348.
Röös, E., Sundberg, C., Tidåker, P., Strid, I., Hansson, P.-A., 2013. Can carbon footprint serve as an indicator of the environmental impact of meat production? Ecol. Indic. 24, 573–581. http://dx.doi.org/10.1016/j.ecolind.2012.08.004.
Röös, E., Patel, M., Spångberg, J., Carlsson, G., Rydhmer, L., 2015. Limiting livestock production to pasture and by-products in a search for sustainable diets. Food Policy 58, 1–13. http://dx.doi.org/10.1016/j.foodpol.2015.10.0.
Röös, E., Bajželj, B., Smith, P., Patel, M., Little, D., Garnett, T., 2017. Protein futures beyond sustainable intensification: potential land use and climate impacts of different consumption scenarios in Western Europe. Reg. Environ. Change 17 (2), 367–377. http://dx.doi.org/10.1007/s10113-016-1013-4.
Ray, D.K., Foley, J.A., 2013. Increasing global crop harvest frequency: recent trends and future directions. Environ. Res. Lett. 8 (4), 044041.
Rivers Cole, J., McCoskey, S., 2013. Does global meat consumption follow an environmental Kuznets curve? Sustainability Sci. Practi. Policy 9 (2), 26–36.
Roberts, C.A., Newton, R., Bostock, et al., 2015. A Risk Benefit Analysis of Mariculture as a Means to Reduce the Impacts of Terrestrial Production of Food and Energy. SARF Project Reports, SARF106. Scottish Aquaculture Research Forum, Pitlochry, Scotland.
Rogelj, J., Hare, W., Lowe, J., et al., 2011. Emission pathways consistent with a 2 degree C global temperature limit. Nat. Clim. Change 1 (8), 413–418. http://dx.doi.org/10.1007/s10584-011-0105-x.
Rousseau, O., 2015. Rise of Semi-vegetarians. (GlobalMeatnews.com. Retrieved from). http://www.globalmeatnews.com/Industry-Markets/Rise-of-the-semi-vegetarians?utm_source=RSS_text_news&utm_medium=RSS_feed&utm_campaign=RSS_Text_News.
Ruby, M.B., Heine, S.J., 2011. Meat, morals, and masculinity. Appetite 56 (2), 447–450. http://dx.doi.org/10.1016/j.appet.2011.01.018.
Säll, S., Gren, I.-M., 2015. Effects of an environmental tax on meat and dairy consumption in Sweden. Food Policy 55, 41–53. http://dx.doi.org/10.1016/j.foodpol.2015.05.008.
Salemdeeb, R., Font Vivanco, D., Al-Tabbaa, A., zu Ermgassen, E.K.H.J., 2017. A holistic approach to the environmental evaluation of food waste prevention. Waste Manage. 59, 442–450. http://dx.doi.org/10.1016/j.wasman.2016.09.042.
Schösler, H., de Boer, J., Boersema, J.J., Aiking, H., 2015. Meat and masculinity among young Chinese, Turkish and Dutch adults in the Netherlands. Appetite 89, 152–159. http://dx.doi.org/10.1016/j.appet.2015.02.013.
Schader, C., Muller, A., Scialabba, N.E.-H., et al., 2015. Impacts of feeding less food-competing feedstuffs to livestock on global food system sustainability. J. R. Soc. Interface 12 (113). http://dx.doi.org/10.1098/rsif.2015.0891.
Schmitz, C., Biewald, A., Lotze-Campen, H., et al., 2012. Trading more food: implications for land use, greenhouse gas emissions, and the food system. Global Environ. Change 22 (1), 189–209. http://dx.doi.org/10.1016/j.gloenvcha.2011.09.013.
Smetana, S., Mathys, A., Knoch, A., Heinz, V., 2015. Meat alternatives: life cycle assessment of most known meat substitutes. Int. J. Life Cycle Assess. 20, 1254–1267. http://dx.doi.org/10.1007/s11367-015-0931-6.
Smith, P., Martino, D., Cai, Z., et al., 2008a. Greenhouse gas mitigation in agriculture. Philos. Trans. R. Soc. B 363, 789–813.
Smith, P., Martino, D., Cai, Z., et al., 2008b. Greenhouse gas mitigation in agriculture. Phil. Trans. R. Soc. B : Biol. Sci. 363 (1492), 789–813. http://dx.doi.org/10.1098/rstb.2007.2184.
Smith, P., Haberl, H., Popp, A., et al., 2013. How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? Global Change Biol. 19 (8), 2285–2302. http://dx.doi.org/10.1111/gcb.12160.
