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How can the EU climate targets be met? A combined analysis of technological and demand-side changes in food and agriculture

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ABSTRACT

To meet the 2 °C climate target, deep cuts in greenhouse gas (GHG) emissions will be required for carbon dioxide from fossil fuels but, most likely, also for methane and nitrous oxide from agriculture and other sources. However, relatively little is known about the GHG mitigation potential in agriculture, in particular with respect to the combined effects of technological advancements and dietary changes. Here, we estimate the extent to which changes in technology and demand can reduce Swedish food-related GHG emissions necessary for meeting EU climate targets. This analysis is based on a detailed representation of the food and agriculture system, using 30 different food items.

We find that food-related methane and nitrous oxide emissions can be reduced enough to meet the EU 2050 climate targets. Technologically, agriculture can improve in productivity and through implementation of specific mitigation measures. Under optimistic assumptions, these developments could cut current food-related methane and nitrous oxide emissions by nearly 50%. However, also dietary changes will almost certainly be necessary. Large reductions, by 50% or more, in ruminant meat (beef and mutton) consumption are, most likely, unavoidable if the EU targets are to be met. In contrast, continued high per-capita consumption of pork and poultry meat or dairy products might be accommodated within the climate targets. High dairy consumption, however, is only compatible with the targets if there are substantial advances in technology. Reducing food waste plays a minor role for meeting the climate targets, lowering emissions only by an additional 1–3%.

Introduction

Climate change mitigation efforts have mainly focused on carbon dioxide (CO_2) emissions from fossil fuel use and deforestation, which is sensible since these account for over three quarters of total current greenhouse gas (GHG) emissions (Edenhofer et al., 2014, p. 6). However, if the global 2 °C target (UNFCCC, 2010) is to be met, focusing on fossil fuels and deforestation may not be enough, because methane (CH_4) and nitrous oxide (N_2O) emissions from agriculture may become too large (Hedenus et al., 2014).

In response to the global 2 °C target, the European Union (EU) has adopted targets for reducing its total GHG emissions by at least 80%, or possibly up to 95%, by 2050 relative to 1990 levels (European Commission, 2011). For Sweden, this corresponds to a total emission allowance per capita of 300–1300 kg CO_2-eq per year (including all sectors, not only agriculture),[1] given expected population change. For agricultural CH_4 and N_2O emissions, the EU roadmap allocates about 500 kg CO_2-eq per capita per year for the 80% reduction level (European Commission, 2011). This is to be compared with current food-related emissions, which range from 1.4 to 2.7 metric tons CO_2-eq per capita per year in Western Europe (Barker et al., 2007; Berners-Lee et al., 2012; Pradhan et al., 2013; Risku-Norja et al., 2009) depending on system boundaries and data sources. Hence, for the 80% reduction level, the implied necessary emission reduction for food and agriculture is roughly 65–80%.

Options for reducing CH_4 and N_2O in food and agriculture may be grouped into four broad categories: (i) increase in agricultural productivity and efficiency (e.g. of nitrogen use); (ii)

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[1] Swedish base year (1990) emissions were 73 million metric tons CO_2-eq per year (Naturvårdsverket, 2012). A reduction by 80–95% corresponds to an allowance of 3.7–15 million metric tons CO_2-eq per year. Expected population in 2050 is 11.5 million (SCB, 2012), which gives a per-capita allowance of about 300–1300 kg CO_2-eq per year.

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implementation of specific technology options (e.g., low-emitting manure storage); (iii) change of human diets towards less emission-intensive food; and (iv) reduction of food waste.

In many regions of the world, there is great scope for increasing crop and livestock productivity and thereby reducing the amount of greenhouse gases emitted per unit of meat and dairy produced (Tilman et al., 2011; Valin et al., 2013; Wirsenius et al., 2010). However, in Sweden and most of the EU, agricultural productivity is already relatively high (cf. Grassini et al., 2013) and the remaining potential is unlikely to contribute substantially to reducing agricultural emissions.

In contrast, specific technology options could offer substantial reductions, at least for some sources, such as manure management (Montes et al., 2013). However, many other, potentially significant, options, such as nitrification inhibitors that reduce N_2O emissions from soils (Akiyama et al., 2010), and fat additives that reduce CH_4 from ruminants (Grainger and Beauchemin, 2011), are still only at the experimental or pilot-scale level, and do not yet have any proven long-term records of sustained emission reductions. Hence, for these large sources – N_2O from soils and CH_4 from ruminants – specific mitigation technologies offer only relatively limited and uncertain reduction potentials (Smith et al., 2008).

Diets greatly affect GHG emission levels, since vegetable protein sources generally give rise to lower emissions than protein sources of animal origin (Davis et al., 2010). Ruminant meat (beef and mutton) causes particularly high emissions, far higher than most other types of food. Consequently, dietary change holds a large theoretical mitigation potential, which has been shown in several studies (Berners-Lee et al., 2012; Risku-Norja et al., 2009; Saxe et al., 2012; Westhoek et al., 2014). However, apart from a few studies (e.g. Green et al., 2015; Wirsenius et al., 2011), such analyses have largely been based on purely hypothetical changes in diets, with little consideration of existing constraints, such as consumer preferences, which tend to be conservative, at least in the short term.

Given that the remaining potential for emission reductions from productivity increases is small, that specific mitigation technologies offer rather limited and uncertain reductions, and that diets are constrained by conservative preferences, it seems likely that combining all of them would be the most effective strategy of meeting the emission targets for EU agriculture. To date, however, most analyses of GHG mitigation in food and agriculture have not investigated the combined effect of technology and diets in a consistent manner. In studies that have included the reduction potential of specific mitigation technologies, this has often been done simplistically, with no explicit differentiation between mitigation potentials based on dietary developments (see e.g. Lucas et al., 2007; Stehfest et al., 2009). Similarly, in most studies that have investigated mitigation potentials from dietary changes using current life cycle assessment (LCA) data (Berners-Lee et al., 2012; Risku-Norja et al., 2009) or models (Westhoek et al., 2014), the effect of productivity increases and specific mitigation technologies on the GHG intensity in supply has been ignored.

Here, we address these knowledge gaps by systematically assessing the combined mitigation potentials of (i) productivity and efficiency increases, (ii) specific technology options, (iii) dietary changes, and (iv) food waste reductions. The aim of this paper is to estimate the mitigation potentials of Swedish food-related emissions from such technological and demand-side changes, as a basis for assessing how the EU climate targets for agriculture in 2050 can be met. We also examine the implications of our findings for climate policy.

Method and data

This study consists of three parts. We first focus on demand-side options, through the design of a baseline scenario, which describes changes in the current average diet up to 2050, as well as five alternative scenarios with less GHG intensive diets. In the second part, we estimate GHG emission intensities in current food supply systems. In the third part, we assess potentials for reducing the emission intensities in supply by a broad range of technology options.

These estimates were based on a representation of the food and agriculture system using 30 different food items (Table 1). These items cover all types of food consumed in current diets, with the exceptions of game meat, reindeer and offal, which amount to less than 0.5% of total food consumption in energy terms (Jordbruksverket, 2014). In the design of this food system representation, higher disaggregation was chosen for livestock products and vegetable protein substitutes, since these items were in focus in the demand-side scenarios. For other food items, the level of disaggregation was determined by the need to capture variation in GHG emission intensity and nutritional properties.

Scenarios of food demand in 2050

Major features of diet scenarios

To obtain a baseline of food consumption in 2050, two scenarios were created. The *Current* diet scenario represents average consumption per capita in Sweden in 2013, estimated using data from Jordbruksverket (2014) and Livsmedelsverket (2012). *Baseline* represents a continued development of current and recent trends of increasing meat consumption at the expense of dairy products and carbohydrate-rich food (Jordbruksverket, 2014). We assumed that there is a saturation level of meat consumption at about 120 kg (in carcass weight) per capita per year, which corresponds to current meat consumption in the USA (FAOSTAT, 2014).

