Food Policy 58 (2016) 1–13

Contents lists available at ScienceDirect

Food Policy

journal homepage: www.elsevier.com/locate/foodpol

Limiting livestock production to pasture and by-products in a search for sustainable diets

Elin Röös [a,*], Mikaela Patel [b], Johanna Spångberg [a], Georg Carlsson [c], Lotta Rydhmer [d]

[a] Department of Energy and Technology, Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden
[b] Department of Animal Nutrition and Management, Swedish University of Agricultural Sciences (SLU), P.O. 7024, SE-750 07 Uppsala, Sweden
[c] Department of Biosystems and Technology, Swedish University of Agricultural Sciences (SLU), Alnarp, Sweden
[d] Department of Animal Breeding and Genetics, Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden

ARTICLE INFO

Article history:
Received 11 May 2015
Received in revised form 8 October 2015
Accepted 30 October 2015
Available online 30 November 2015

Keywords:
Sustainable diets
Ecological leftovers
Livestock production
Climate change
Land use
Food consumption

ABSTRACT

A method was developed for designing 'fair' diets (not using more than globally available arable land per capita) and for assessing the sustainability of such diets. The diets were based on the principle of 'ecological leftovers' for livestock production, i.e. raising livestock on pasture and by-products not suitable for or wanted by humans. The method was applied to Sweden using three different scenarios for livestock production, all taking the starting point that semi-natural pastures should be grazed by ruminants for reasons of biodiversity conservation. The scenarios also included differing use of by-products (from crop production and food processing) to either boost milk production (I-Milk scenario) or produce eggs and pig meat (E-Milk and Suckler scenarios). In I-Milk, milk and meat were produced in intensive systems in which dairy cows and their offspring only grazed to a limited extent, resulting in the human diet containing recommended levels of dairy products (350 ml milk per day) and meat twice a week. Milk could also be exported. In E-Milk, pasture was used more for dairy cows and their offspring, resulting in fewer animals and less milk (150 ml milk per day) and four servings of meat per week. In the Suckler scenario, pasture was grazed by suckler herds providing no milk but meat four times per week. The environmental impacts of the diets were assessed using the planetary boundaries framework. The results showed substantially lower environmental impacts compared with the average current Swedish diet, but the strict absolute climate boundary and the N and P input boundaries were still exceeded for all diets. The approach adopted, of letting the ecological resource capacity act as the constraining factor for livestock production, is in line with agroecology principles and efficient use of land to improve food security, and could be useful in discussions about sustainable consumption of animal products.

Introduction

Western dietary patterns are clearly unsustainable in terms of environmental impact and health (Foley et al., 2011; Sabaré and Soret, 2014; Smith and Gregory, 2013; Tillman and Clark, 2014). Most importantly, overconsumption and waste must be curbed and consumption of resource-demanding foods must decrease in order to reach environmental objectives such as limiting expansion of agricultural land and reducing greenhouse gas emissions (Garnett, 2011; Bajzelj et al., 2014). The amount and type of protein consumed are key factors, as protein is currently overconsumed in the Western diet and is largely supplied by resource-demanding, animal-based products. However, while there can be major environmental and health benefits with vegetarian or vegan diets (Scarborough et al., 2014; Tillman and Clark, 2014), such diets may not be the best option for the entire population since: (1) dairy and egg production for vegetarian diets also give meat; and (2) some land types (e.g. permanent pasture) are unsuitable for cultivation of crops for a vegan diet and may also need to be grazed for biodiversity conservation (Jerrentrup et al., 2014; Rook et al., 2004). Furthermore, some vegetarian diets are actually more land-demanding (Peters et al., 2007) or climate-impacting (Vieux et al., 2012) than diets with a limited amount of meat. It is also unclear what production systems without livestock would comprise and how they would affect environmental, economic and social sustainability. In addition, the high content of essential amino acids and micronutrients in livestock products is important for malnourished people in developing countries and people suffering from nutrient deficiency (Smith et al., 2013). Livestock products are also an important way of securing a livelihood among the poor and of creating job opportunities for

* Corresponding author.
E-mail address: elin.roos@slu.se (E. Röös).

http://dx.doi.org/10.1016/j.foodpol.2015.10.008
0306-9192/© 2015 The Authors. Published by Elsevier Ltd.

a large proportion (30%) of the world's population (World Bank, 2014). Livestock also provide benefits other than food, such as biodiversity, other ecosystem services, and recycling plant nutrients. However, these benefits must be valued and tuned so that the system fits the land (Janzen, 2011) and the dietary needs of the population.