Smith, P., Bustamante, M., Ahammad, H., et al., 2014. Agriculture, forestry and other land use (AFOLU). In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., Minx, J.C. (Eds.), Climate Change 2014: Mitigation of Climate Change, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Smith, P., 2012. Soils and climate change. Curr. Opin. Environ. Sustain. 4, 539–544.
Smith, P., 2013. Delivering food security without increasing pressure on land. Global Food Secur. 2 (1), 18–23. http://dx.doi.org/10.1016/j.gfs.2012.11.008.
Stehfest, E., Bouwman, L., Van Vuuren, D.P., Den Elzen, M.G.J., Eickhout, B., Kabat, P., 2009. Climate benefits of changing diet. Clim. Change 95 (1–2), 83–102. http://dx.doi.org/10.1007/s10584-008-9534-6.
The Royal Society, 2009. Reaping the Benefits: Science and the Sustainable Intensification of Global Agriculture. The Royal Society, London, UK (RS Policy document 11/09).
The Royal Society, 2012. People and the Planet.The Royal Society Science Policy Centre Report 01/12. The Royal Society, Science Policy, London.
Thornton, P.K., 2010. Livestock production: recent trends, future prospects. Philos. Trans. R. Soc. B 365, 2853–2867. http://dx.doi.org/10.1098/rstb.2010.0134.
Thow, A.M., Jan, S., Leeder, S., Swinburn, B., 2010. The effect of fiscal policy on diet, obesity and chronic disease: a systematic review. Bull. World Health Organ. 88 (8), 609–614. http://dx.doi.org/10.2471/BLT.09.070987.
Tilman, D., Clark, M., 2014. Global diets link environmental sustainability and human health. Nature 515 (7528), 518–522. http://dx.doi.org/10.1038/nature13959.
Tittonell, P., Giller, K.E., 2013. When yield gaps are poverty traps: the paradigm of ecological intensification in African smallholder agriculture. Field Crops Res. 143 (0), 76–90. http://dx.doi.org/10.1016/j.fcr.2012.10.007.
Tuomisto, H.L., Teixeira de Mattos, M.J., 2011. Environmental impacts of cultured meat production. Environ. Sci. Technol. 45, 6117–6123. http://dx.doi.org/10.1021/es200130u.
UN, 2012. World Population Prospects: The 2012 Revision. United Nations, New York, USA.
UN, 2015. Paris Agreement. C.N.63.2016. United Natons, Paris, France (TREATIES-XXVII.7. d.).
Velarde, A., Fàbrega, E., Blanco-Penedo, I., Dalmau, A., 2015. Animal welfare towards sustainability in pork meat production. Meat Sci. 109, 13–17. http://dx.doi.org/10.1016/j.meatsci.2015.05.010.
WRAP, 2012. Household Food and Drink Waste in the United Kingdom 2012. WRAP, Banbury, UK.
WRAP, 2014. Econometric Modelling and Household Food Waste. WRAP, Banbury, UK.
WRAP, 2017. Household Food Waste in the UK, 2015. WRAP, Banbury, UK.
Westhoek, H., Lesschen, J.P., Rood, T., et al., 2014. Food choices, health and environment: effects of cutting Europe's meat and dairy intake. Global Environ. Change 26, 196–205. http://dx.doi.org/10.1016/j.gloenvcha.2014.02.004.
White, R., Murray, S., Rohweder, M., 2000. Pilot Analysis of Global Ecosystems – Grassland Ecosystems. World Resources Institute, Washington DC, USA.
Wirsenius, S., Azar, C., Berndes, G., 2010. How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? Agric. Syst. 103 (9), 621–638. http://dx.doi.org/10.1016/j.agsy.2010.07.005.
Wirsenius, S., Hedenus, F., Mohlin, K., 2011. Greenhouse gas taxes on animal food products: rationale, tax scheme and climate mitigation effects. Clim. Change 108 (1), 159–184.
de Boer, J., Schösler, H., Aiking, H., 2014. Meatless days or less but better? Exploring strategies to adapt Western meat consumption to health and sustainability challenges. Appetite 76, 120–128. http://dx.doi.org/10.1016/j.appet.2014.02.002.
de Oliveira Silva, R., Barioni, L.G., Hall, J.A.J., et al., 2016. Increasing beef production could lower greenhouse gas emissions in Brazil if decoupled from deforestation. Nat. Clim. Change 6, 493–497. http://dx.doi.org/10.1038/nclimate2916.
van Zanten, H.H., Meerburg, B.G., Bikker, P., Herrero, M., de Boer, I.J., 2016. Opinion paper: the role of livestock in a sustainable diet: a land-use perspective. Animal 10 (4), 547–549. http://dx.doi.org/10.1017/S1751731115002694.