To assess the mitigation potential from dietary changes, we created five alternative diet scenarios: *Less Meat, Dairy Beef, Vegetarian*, *Climate Carnivore*, and *Vegan* (Fig. 1). Each diet scenario is less GHG intensive than the baseline by having lower amounts of livestock products and fish, which are by far the most GHG intensive products, and together account for about 75% of all food-related emissions (Table 1). The focus on livestock products for demand-side mitigation is particularly relevant because this group accounts for about 90% of food-related CH_4 and N_2O emissions (Table 1), and technological options for these are more limited and costly compared to CO_2 mitigation from fossil fuels (Wirsenius et al., 2011).

The diet scenario *Less Meat* is based on the baseline, but all meat consumption (including fish and eggs) is decreased by 50%. This is compensated for by an increased consumption of legumes, oil, and cereals to maintain protein and fat intake at high levels. In this scenario, total meat consumption per capita is significantly lower, but protein intake is still roughly equivalent to current levels (see Table S3 in the Supplementary Material).

Dairy Beef is based on baseline developments, but all beef except that from the dairy sector is here replaced by poultry meat, which gives a ruminant meat consumption about 80% lower than the *Baseline*. Here, there is no production of beef from single-purpose (i.e., non-dairy) systems, which is more GHG intensive than beef from dairy systems. However, beef from culled dairy cows is consumed, and surplus dairy calves are raised for beef. Hence, in this scenario, total meat consumption is not reduced, but beef consumption is lowered to the point where no single-purpose beef cattle production is needed.

In the *Vegetarian* diet scenario, meat is replaced by legumes, eggs and significant quantities of cheese. Beef from culled dairy cows is eaten in this scenario; in contrast to the *Dairy Beef* scenario, however, surplus dairy calves are culled at birth. Consumption of legumes and eggs is increased to maintain a high protein intake (see Table S3 in the Supplementary Material).

Table 1
Structure of food-system representation in this study, and the relative importance of each food item in terms of energy and protein intake (actual intake after food waste) and GHG emissions. Energy and protein intake refers to the current (2013) Swedish average diet; GHG emissions refer to current diet and current emission intensities in supply; the latter was estimated in this study based on sources stated.

Food item	ME (%)	Protein (%)	Total GHG em.[a,b] (%)	N_2O and CH_4 em.[b] (%)	Data sources for GHG emission intensities
Ruminant meat	2.6	10	38	52	
Beef	2.5	9.5	36	48	
Beef (non-dairy)	1.6	6.2	29	39	See SM Section 2.2
Dairy bulls/steers	0.51	2.0	4.5	5.9	See SM Section 2.2
Dairy cows	0.34	1.3	2.5[c]	3.2[c]	See SM Section 2.2
Mutton	0.16	0.70	2.6	3.6	Wallman et al. (2011)
Other meat, egg, fish	9.7	32	15	12	
Pork	2.9	11	7.2	8.5	Cederberg et al. (2009)
Poultry meat	2.7	11	2.7	2.2	Cederberg et al. (2009)
Eggs	1.9	4.3	0.77	1.0	Cederberg et al. (2009)
Fish, sea food (wild)[d]	0.83	3.2	1.3	0.0	Winther et al. (2009)
Fish, sea food (farmed)[d]	1.3	3.3	2.8	0.0	Winther et al. (2009)
Vegetable protein	3.5	4.8	0.30	0.13	
Legumes	1.5	3.3	0.13	0.05	da Silva et al. (2010), Hallström (2009)
Nuts, seeds	1.7	1.5	0.17	0.08	Nemecek et al. (2011)
Soy milk[e]	~0	~0	~0	~0	da Silva et al. (2010), Feraldi et al. (2012)
Dairy	18	27	23[c]	28[c]	
Liquid products	9.5	13	10	12	See SM Section 2.2[f]
Cheese	7.2	13	12	14	See SM Section 2.2[f]
Butter	1.6	0.03	1.3	1.8	Cederberg et al. (2009), Flysjö (2012)
Vegetable oils	11	0.0	1.6	1.9	Ecoinvent Center (2007), SIK Foder (2014)
Cereals	23	17	2.8	2.6	
Rice	1.8	1.2	0.51	0.68	Blengini and Busto (2009), FAOSTAT (2014), Höglund-Isaksson (2012), Kasmaprapruet et al. (2009)
Bread	13	9.6	1.8	1.4	Röös et al. (2011)
Pasta	3.0	2.6	0.27	0.21	Röös et al. (2011)
Other grains, flour[g]	5.1	3.7	0.26	0.30	Ecoinvent Center (2007), SIK Foder (2014)
Vegetables	5.9	3.6	2.2	0.59	
Green vegetables, etc.	0.40	0.47	1.2	0.17	Davis et al. (2011)
Cabbage, onions, etc.	0.39	0.48	0.20	0.11	Davis et al. (2011)
Potatoes, roots	5.1	2.7	0.77	0.30	Davis et al. (2011), Röös et al. (2010)
Fruits	3.8	0.92	2.8	0.73	
Fruits imported	2.6	0.77	2.4	0.66	Sanjuán et al. (2005), Svanes (2012)
Fruits domestic	1.3	0.15	0.34	0.07	Davis et al. (2011)
Snacks, etc.	22	4.3	14	2.8	
Sugar	2.7	0.0	1.5	0.49	Klenk et al. (2012)
Alcohol	3.2	0.59	7.4	1.4	Saxe (2010)
Snacks	1.0	0.27	0.22	0.0	Nilsson et al. (2011)
Sweets	11	3.5	2.7	0.28	Nilsson et al. (2011)
Soft drinks	3.8	0.0	2.4	0.65	Nilsson et al. (2011)

ME: metabolizable energy (“calories”); SM: Supplementary Material.

[a] CO_2 emissions from land-use changes (i.e. carbon stock changes in vegetation and soils) were not included due to lack of data.

[b] In CO_2 equivalents. Calculated using 100-year GWP in Myhre et al. (2013) (34 for CH_4, 298 for N_2O).

[c] Emissions from dairy cows operations were allocated to milk output by 90%, and the remainder to dairy cow meat output.

[d] No data on the relative fractions of wild and farmed fish and seafood were found; the shares were assumed to be equal on a per weight basis.

[e] No consumption data were available; here assumed to be negligible.

[f] Data on post-farm-gate GHG emissions in milk and cheese production was based on Cederberg et al. (2009) and Flysjö (2012).

[g] Flour and grains from wheat, rye, oats, and maize.

In the *Climate Carnivore* diet scenario, there is no consumption of ruminant products. Total meat consumption is equal to baseline, but beef and mutton are replaced by poultry meat. Pork remains at the current level, with poultry meat replacing the drop in pork consumption compared to *Baseline*. Dairy products are replaced mainly by soymilk, but also by vegetable oils, to maintain protein and fat intake at recommended levels (see Tables S3 and S4 in the Supplementary Material). Hence, in this scenario, total meat consumption is not reduced, but it is limited to meat with low GHG intensity.

Vegan is a diet scenario in which no animal products are consumed. This diet is similar to *Climate Carnivore*, in that dairy products are replaced by soy products and vegetable oils. Other meat, eggs, and seafood are replaced by vegetable sources of protein – mainly legumes, nuts and seeds – to maintain protein intake at recommended levels (see Table S3 in the Supplementary Material). Cereal and starchy roots consumption is slightly lower to keep energy intake at a level equal to *Baseline*.