Important unanswered questions in this regard are what comprises a sustainable level of livestock product consumption, what types of livestock products are most sustainable and what production systems should provide these. Depending on individual values and viewpoints, there are several ways of examining these questions. One approach is to let the ecological resource capacity be the constraining factor for livestock production, i.e. to feed animals with resources not suitable for human consumption, such as grass from marginal land unsuited for other production and by-products from crop production and food processing, thus also recycling resources and managing landscapes. This principle is referred to as producing livestock on 'ecological leftovers' (Garnett, 2009). In a future in which livestock production is restricted by the principle of feeding on ecological leftovers, food systems would need to be more localised and the availability of land, water and by-products would constitute site-specific constraints and opportunities for agriculture (Garnett, 2009).

The principle of livestock production from ecological leftovers is attractive in several ways. Similarly to the agroecology concept, it emphasises the principles of efficient use of resources, recirculation of nutrients and development of production systems adapted to unique local conditions (Francis et al., 2003). For many consumers, a diet which contains some meat is probably more acceptable than a diet without any meat (Schösler et al., 2012; Dagevos and Voordouw, 2013). Furthermore, in studies concerned with food security in light of the increasing wealthy global population feeding animals ecological leftovers instead of products edible to humans is often proposed as a means to increase food supply (e.g. Godfray et al., 2010; Foley et al., 2011). However, little is known about what a diet based on ecological leftovers would actually comprise. Furthermore, it is not obvious how by-products from the food system could be incorporated into animal diets, depending on animal species and the nutrient content of the feed. Moreover, the supply of by-products depends on production of plant-based foods and competition for by-products for other purposes, as well as cultural traditions of what is considered edible food. Finally, it is not known whether a diet based on ecological leftovers would be sustainable.

In this study, a method for designing diets based on the principle of ecological leftovers for livestock production and for assessing the sustainability of such diets was devised. The method was applied to the case of Sweden, examining three different ways of using marginal land and by-products following different viewpoints on how to efficiently produce food. The implications for Swedish agricultural production and the environmental and social impacts of such diets were assessed and discussed.

Method

Summary of the method

The 'ECOLEFT' method proposed here builds on a set of normative principles based on the concept of ecological leftovers for livestock production (Garnett, 2009):

1. Arable land should primarily be used for the production of plant-based food for humans.
2. Livestock should be fed biomass not suitable for or wanted by humans.
3. Semi-natural grassland should be used for livestock production if grazing can be justified by reasons other than meat and milk production, e.g. biodiversity conservation, providing a livelihood for vulnerable populations, etc.

With these principles as the starting point, a sustainable diet can be designed for a region or a country. In principle, it would also be possible to develop a global ECOLEFT diet, but this would be less relevant due to the large global diversity of eating practices and diets and since governance systems function on national, rather than global, scales (discussed further in Section 'Policy relevance of the ECOLEFT diets'). These basic principles apply to most contexts, but can be applied very differently depending on the situation. For example, the role of livestock for biodiversity conservation, food security and livelihoods varies substantially between different regions and its importance in the specific context must be factored in when designing a sustainable diet. Principle 3 introduces a further specification of the concept of ecological leftovers, as it limits the use of semi-natural grassland to situations where this provides additional benefits apart from food production. By doing so, the concept of ecological leftovers acknowledges that semi-natural grassland is a 'leftover' only from a human consumer perspective. For example, it is highly valuable for conservation of wild species and natural ecosystems.