Nutritional and consumer-preference constraints in alternative diet scenarios

Apart from livestock products and fish, a conservative approach was taken with respect to dietary changes in the design of the alternative diets. Hence, we assumed unchanged preferences for various non-essential items, such as sweets and alcohol, and their per-capita consumption equals that in the baseline diet. The conservative approach also means that the nutritional properties of the alternative diets are close to those of the current average diet. Therefore, the alternative diets contain high levels of protein and

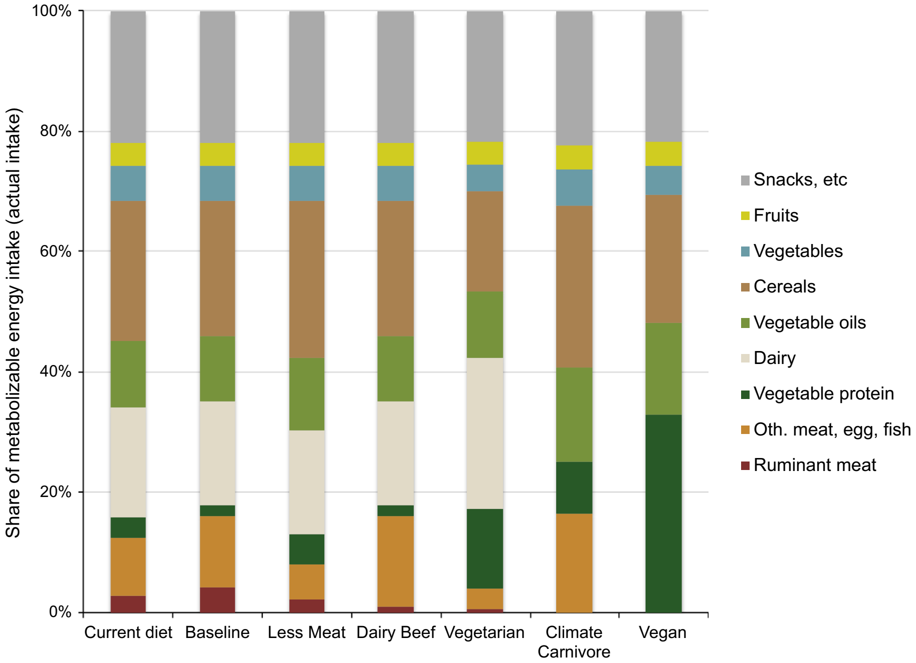

Fig. 1. Dietary structure (in energy terms) of food demand scenarios in this study. More detailed data are given in Tables S1–S5 in the Supplementary Material.

fat, in excess of requirements – as is the case in today's average diet.

Intake of metabolizable energy ("calories") was set to be constant across all diets, at the same level as in current diet. Not assuming further increases in energy intake may be considered a reasonable assumption, since current diets hardly represent a deficit compared to energy requirements. (It should be noted that intake here refers to actual intake, which is different from food "consumption", whose proxy in statistics normally is food supply at whole-sale level. Actual intake of each food item was estimated by subtracting food waste, as calculated in this study, from consumption.)

The hypothesized reductions in livestock products and fish in the alternative diet scenarios (see previous Section) were compensated for by adjustments (from baseline) in the quantity of one or more of these items: vegetable protein products, vegetable oil, cereals, and vegetables. These adjustments were made through manual iteration under the constraints of (i) maintaining energy intake constant, and (ii) keeping intake of protein, fat, and dietary fiber within recommended nutritional levels (Nordic Council of Ministers, 2014). Details on the outcome for these nutritional parameters are given in Tables S2–S5 in the Supplementary Material.

The conservative approach means that none of the alternative diets is perfectly aligned with current nutritional recommendations. Hence, as is the case with current average diets, they are sub-optimal from a health point of view. For instance, they all imply sugar intake above recommendations, since non-essential items were kept at the same level as in baseline. Naturally, health aspects are highly relevant in a discussion on desirable dietary changes, and exploring synergies and trade-offs between health and environmental aspects is vital (see, e.g., van Dooren et al., 2014). However, in this study we take a pure climate mitigation perspective.

Scenario of food waste reduction

To assess the mitigation potential from reductions in food waste, we created a dataset on current waste rates, see Section 1.2 in the Supplementary Material. For our food system representation of 30 food items, current average waste rate (including inedible/non-preferred fractions, e.g. bones, peelings) was estimated at about 20% of the amount supplied at whole-sale level.

Due to lack of evidence-based data, as a food waste reduction scenario we here simplistically assumed a halving of the edible and/or preferred fraction of current waste rates (see Table S6 in Supplementary Material). This waste reduction scenario was implemented as an additional variant in all combined technology and diet scenarios. In its implementation, actual food intake was assumed to remain the same as in the non-waste-reduction scenario variant, which means that supply is reduced to the same extent as waste (in absolute quantities).

Emission intensities in food and energy supply

To assess the mitigation potential from increases in agricultural productivity/efficiency and implementation of specific technology options, we constructed three cases of emission intensities in food and energy supply systems. The first case represents the emission intensities for current technology. In addition to providing an estimate of emissions per capita for the base year (around 2010) of this study, it also provides a high estimate of future per capita emissions for a given diet, representing the scenario of no implementation of climate mitigation policy aimed at the supply side. The two other cases, *Moderate* and *Optimistic*, are technological change scenarios of low- and high-end estimates for reductions of emission intensities in 2050, assuming that stringent mitigation policies indeed are implemented.

For each of the items in our food system representation (Table 1), we estimated GHG emission intensities per output using mainly Swedish and EU data. Exceptions were items that are produced mainly outside the EU, such as rice, tropical fruits and soybean. For all products except beef and dairy, we used GHG emission data from life cycle assessment (LCA) studies, representative of current production systems. For beef and dairy production, we estimated emission intensities using a biophysical model (see Section S5 in the Supplementary Material). All major sources of

GHG were included in the dataset, except CO_2 from land-use changes, due to lack of data in LCA studies.

The net GHG balance of food systems is indirectly influenced by land use, since occupying land for food production implies relinquishing the carbon stocks in natural vegetation, which on average are far higher than those in agricultural crops. Therefore, in addition to recurrent GHG emissions, we estimated land use in food supply.

Current emission intensities in supply

Table 1 states the sources used for creating the dataset of current GHG emission intensities of the items in our food-system representation. Two main purposes guided the design of this dataset. First, it should allow re-calculation of GHG data in LCA studies into CO_2 equivalents using the most recent Global Warming Potential (GWP) estimates (Myhre et al., 2013). Second, it should allow analysis of the mitigation effects from increased agricultural productivity/efficiency and implementation of specific technology options. To that end, emission data in the LCA studies were structured in these categories: CO_2 emissions from fuels and electricity; N_2O from fertilizer production, agricultural soils, and manure management; and CH_4 from rice cultivation, feed digestion, and manure management. Land use was structured into arable land for crops except perennial grasses/legumes ("leys"), arable land for perennial grasses/legumes, and permanent pastures. Energy use was grouped into fuels and electricity. The hereby-obtained data set is presented in Table S10 in the Supplementary Material.

Cattle (beef and dairy) production has a large climate impact, accounting for about 70% of livestock GHG emissions in the EU (Weidema et al., 2008). In addition, due to the fact that dairy systems also supply meat, the average GHG intensity of aggregate beef supply is influenced by the relative sizes of the dairy and beef (i.e., single-purpose) systems. These scale relations are affected not only by the relative size of milk and beef supply, but also by the productivity of the dairy and beef systems. Due to these complexities and the large contribution to aggregate emissions, we modeled the cattle sector's GHG emissions instead of using LCA data. The model used was calibrated against mainly Swedish data to give an estimate of current GHG emissions from beef and dairy production, see Section 2.2 in the Supplementary Material for details. The obtained model estimates of GHG intensities for cattle products are given in Tables S10 and S11 in the Supplementary Material.

Scenarios of emission intensities in supply in 2050

Using the dataset on current emission intensities as a basis (see previous Section), we estimated the potential in year 2050 for GHG reductions related to improved agricultural productivity and efficiency, and the implementation of specific mitigation technologies. These estimates were made under the assumption that stringent climate policies aimed at the supply side are implemented well ahead of year 2050.

The mitigation potentials of several options are highly uncertain for various reasons. First, due to limited experience from long-term and full-scale usage, there are uncertainties regarding the actual reduction effect of some technologies, such as nitrification inhibitors and feed additives for ruminants. Second, costs are unclear for many options, in particular for technologies that have not yet been tested even at pilot scale, such as covering and flaring of slurry facilities. Third, dissemination rates of new technologies and practices are uncertain; historical evidence suggests that technological transitions occur over time scales of decades, with large variation in adoption rates among market segments and individual farms (Fuglie and Kascak, 2001; Grieshop et al., 1988; Johnson and Ruttan, 1997; Olmstead and Rhode, 2001). Our two technological change scenarios reflect these profound uncertainties in the mitigation potential:

- *Moderate*. In this scenario, we assumed limited reduction effects of the technology options and modest dissemination. Although this scenario represents advancements compared to today, driven by climate policy, the mitigation effects are assumed to be rather limited.
- *Optimistic*. In this scenario, we assumed greater reduction effects and greater dissemination. This scenario represents an upper limit, to the best of our understanding, for how much technological change can help reduce emissions, assuming very substantial technological development and favorable conditions for dissemination.

Table 2 summarizes the quantitative assumptions in each scenario. Details behind these assumptions are described in Section S2 in the Supplementary Material.

The effect of carbon stocks changes on the net GHG balance of food supply

Through its effect on carbon stocks in vegetation and soils, land occupation in itself influences the net GHG balance of food systems. We took a limited approach to this complex issue and only offer a rough estimate of its contribution to the total climate impact of food.

Foregone carbon stocks: the carbon opportunity cost of land use

Most food systems have a far smaller vegetation stock aboveground than the preexisting natural vegetation at the site, the major exception being irrigated systems in arid regions. Hence, using land for food production implies that carbon stocks are relinquished, and that the atmospheric CO_2 content is higher than what otherwise would be the case, due to foregone carbon storage. Here, this effect on the carbon cycle is defined as the "carbon opportunity cost" of land use.

The implication of this is that using more land for food (or, e.g., bioenergy) almost always contributes to higher atmospheric CO_2 content. This is a well-known effect and a major concern in relation to agricultural expansion and so-called "indirect land-use change" (Broch et al., 2013). Conversely, using less land opens up—at least, hypothetically—the possibility to sequester carbon by restoring natural vegetation on the spare land, which would contribute to lower atmospheric CO_2 content. Since these carbon stock changes can be substantial, it is clear that the magnitude of land occupation in itself must be of major concern in assessments of the climate impact of land-using systems.

Only a few attempts have been made to systematically account for these aspects in LCA methodology (Schmidinger and Stehfest, 2012), and no common practices exist for estimating the carbon opportunity cost of land use. Here, we took a simple approach, and assumed one single, but conservative, carbon-stock-per-ha number for all land-use changes in the scenarios. This number was estimated on the assumption that semi-intensive production forest is the alternative land use to food production, which is likely to be accurate for Sweden and large parts of the EU. As is the case with natural forests, these production forests have high carbon stocks per ha.

Average biomass stock per ha of standing spruce or pine forest in Sweden is about 100 metric tons dry matter (Eliasson et al., 2013; Jalkanen et al., 2005), which for a carbon content of 50% (Lamlom and Savidge, 2003) gives a carbon stock of about 50 metric tons carbon per ha. Carbon stocks of agricultural crops were assumed to be zero. To compare this stock change with recurrent GHG emissions, we amortized the change over a 100-year period, since this conforms approximately to the actual growth cycle of Swedish forests. For simplicity, we used the 100-year amortization period also for losses in carbon stocks due to increases in land area, which clearly understates the climate impact, since deforestation

Table 2
Summary of assumptions in scenarios of reduced emission intensities in supply due to technological changes. All numbers refer to changes in 2050 from current (around 2010) levels. For more details, including data sources, see Section S2 in the Supplementary Material.

Technology option	Sub-system	Gas	Technological change scenario	
			Moderate (%)	*Optimistic* (%)
Agriculture				
Feed use per meat/milk output	Beef (non-dairy)	n.a.	−2.6	−12
	Dairy bulls/steers	n.a.	−5.1	−22
	Dairy	n.a.	−5.0	−14
	Mutton	n.a.	−2.6	−12
	Pork	n.a.	−5	−10
	Poultry	n.a.	0	−5
Feed additives, etc.[a]	All ruminants	CH_4	−8	−16
Low-emitting manure management technology[b]	Beef (non-dairy), mutton	N_2O	−35	−80
		CH_4	−50	−85
	Dairy bulls/steers	N_2O	−40	−80
		CH_4	−50	−85
	Dairy	N_2O	−10	−70
		CH_4	−10	−70
	Pigs	N_2O	0	−70
		CH_4	0	−70
	Poultry	N_2O	0	0
		CH_4	0	0
Low NH_3-emitting manure storage technology	All cattle	N_2O[c]	∼−40	∼−90
Land use per crop output	Arable-land crops other than grasses/legumes	n.a.	−5	−10
	Grasses/legumes on arable land	n.a.	−10	−20
Low NH_3-emitting manure application technology	All crops	N_2O[c]	∼−25	∼−50
Nitrification inhibitors[d]	All arable land	N_2O	−18	−38
	Permanent pasture	N_2O	0	0
Management rice production	Rice	CH_4	−20	−40
Energy supply, fertilizer production				
Biofuels		CO_2	−30[e]	−60[e]
Decarbonization electricity system		CO_2	−93	−99
End-of pipe cleaning nitrogen fertilizer prod.		N_2O	−40	−80

n.a.: not applicable; NH_3: ammonia.

[a] Reduction percentages were applied to model-based calculations of CH_4 from feed digestion (see Section 2.2 in the Supplementary Material).

[b] Reduction percentages are the aggregate effects of structural changes towards low-emitting manure management systems (see Section 2.1.3 in the Supplementary Material).

[c] Ammonia emission levels influence the need for external N inputs from fertilizer as well as the magnitude of "indirect" N_2O emissions (see Sections 5.2 and 5.3 in the Supplementary Material).

[d] Reduction percentages were applied to all sources of N_2O from agricultural soils.

[e] Net CO_2 reduction.

emissions typically are pulse emissions. On balance, the chosen data is likely to underestimate the mitigation effect, since in Sweden, as in any region, agricultural land almost always has higher fertility than the average forest land.

Other carbon stock changes: soil carbon under permanent pastures

Soil carbon sequestration under permanent pastures in Sweden is reported to be 60 kg carbon per ha per year (Jordbruksverket, 2010). This rate is expected to drop over time as soil carbon reaches equilibrium (Smith, 2014). For simplicity, however, we made an upper-end estimate and assumed a rate of 60 kg carbon per ha per year for a full century on all permanent pastures.

Results

Greenhouse gas emissions

Figs. 2 and 3 show aggregate GHG emissions by gas and food type, respectively, for different diet and technology scenarios (but excluding the reduced food waste scenario, see below). Notably, if current dietary trends continue and there are no technological advancements, CH_4 and N_2O emissions[2] will increase by about 40% by 2050, to over 1.7 metric tons CO_2-eq per capita per year. This is far from the EU climate targets for 2050, which for agricultural CH_4 and N_2O correspond to about 500 kg CO_2-eq per capita per year, for an 80% reduction level (see Section 'Introduction'). In the *Optimistic* technology scenario, advances in agricultural productivity/efficiency and specific mitigation technologies cut these emissions from both the current and baseline diets by nearly 50% respectively, down to about 600–900 kg CO_2-eq per capita per year; however, this is still insufficient for meeting the targets.