The first step in using the ECOLEFT method is to establish the amount of livestock products that the resources of the area can provide, by applying principles 1–3 to the region under study. The next step is to consider the nutrient requirements in the diet, establish how much of these are met by the livestock products and calculate the quantity and type of plant-based foods needed in the diet in order to meet the requirements. By-products from plant production are used as feed to livestock in this approach, providing additional livestock products.

ECOLEFT diets for Sweden

We applied the ECOLEFT method to the case of Sweden. Swedish agriculture used to consist of small-scale mixed farms, but recent decades have seen the emergence of large specialist pig, poultry, dairy and beef units. The reliance on domestic food supply in Sweden is approximately 50% for beef, 65% for pork and poultry, 90% for dairy, 100% for cereals and 20% for fruit and vegetables (NFA, 2011; SBA, 2013a, 2013b); hence Sweden is currently dependent on food imports from other countries. The location of Sweden in Fennoscandia makes agriculture challenging in the north of the country, where grass/clover leys and barley are the most common crops. Southern Sweden is characterised by plains and cash-crop agriculture and is also where most pig and poultry production takes place, whereas most cattle farms are located in plains and forest districts in central and southern Sweden (SBA, 2013c). Arable land occupies about 6% of total land in Sweden, while the rest is dominated by forest (50%), marsh and moorland (16%), mountain (1%) and urban areas (1%) (SS, 2000). Semi-natural pastures and meadows occupy 1% of the land, but the area is steadily decreasing due to a decline in grazing animals and production intensification (SBA, 2014a). Many of Sweden's red-listed species can be found in its semi-natural pastures and therefore preserving these pastures is one of Sweden's most important environmental goals (SEPA, 2014).

We applied the ECOLEFT principles to Sweden based on the following assumptions:

(i) Arable land is used to produce crops for human consumption, with the exception of winter feed and concentrates (if necessary) for grazing animals and feedstuffs to supplement by-products in the diet of monogastric animals.

(ii) By-products from the food industry and cultivation are fed to animals according to current practices and regulations.
(iii) Semi-natural pastures (occupying 443,000 ha) are grazed by animals on the grounds of biodiversity preservation; this corresponds to the area of semi-natural pastures in 2013 (SBA, 2014a) and the goal set by Swedish EPA to preserve these (SEPA, 2014).

For the human diet to be nutritionally adequate, it should fulfil the Nordic nutrition recommendations (Norden, 2012) and resemble current Swedish eating patterns regarding non-livestock products. For these reasons, the Swedish Nutrition recommendations Objectified (SNÖ) diet developed by the Swedish Food Agency (Enghardt Barbieri and Lindvall, 2003) was used as the base diet. The SNÖ diet is a conversion of the Nordic nutrition recommendations into food items.

The step-wise procedure for producing the ECOLEFT diets for Sweden is illustrated in Fig. 1. For plant-based foods (fruits, vegetables, roots, cereals, etc.), the recommended per capita amounts for consumption were translated into the total supply of commodities needed, using factors for waste and losses and the edible parts of different crops taken from FAO (2011). Land use for the plant-based foods was then calculated using average yield per hectare (Supplementary Material S4). For animal production, the number of animals that could be raised on the available by-products, or the biomass on semi-natural pastures in the case of ruminants (Table S3.3), was calculated and used to determine the additional complementary feed needed and the land area needed to produce that feed. The amount of animal products produced from the ecological leftovers determined the amount of additional cereals, grain legumes and vegetable oil that needed to be produced to meet the protein and fat requirements in the human diet.

Sweden was assumed to be self-sufficient in all products which can be produced within the country. Coffee, tea, cocoa, bananas, citrus fruit and nuts corresponding to recommended levels in SNÖ (Supplementary Material S6) were assumed to be imported using a land area of 0.018 ha per capita outside Sweden (calculated based on world average hectare yields; Supplementary Material S4). For a diet to be 'fair', it was decided that the use of arable land for supplying the diet should not exceed the global per capita availability of arable land, which is 0.21 ha (Section 'Environmental impact assessment'). Hence the per capita availability of land for producing the remaining foods in the diet was 0.19 ha (0.21 minus 0.018 ha), which meant that the 2.6 million hectares of Swedish arable land should provide 13.5 million people with food corresponding to the SNÖ diet, except for imported products. In comparison, the Swedish population was 9.7 million in 2014 (SS, 2014).