If technological advancements are combined with dietary changes, deeper emission cuts are possible, and several possibilities exist for meeting the 500 kg target, as well as the more stringent targets needed at an 95% reduction level, which corresponds to a maximum of about 300 kg CO_2-eq (for all sectors, see Section 'Introduction'). In the *Moderate* technology scenario, CH_4 and N_2O emissions from all alternative diets except *Less Meat* and *Dairy Beef* meet the 500 kg target (Fig. 2). In the *Optimistic* technology scenario, also *Dairy Beef* meets the 500 kg target. Notably, irrespective of technology level, CH_4 and N_2O emissions from both *Climate Carnivore* and *Vegan* come close to, or fall below, the 300 kg level. Hence, a diet with a lot of meat but no ruminant products may be compatible also with the more stringent climate targets needed in the very long term.

Implementing also reduced food waste, in addition to dietary and technological changes, does not substantially change the results. For a halving of the edible waste, emissions are reduced by 4–6% across the different scenarios (see Fig. S1b in the Supplementary Material). Since the potential reductions by dietary and

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[2] Note that the reason for focusing on CH_4 and N_2O emissions here (as well as in the discussion and conclusions) is that these are the sources that pertain to the agricultural sector in the EU roadmap for 2050 (European Commission, 2011). CO_2 emissions from fuels and electricity pertain to the energy sector, and have been given allowances different to those for agricultural CH_4 and N_2O under the EU climate targets.

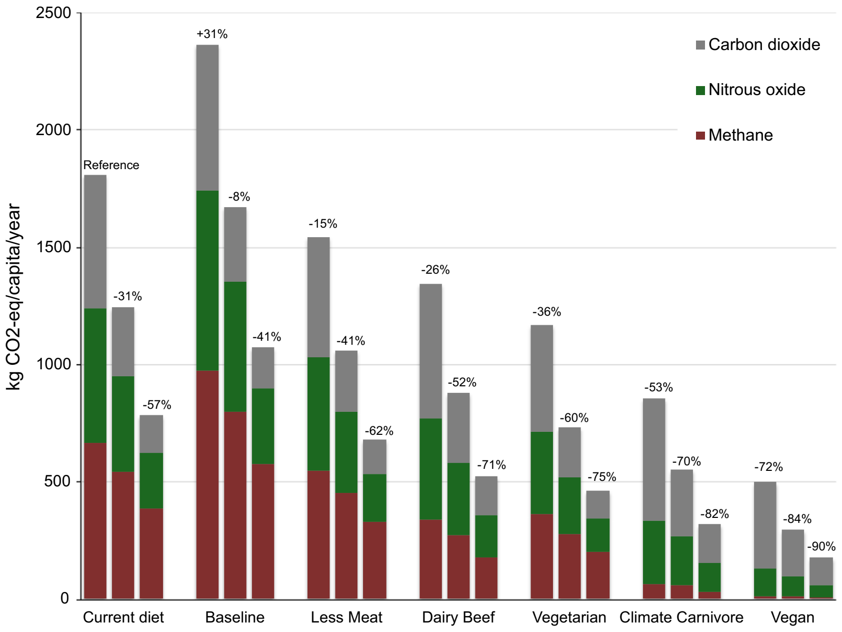

Fig. 2. Greenhouse gas emissions (by gas) per capita by diet and technology level. For each diet, emissions are shown for the current technology (left), *Moderate* technology advances (middle), and *Optimistic* technology advances (right). Numbers above bars refer to changes relative to the current diet and technology ("Reference"). Note that the scenario of reduced food waste is not implemented in this graph; for results including reduced food waste, see Fig. S1a in the Supplementary Material.

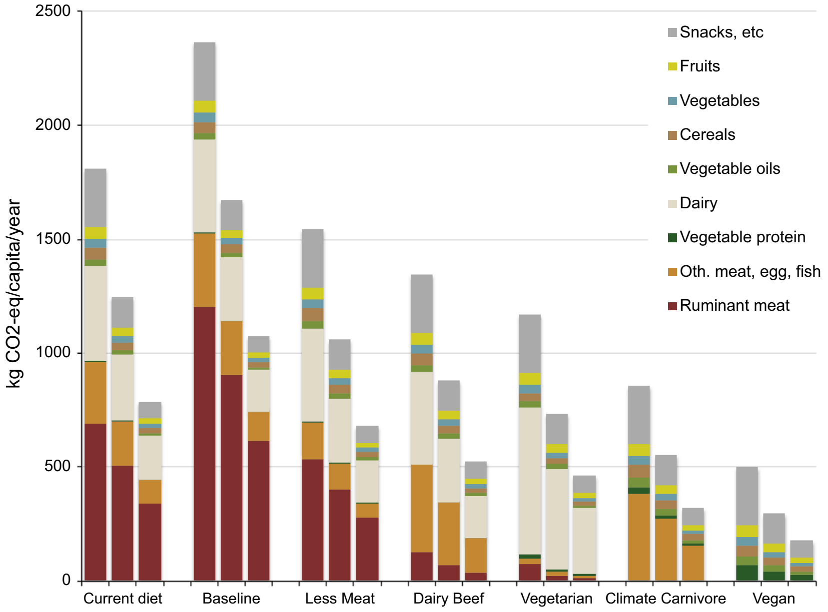

Fig. 3. Greenhouse gas emissions (by food type) per capita by diet and technology level. For each diet, emissions are shown for the current technology (left), *Moderate* technology advances (middle), and *Optimistic* technology advances (right). Note that the scenario of reduced food waste is not implemented in this graph; for results including reduced food waste, see Fig. S2 in the Supplementary Material.

technology changes are far greater, reducing food waste adds only some 1–3 percentage points to the total reductions in these scenario combinations (compare Fig. 2 and Fig. S1a in the Supplementary Material).

Interestingly, as shown in Figs. 2 and 3, larger emission cuts are achieved by *replacing* beef from single-purpose beef production with poultry meat (the *Dairy Beef* diet)—while maintaining total meat demand—than by cutting meat demand in *half*, across the board (the *Less Meat* diet). The reason for this is the far higher GHG intensity of beef compared to pork and poultry, see Fig. 4 and Table 3. Also, the vegetarian diet has noticeably higher emissions than the carnivorous but ruminant-free *Climate Carnivore* diet. The reason is that the GHG intensity of dairy products is roughly on par with that of pork, but it is distinctly higher than for poultry meat, especially if compared on a per-kg-of-protein basis (Fig. 4).

Hence, ruminant products have higher GHG intensities than most other types of food. Single-purpose beef (i.e., non-dairy) systems have particularly high GHG intensities, about 10–20 times that of pork and poultry (Table 3). The GHG intensity of dairy

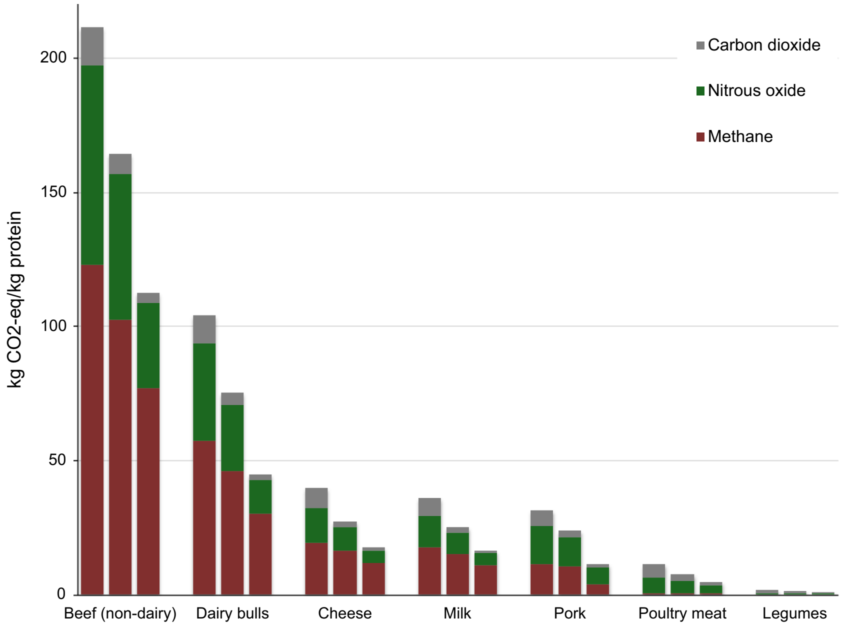

Fig. 4. Greenhouse gas emission intensity of major protein sources by technology level. Emission levels are shown for current technology (left), *Moderate* technology advances (middle), and *Optimistic* technology advances (right). Emissions for legumes are about 1% of those for non-dairy beef.

products is about four times that of chicken if measured per unit of protein (Fig. 4).

These differences can be attributed to (i) differences in feed efficiency, which scale all up-stream emissions from feed production, and (ii) CH_4 production in ruminants' feed digestion. The very high GHG intensities of single-purpose beef are due to low feed efficiencies, 2–3% compared to about 20% for poultry (Wirsenius, 2003a), in combination with substantial CH_4 production from feed digestion (5–6% of feed energy intake). High-productive dairy systems have feed efficiencies almost as high as those of high-productive poultry (Wirsenius, 2003a). In addition, dairy feed comes largely from perennial grasses and legumes, which tend to have lower emissions than cereal crops. However, CH_4 from feed digestion, which constitutes about half of the emissions from dairy, cancels out any such advantage and puts the aggregate GHG intensity clearly above that of poultry.

Land use

Fig. 5 shows aggregate land use for the different diets and technology levels. Overall, the pattern for land use among diets is comparable to that for GHG emissions (Figs. 2 and 3), with low-emitting diets having lower land use and vice versa. This is because feed conversion efficiencies, which largely influence GHG emission intensities, also greatly control land use per output.

Conspicuously, land use for biofuels that substitute for fossil fuels used in food production, as assumed in the technology scenarios *Moderate* and *Optimistic*, add most significantly to overall land use. For the current diet, biofuels imply additional land use corresponding to about 25% of current land use for food, in both the technology scenarios.

Net greenhouse gas balances including carbon stock changes

Fig. 6 shows rough estimates of amortized carbon stock changes in vegetation and soils, and the resulting net GHG emissions, by diet, in the *Moderate* technology scenario. Note that positive values for the "carbon opportunity cost" (see Section 'Foregone carbon stocks: the carbon opportunity cost of land use') imply carbon stock losses due to land area expansion, and negative values imply carbon sequestration in re-growing vegetation following area contraction.

In the diet scenarios *Vegetarian* and *Climate Carnivore*, which both exhibit much lower land use than current (Fig. 5), the implied carbon sequestration corresponds to about 20% of current emissions, and puts net emissions well below the EU climate target of 500 kg CO_2-eq per capita per year. In *Vegan*, carbon sequestration more than cancels all recurrent emissions. These quantities apply to the *Moderate* technology scenario; for the *Optimistic* scenario, mitigation from carbon sequestration would be even larger. For *Climate Carnivore* and *Vegan*, about 100 and 300 years respectively, of recurrent emissions would be negated in the *Optimistic* scenario.

Mitigation effect per technology option

Fig. 7 illustrates the mitigation effect from each of the major technology options included in the analysis (excluding carbon sequestration). Clearly, switching to biofuels and decarbonizing the electricity supply are options that have large effects in both technology scenarios. This illustrates not so much that energy use is a dominant source of CO_2 in food systems (about 30% of the current total, see "Reference" bar in Fig. 2), as that reduction potentials for CO_2 in energy supply are generally much higher than for biogenic CH_4 and N_2O sources in agriculture.

End-of-pipe cleaning of N_2O emissions in fertilizer production and use of nitrification inhibitors offer significant reductions independent of diet; they are therefore of particular strategic mitigation importance. For diets that contain meat and dairy products, increased animal productivity and implementation of low-emitting manure management technology offer substantial mitigation of approximately equal importance in most scenario combinations.

Table 3
Estimated GHG emission intensities in food supply for current (around 2010) technology and in the two technological change scenarios in 2050. Numbers are given in g CO_2 equivalents[a] per MJ metabolizable energy[b] and rounded to two significant digits. (Numbers per kg fresh weight of product and per kg of protein are provided Table S9 in the Supplementary Material.)

	Current (g CO_2-eq/MJ)	Moderate (g CO_2-eq/MJ)	Optimistic (g CO_2-eq/MJ)
Ruminant meat[c]			
Beef (non-dairy)	7800	6100	4200
Dairy bulls/steers	3900	2800	1700
Dairy cows[d]	3200	2800	1800
Mutton	7000	5600	4200
Other meat[c], eggs, fish			
Pork	1100	880	390
Poultry meat	440	300	190
Eggs	170	120	79
Fish, sea food (wild)	640	430	250
Fish, sea food (farmed)	870	580	340
Vegetable protein			
Legumes	35	26	17
Nuts, seeds	47	22	11
Soy milk	130	57	34
Dairy[d]			
Liquid products[e]	490	340	220
Cheese	720	490	320
Butter	360	270	210
Vegetable oils	58	43	26
Cereals			
Rice	120	91	68
Bread	41	25	16
Pasta	38	25	16
Other grains, flour	21	15	10
Vegetables			
Green vegetables, etc.	960	700	430
Cabbage, onions, etc.	160	120	73
Potatoes, roots	47	34	21
Fruits			
Fruits imported	290	210	130
Fruits domestic	85	62	32
Snacks, etc.			
Sugar	240	170	100
Alcohol	1100	390	190
Snacks	100	42	23
Sweets	110	78	46
Soft drinks	280	190	110

[a] Converted to CO_2 equivalents using 100-year GWP in Myhre et al. (2013) (34 for CH_4, 298 for N_2O).
[b] For converting to g CO_2 eq. per kcal, multiply by 0.0042.
[c] Refers to bone- and fat-free carcass, not entire carcass.
[d] Emissions from dairy cows operations were allocated to milk output by 90%, and the remainder to dairy cow meat output.
[e] Whole-milk equivalents.

Discussion

Implications for climate policy

From the results of this study, it is obvious that current trends in food-related CH_4 and N_2O emissions are at odds with the EU climate targets for reaching the 2 °C target, which for a 80% reduction level entail an emission allowance for CH_4 and N_2O in agriculture of about 500 kg CO_2-eq per capita per year in 2050 (see Section 'Introduction').

Not even under optimistic assumptions regarding technological changes do emissions from neither the current diet nor the 2050 baseline diet meet the 500 kg CO_2-eq target. Therefore, to meet this target, and the even more stringent targets needed in the very long term, diets will need to change towards less GHG-intensive food items. In particular, deep cuts in beef and mutton consumption seem to be unavoidable if the climate targets are to be met.

However, dietary changes for meeting climate targets need not—as is often claimed—necessarily entail a reduction in total meat consumption. This study shows that so long as consumption is limited to non-ruminant meat (i.e., pork and poultry), very high per-capita consumption levels (120 kg, or 40% higher than current) could be accommodated not only within the 500 kg CO_2-eq target, but most likely also within the more stringent targets needed for reductions larger than 80%.

Policies for structural changes in demand

Little is known about the effectiveness of different policy interventions for guiding diets towards low-emitting food. More and broader research is needed on this topic. Price-based policy instruments, such as consumption taxes differentiated by emission levels, are likely to be essential policy components since they may be more effective than other options. However, very few, and rather limited, studies have been carried out on such options (Edjabou and Smed, 2013; Säll and Gren, 2015; Wirsenius et al., 2011), and more comprehensive analyses are needed of the potentials, administrative and social costs, and implementation hurdles of such interventions.