The SNÖ diet contains 369 g of seafood per week. This amount was included in all the ECOLEFT diets for Sweden, since seafood is associated with several health benefits (Norden, 2012) and since there are promising prospects for developing low-impact aquaculture due to the high feed conversion efficiency of ectothermic animals (Olsen, 2011). It was assumed here that a small proportion of the seafood in the ECOLEFT diets would come from the national

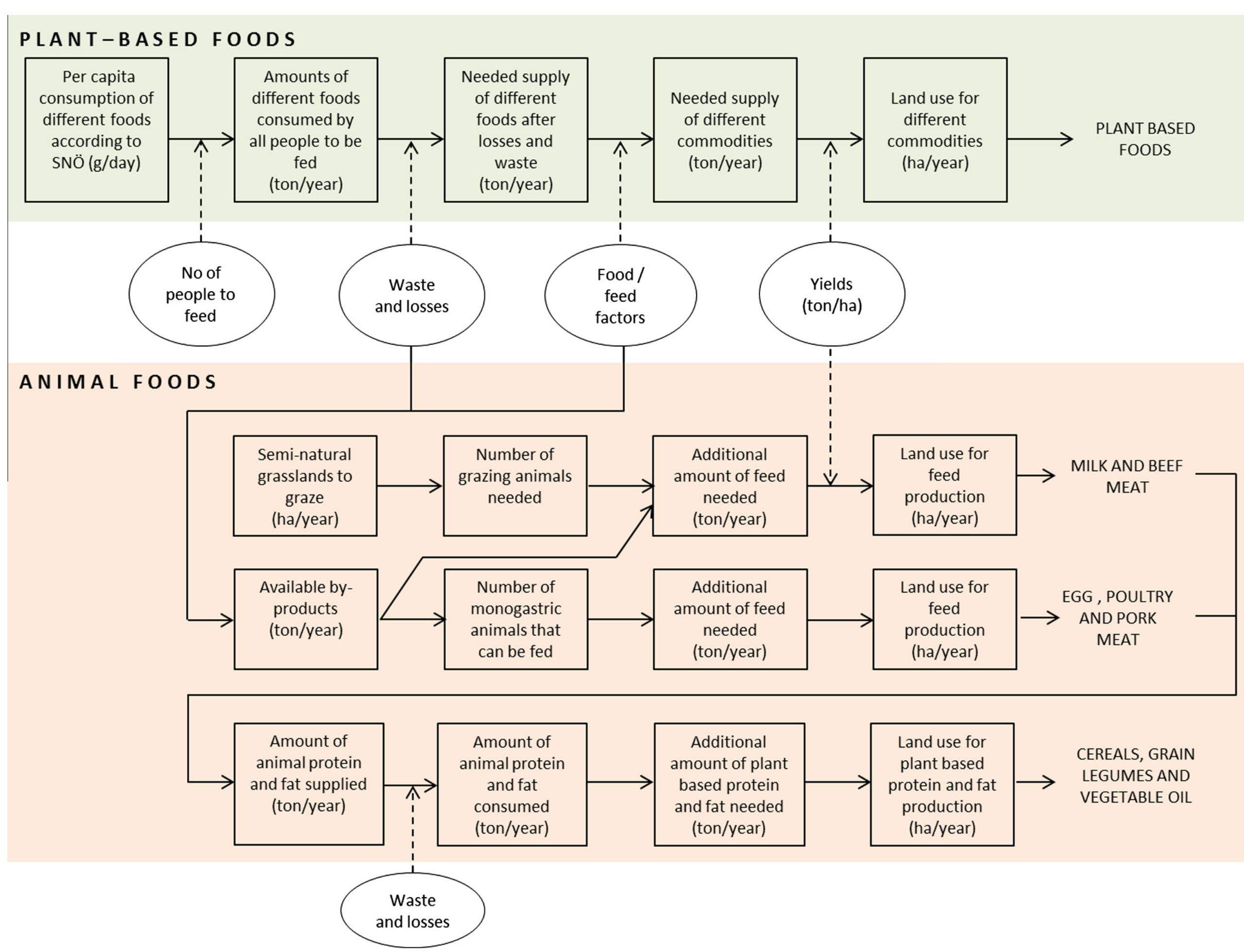


Fig. 1. Procedure used for creating ECOLEFT diets for Sweden.

fish catch, e.g. herring and other fish from the Baltic Sea, while the majority would be supplied by different types of aquaculture, including fish, mussels and other filter feeders and more novel products such as algae. It was assumed that the seafood needed in the ECOLEFT diet could be reared on novel feed sources now being developed that do not compete with other feed or food production resources, such as single-cell bacteria, yeasts or microalgae (Tacon, 1995; Vidakovic et al., 2015) or e.g. insects reared on waste streams (van Huis, 2013).

Production scenarios for Sweden

Three alternative scenarios for livestock production based on ecological leftovers were examined in this study. The starting point for all was the use of grazing livestock to produce food from semi-natural pastures not suitable for other food production. The three scenarios represent different views on the concept of efficient food production (Garnett et al., 2015). The intensive production scenario was built on the viewpoint that using the full genetic potential of the currently available high-producing dairy cow breeds to maximise milk production, and hence reduce impacts per unit of produce, is the most efficient way of using feed biomass. As a consequence of this reasoning, all by-products usable in the ruminant diets were used for feeding the dairy cattle (Table S3.3). Extensive production, in which cows are fed forage only, was built on the principle that cattle should be fed only on roughage and not on foodstuffs edible to humans. In the third scenario, only meat was produced from the pastures using suckler herds, as the number of animals needed to graze this land could then be reduced, since suckler cows can subsist on semi-natural grassland to a larger extent than dairy cows. Hence, biodiversity conservation of the pastures, which justified grazing, can be performed with reduced enteric methane emissions and the production of food (instead of feed) can be maximised on cropland. This follows the viewpoint that plants or plant-based products consumed directly by humans is the most efficient way of producing food (Garnett et al., 2015). These three different production scenarios are summarised below:

1. **I-Milk**. Intensive dairy production system producing 9300 kg energy corrected milk (ECM) per cow and year delivered to dairies. All suitable by-products from the production of plant-based foods in Sweden were used as feed for cattle and supplemented with cereals to maximise milk production. Of the total pastures used by dairy cows, 10% was on semi-natural grassland and the rest on arable land. During the grazing season, heifers grazed the semi-natural pastures to 90% of their total intake. All male calves were kept as intact bulls to utilise their faster growth rate (compared with steers) and reduce their lifetime enteric methane emissions. The bulls grazed grassland on arable land to some extent as cheap fodder, but were not kept on semi-natural grassland due to the potential danger of keeping them far from the farm. Based on these rates of grazing semi-natural grassland, 633,000 dairy cows (total 1.8 million cattle) were needed to preserve the 443,000 ha of semi-natural grassland. This yielded total yearly production of 5,880,000 tons milk and 133,000 tons bone-free beef. Some pork (63,000 tons bone-free) was produced from the by-products whey and bakery waste complemented with cereals and grain legumes to provide an appropriate pig diet. No eggs were produced in this scenario as by-products that could have been used for poultry production were used to boost milk production.
2. **E-Milk**. Extensive dairy production system producing 4600 kg ECM per cow and year delivered to dairies. Semi-natural grassland was grazed by the dairy cows to a larger extent (30% of total intake) than is common in current intensified dairy production systems in Sweden. All male calves were raised as steers and grazed the semi-natural pastures together with heifers during the grazing period, to 90% of total intake. A small amount of by-products was fed to young animals to ensure adequate growth rates. The total number of cattle needed to preserve the 443,000 ha of semi-natural grassland was 870,000, of which 304,000 were dairy cows. Yearly milk production totalled 1,400,000 tons and beef production 62,000 tons of bone-free meat. Surplus by-products supplemented with cereals and grain legumes were fed to poultry and pigs, delivering yearly amounts of 151,000 tons of eggs, 12,000 tons of poultry meat and 292,000 tons of pork (bone-free).
3. **Suckler**. By using pure suckler herds for grazing semi-natural grassland, the number of cattle needed to preserve the 443,000 ha was reduced even further, to 543,000. No milk was produced in this scenario, but 39,000 tons of bone-free beef meat were produced. As in the E-Milk scenario, by-products supplemented with cereals and legumes were used to feed poultry and pigs, yielding 151,000 tons of eggs, 12,000 tons of poultry meat and 318,000 tons of pork (bone-free).