In addition to climate taxes on food and other instruments that specifically address the demand side, policy makers in the EU could also adjust existing producer subsidies for a better alignment with climate targets. In aggregate, EU agriculture receives producer subsidies amounting to about 20% of gross receipts (OECD, 2013). Large fractions of these subsidies prop up beef and mutton production, which are segments that—according to the results of this study—almost certainly need to shrink if EU climate targets are to be met. Therefore, it would seem to be a sound policy to abolish existing general production subsidies to the ruminant sector and only keep targeted support for biodiversity conservation (see Section 'Biodiversity and landscape').

Policies for technological change

In addition to CO_2 reductions in fuels and electricity, in Sweden and the EU, nitrification inhibitors (which reduce N_2O emissions from soils) and end-of-pipe cleaning in fertilizer industry offer important abatement opportunities, since they would yield significant reductions irrespective of dietary developments (cf. Fig. 7). For diets containing meat and dairy, low-emitting manure management technology is a key mitigation option with a large potential.

However, in Sweden and in the EU in general, there are currently very few policies in place that specifically target GHG mitigation through development and dissemination of these technologies. In addition to energy policies, which are not dealt with here, there is an urgent need for stronger policies in this area, in particular regarding: (i) support for long-term field testing of nitrification inhibitors over a wide range of agronomic and environmental conditions, with the aim of assessing long-run reduction potentials as well as any negative side-effects, and (ii) support for development and full-scale testing of manure management technologies that potentially offer near-zero emissions, such as covering and flaring of slurry storage.

Other policy aspects: food security, biodiversity and animal welfare

As shown in this study, replacing ruminant products is the dietary change that would yield the largest GHG reductions (per intake of protein), and a reduction of the ruminant sector is almost certainly inescapable if the EU climate targets are to be met. However, the prospect of downsizing the ruminant sector may raise concerns regarding global food security, biodiversity, and animal welfare.

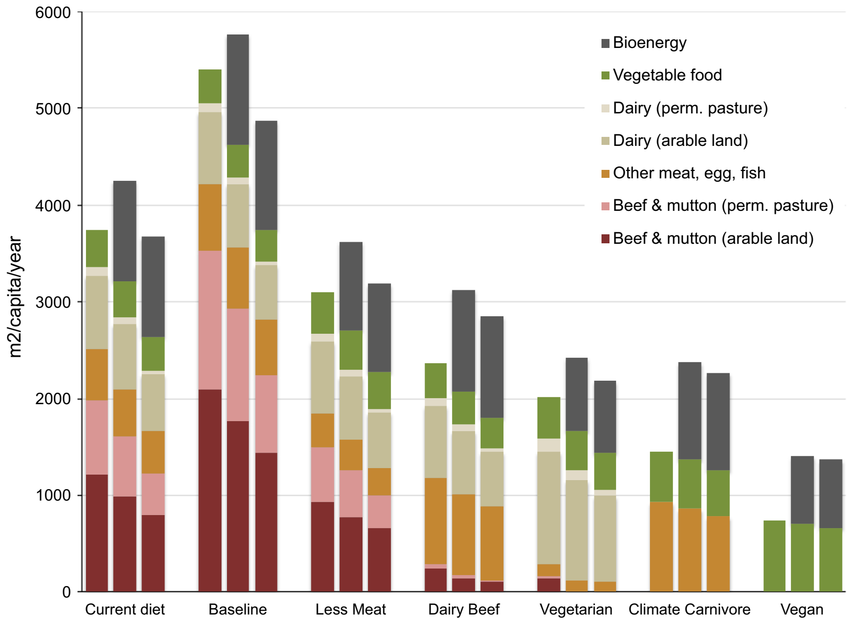

Fig. 5. Aggregate land use per capita by diet and technology level. For each diet, land use is shown for current technology (left), *Moderate* technology advances (middle), and *Optimistic* technology advances (right). Land use for bioenergy is related to substitution for fossil fuels currently used in agriculture (see Section 2.1.8 in the Supplementary Material).

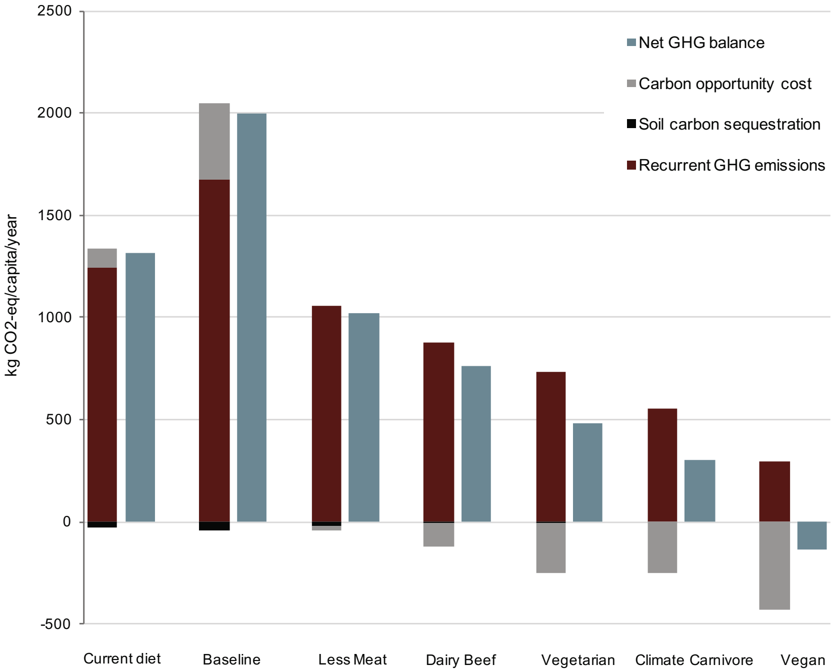

Fig. 6. Net greenhouse gas emissions per capita including effects on carbon stocks in vegetation and soils. Of consideration of space, emission levels are here shown only for the scenario of *Moderate* technology advances.

Global food security

A frequently voiced argument in favor of ruminant production is that ruminants add to the food supply by delivering food out of inedible biomass from rangeland and other land that has low opportunity cost as a means to produce other food (cf. Bradford, 1999). The implication is that having fewer domestic ruminants would be harmful for food security. This claim holds true for some segments of the world's ruminant production, e.g., the grassland-based systems in Oceania and the humid rangelands of South America. Also, in low-income regions, forage-fed ruminants are vital for the food security of large groups of resource-poor households (Smith et al., 2013). Yet, at a global level, grassland-based systems contribute very little to the human food supply, accounting for no more than about 2% of its edible protein (Herrero et al., 2015).