The feed rations for cattle were calculated according to nutrition recommendations for ruminants (Spörndly, 2003). Feed rations for monogastrics were calculated according to separate recommendations for poultry (Elwinger, 2013; NRC, 1994) and for pigs (Göransson and Lindberg, 2011). Harvest yields, feed rations and other production parameters are described in detail in Supplementary Material S3–S5. In the I-Milk scenario, all by-products except for whey and bakery waste were consumed by the cattle. In the E-Milk and Suckler scenarios, the remaining by-products after cattle production were first and foremost utilised to produce eggs corresponding to the recommended amounts in SNÖ. To utilise existing resources for food production, the male chickens in laying hen breeding were reared for meat (Leenstra, 2013) and the meat from the hens (after the egg-laying period) was also used as food. Remaining by-products after egg production were used to produce pig meat. The by-products needed to be complemented with cereals, grain legumes and synthetic amino acids in order to achieve a nutritionally balanced diet for the monogastrics (Supplementary Material S3).

Since all scenarios provided less livestock products than stated in the SNÖ diet, cereals, grain legumes and rapeseed oil for human consumption were produced and included in all ECOLEFT diets (but to different extents), so that these diets provided the recommended amounts of energy, protein and fat. This was done so that all diets supplied the same amount of energy for consumption (10.4 MJ per capita and day). Plant production for these replacement products and for the cereals, legumes, oilseeds, roots, fruit and vegetables specified by SNÖ is described in Supplementary Material S4.

In all scenarios, manure (including straw used for bedding), slaughter waste, food waste and waste not permitted/suitable for use as animal feed were digested in a biogas reactor. The biogas produced from these residues was used as tractor fuel and to produce heat, electricity and mineral nitrogen (N) fertiliser needed in production of the diets (Supplementary Material S5). However, the energy produced from these residues was not enough to meet the energy requirement in agricultural production and in all scenarios some land had to be used to produce additional bioenergy through cultivation of ley biomass that was digested together with the manure and wastes. The digestate (nutrient-rich residue from anaerobic digestion) was used to fertilise crops, complemented with 'green' mineral nitrogen and mined phosphorus (P) fertiliser when needed (Table S4.1).

The amounts of different foods in the three ECOLEFT diets were compared against current Swedish food consumption and the SNÖ diet. Current consumption of different commodities in Sweden was determined based on the latest Riksmaten food intake survey (Amcoff et al., 2012), with some adjustments to account for underreporting (Supplementary Material S6). Waste was accounted for throughout the food chain for the ECOLEFT diets using factors for estimated current food losses from FAO (2011). Total losses and waste (including edible and non-edible parts of the foods) ranged from 9% to 47% for different types of food items.

Environmental impact assessment

To evaluate the environmental sustainability of the ECOLEFT diets, these were evaluated in relation to the planetary boundaries (PB) first defined by Rockström et al. (2009) and later updated by Steffen et al. (2015). Transgressing these boundaries, which have been established for nine environmental protection areas, could generate abrupt or irreversible environmental changes, with great risks to the prosperity of human societies. The planetary boundary concept is based on the global level, so for this study they had to be downscaled to national level (Sweden) and also adapted to diet.