Furthermore, the vast majority, about 90%, of the global ruminant production (in protein terms) occurs in "mixed" systems (Herrero et al., 2013), and hence is partly based on arable land—which of course does have a high opportunity cost for production of other food. On average globally, mixed ruminant meat systems

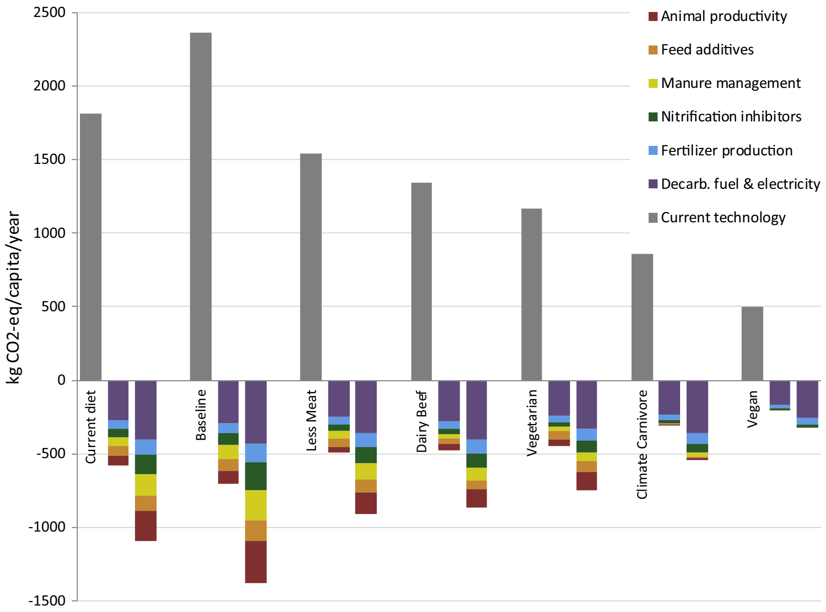

Fig. 7. Emission reductions separately per major technology option, by diet and technology scenario. Numbers are shown as negative numbers; *Moderate* technology advances on the left, *Optimistic* technology advances on the right. Emissions for current technology are shown (as positive numbers) for reference.

use about 10 ha of arable land per metric ton of protein output, which is equal to the average arable land use per protein output of the global pork and poultry sector (Herrero et al., 2015). Hence, despite relying largely on grassland resources and inedible crop residues, mixed ruminant meat systems subtract from the global food supply to about the same extent as do pork and poultry.

In Europe, long winters necessitate substantial use of conserved feed (e.g., silage and grains), produced on arable land, in cattle production, why European beef production uses 4–5 times more arable land per meat output compared to pork and poultry meat (Wirsenius, 2003b). Similarly, European dairy production uses roughly 3 times more arable land per protein output than vegetable protein production. For a given arable land use, a structural shift in European production from beef to pork and/or poultry meat, or from dairy to vegetable food, could substantially increase—not decrease—the global supply of edible protein.

Biodiversity and landscape

Another argument in support of ruminant production is that it is a necessary component for maintaining grassland ecosystems of cultural significance that have evolved over long time under the influence of domestic herbivores (Bignal and McCracken, 1996). In some regions, particularly Europe, such grasslands are largely found in biomes where forests are the predominant native vegetation, why sustained grazing or other vegetation control is required for grassland persistence. Since these areas add to the habitat diversity at the landscape level and have relatively high species diversity (compared to other agricultural land and managed forests), they represent significant repositories of biodiversity. Still, large fractions of the species are not endemic to these cultural grasslands but occur also in natural grasslands in the same ecozone. In addition, although several species are closely linked to the specific effects of grazing, such as trampling (Metera et al., 2010), many others are not.

Nevertheless, it is clear that European grassland biodiversity largely depends on grazing by domestic ruminants, which means that reducing the climate impact of food will be in tension with biodiversity conservation. However, large reductions in European ruminant numbers could still be reconcilable with biodiversity conservation, given that there are large segments of current ruminant production that rely very little on cultural grasslands as a feed resource. Furthermore, a climate-policy-driven reduction in ruminant numbers could be countered by support for and dissemination of low-intensity-grazing systems designed for maintaining species-rich grasslands (Rosenthal et al., 2012).

Finally, a reduction in ruminant numbers caused by lower demand for meat and dairy should also be considered an opportunity, and not only a threat, from a biodiversity point of view. Since ruminant production is land intensive, also in terms of arable land (cf. Section 'Global food security'), a drop in ruminant consumption would significantly lessen the global land requirements for food production. This would contribute to reducing the incentives for agricultural expansion by deforestation in e.g., South America, thereby helping to conserve biodiversity. In agriculturally consolidated regions, such as Europe, it would allow more room for partial restoration of natural ecosystems ("rewilding") that predate the exploitation for agriculture. In Europe, which arguably is one of the most exploited land masses on the planet, wetlands and old-growth deciduous forests are very scarce, and even a minor restoration of these habitats would add substantially to Europe's biodiversity.

Animal welfare

In current production systems, animal welfare in cattle production tends to surpass that in intensive pork and poultry production. From an animal welfare perspective, therefore, dietary shifts towards poultry meat and pork could have adverse effects. Raising animal welfare standards in EU pork and poultry production could reduce such adverse effects. Improving animal welfare would almost certainly increase production costs but need not necessarily raise GHG emission intensities substantially (LRF Konsult, 2012). Hence, there need not be a conflict between improving animal welfare and reducing greenhouse gas emissions.

Limitations of data and method

There are two main potential sources of error associated with the use of LCA data in this study. First, the system boundaries are not entirely consistent among the LCA studies. LCAs of the category "Snacks, etc." (sugar, alcohol, snacks, sweets, and soft drinks) include emissions from processing and packaging, while most of those of other food categories only include emissions up to the farm gate. However, emissions from processing and packaging are mainly CO_2 from energy use, which means that this inaccuracy diminishes in the technology scenarios of this study, since we assume a high degree of decarbonization of the energy system. Second, there are errors related to the representativeness of the LCA studies. The chosen aggregation of imported fruit in this study is rather crude since it includes both fruits imported via cargo ships, which cause relatively small emissions, and fruits imported via air, which in contrast cause large emissions. We did not obtain any data on the shares of consumption for these categories and thus had to make assumptions. Regardless, emissions from fruits are small in all scenario combinations, so any error of this kind would not greatly affect the overall outcome.

By using Swedish and EU data for estimating GHG intensities in supply, we ignored deviations in emission intensity of food that in reality is imported from outside the EU. Since food produced outside the EU in some cases has higher GHG and land-use intensity than that of EU produce, such as beef (Cederberg et al., 2011), this simplification may understate the true emission levels. However, the opposite may hold for other food items. Also, most of EU food consumption is supplied from within the EU, and the net-imported fraction of the total is small, with a few exceptions, such as soybean and coffee (EUROSTAT, 2014). On balance, this error is likely to underestimate current emissions levels, but less so in the technology scenarios, since it is reasonable to assume significant technological convergence across world regions until year 2050.

Conclusions

This study concludes that CH_4 and N_2O emissions from food consumption may be reduced to the extent necessary to meet the EU climate targets for 2050. Technological advancements, in agricultural productivity and specific mitigation technologies, can play a major role and could under optimistic assumptions cut CH_4 and N_2O emissions by nearly 50% in 2050, down to 600–900 kg CO_2-eq per capita per year. However, since these emissions may need to be reduced to about 500 kg CO_2-eq per capita per year, or less, to meet the climate targets, technological options alone are very unlikely to be sufficient, and changes in diets towards low-emitting food will almost certainly be necessary. Although these findings are mainly drawn from conditions in Sweden, they are likely to hold for the EU as a whole, given the similarities in consumption patterns and technology.

Deep cuts, by 50% or more, in ruminant meat (beef and mutton) consumption—relative baseline development—is the only dietary change that with high certainty is unavoidable if the EU climate targets are to be met. In contrast, continued consumption at high per-capita levels of either non-ruminant meat (pork and poultry) or dairy products can be accommodated within the climate targets. However, high dairy consumption is compatible with the 500 kg CO_2-eq target only if there are substantial advancements in technology.

The GHG mitigation from technological and dietary changes increases substantially if their land-saving effects are factored in. If spare agricultural land were allowed to revert to forest or other natural vegetation, the resulting carbon sequestration in vegetation stocks could, for the non-ruminant diets *Climate Carnivore* and *Vegan* be large enough to cancel out 100 and 300 years, respectively, of all food-related recurrent GHG emissions.

In comparison with technological and dietary changes, reducing food waste plays a minor role for meeting the climate targets. Even if assuming a halving of current avoidable food waste, which may be considered optimistic, emissions are lowered only by an additional 1–3%.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foodpol.2015.12.012.

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