The planetary boundary concept can be regionalised in several ways depending on the application (Dearing et al., 2014). Here we considered the share of land use, greenhouse gas emissions and addition of nitrogen and phosphorus to the Earth system that can be attributed to production of the per capita diet. The first boundary condition for land use presented in 2009 was that no more than 15% of the global land surface should be converted to arable (Rockström et al., 2009). In the updated planetary boundaries, the land use control variable was changed from the area of arable land to the area of forest land that is maintained on ice-free land surfaces, since forests play a stronger role in the land surface-climate coupling than other biomes. Hence, the land use boundary in the updated planetary boundary concept focuses more directly on the biogeophysical processes in land systems, while the biosphere integrity boundary provides constraints on the amount of land use change in all biomes (Steffen et al., 2015). Since the expansion of agricultural land is the major threat to biodiversity loss (MEA, 2005), and since the biosphere integrity planetary boundary has already been exceeded, we assumed here that further expansion of arable land is not operating within the planetary boundary. Hence, we used the initial land use boundary based on the maximum amount of arable land from Rockström et al. (2009) in this study. Using a projected world population of 9.5 billion by 2050 (UN, 2014), the available arable area for sustainable cropping was calculated to be 0.21 ha per capita.

For climate change, the planetary boundary of an atmospheric carbon dioxide (CO_2) concentration of maximum 350 ppm (corresponding to 445 ppm CO_2e on including methane and nitrous oxide concentrations; IPCC, 2007) has already been exceeded (Steffen et al., 2015). Hence ideally and in a long-time perspective net greenhouse gas emissions from the production of food should be zero or negative (through carbon sequestration techniques) in order not to exacerbate climate change further.

For nitrogen flows, the planetary boundary was set to 62 Tg N added per year from industrial and intentional biological N fixation, while the regional planetary boundary for phosphorus was defined as a maximum of 6.2 Tg mined P per year applied to erodible soils (Steffen et al., 2015). Dividing the boundaries for reactive nitrogen and phosphorus additions by the projected global population in 2050 yielded yearly per capita boundaries of 6.5 kg N and 0.65 kg P.

Defining the global planetary boundary for biodiversity loss is highly challenging, since the loss is a slow process without any known global-level thresholds and it has been debated how this should be done (Rockström et al., 2009; Mace et al., 2014). However, there are several suggestions on how to set limits on safe impact of local ecosystems on biodiversity. For example, Griggs et al. (2013) proposed that 70% of species in any ecosystem are needed to secure its health and productivity, although Brook et al. (2013) and Mace et al. (2014) argue that there are no empirical data to support this. Pereira et al. (2013) stated a need for several biodiversity variables to study and manage biodiversity change. Due to this complexity in finding a numerical boundary value for biodiversity loss in Sweden and relating that to the production of a particular diet, an approach based on the national goal for biodiversity conservation in Sweden (SEPA, 2014) was adopted in this study. Thus, for the production of a diet in Sweden to stay within the planetary boundary for biosphere integrity, all current semi-natural pastures and meadows and all arable land should be preserved, as these contain a large proportion of the endangered species and their conservation is ranked as one of the most important strategies for decreasing biodiversity loss in Sweden.

Ozone depletion is not caused by agricultural production, while ocean acidification is only affected indirectly through emissions of carbon dioxide. Therefore these categories were not considered in this study. Regarding freshwater use, Sweden currently has ample water resources (Gerten et al., 2011), so the freshwater use planetary boundary was not further considered in this study. Boundaries for novel entities and aerosol loading have not yet been defined and were not included here. The boundaries conditions for this study is summarised in Table 1.

The climate impact from agricultural production of the diets was estimated using a life cycle perspective, including emissions from land, animals and energy and fertiliser production and use on the farm (Supplementary Material S1). The climate impact from production of the diets was first calculated without considering changes in soil and aboveground biomass carbon pools. A rough estimate of the climate impact from changes in arable soil carbon content (calculated using the Introductory Carbon Balance Method; Andrén et al., 2004), carbon sequestered in soil and tree trunks in orchards for fruit production and forests grown on land not needed to produce the diets was also included (Supplementary

Table 1
Planetary boundaries used in this study.

	Planetary boundary	Boundary used for the diet in this study
Climate change[a]	CO_2 concentration of maximum 350 ppm	Since this boundary has been exceeded, production of the diet should not give any net emissions
Biosphere integrity[a]	10 number of species per million species years	All current semi-natural grassland and arable land in Sweden preserved
Nitrogen cycle[a]	62 Tg of N added per year from industrial and intentional biological N fixation	6.5 kg N per capita added per year to produce the diet
Phosphorus cycle[a]	Maximum of 6.2 mined P applied to agricultural soils	0.65 kg P added per capita per year to produce the diet
Land system change[b]	Max 15% of the global land surface should be converted to arable	Production of the diet uses maximum 0.21 ha arable land per person

[a] Based on Steffen et al. (2015).
[b] Based on Rockström et al. (2009).

Table 2
Social sustainability assessment indicators included in this study.

Oxfam doughnut priority	Indicator used in this study	Source of indicator
Food security	Provisioning of adequate nutrition for a fair number of people	Enghardt Barbieri and Lindvall, 2003
Employment	No. of working hours Accidents among farm workers Toxicity to farm workers	As working hours (UNEP, 2009; PRé Sustainability, 2014) As part of health and safety (UNEP, 2009; PRé Sustainability, 2014)
Voice	Social and cultural acceptability of diets	As part of cultural heritage (UNEP, 2009) and experienced well-being (PRé Sustainability, 2014)

Table 3
Amounts of protein-rich foods in the SNÖ (recommended) diet and in the ECOLEFT diets compared with current consumption patterns.

	Current consumption	Rec. diet (SNÖ)	I-Milk diet	E-Milk diet	Suckler diet
Servings of meat per week (100 g bone-free per serving)	10	8	2	4	4
Servings of seafood per week (100 g bone-free per serving)	4	4	4	4	4
Servings of legumes per week (60 g dry weight per serving)	0.5	1.5	1.5	2.5	3.5
Servings of cereals per week (60 g dry weight per serving)	20	32	31	35	37
Eggs per week	4	3	0	3	3
Slices of cheese per day (10 g per slice)	5	3	3[a]	1	0
Millilitres of milk per day	300	350	350[a]	150	0
Total protein per day (g)	Approx. 100[b]	59–118[c]	82	81	77
Total protein % of total energy	Approx. 17%	10–20%	13%	13%	12%

[a] This scenario supplies more dairy than these amounts, but consumption was capped to the recommended level.
[b] Average 82 g in Riksmaten (Amcoff et al., 2012), but subject to 20–25% underreporting. 110 g according to food trade statistics (SBA, 2014b), which do not include household waste. Hence, here set to approximately 100 g based on these sources.
[c] Based on daily energy intake of 10 MJ.

Material S1.3). Results for these land use change-related emissions or sequestration rates are presented separately due to the large uncertainties in the estimates and the reversibility of carbon sequestration (Flysjö et al., 2012).

Social and economic impact assessment

While the planetary boundary concept provides an 'environmental ceiling' which must be respected in the production of the diets, social requirements on the diets must also be fulfilled. The Oxfam 'doughnut concept' (Raworth, 2012) provides an attractive framework for evaluating social sustainability, since it contains a 'social foundation' to live up to. Above, or outside, this social foundation and within the environmental ceiling (these two boundaries forming a doughnut) is the safe and just operating space (Raworth, 2012; Dearing et al., 2014). The framework includes 11 social priorities which build on submissions by governments to the Rio +20 Earth summit, hence illustrating strong global consensus. These priorities are: food security, income, water and sanitation, health care, education, energy, gender equality, social equality, voice, employment and resilience. Raworth (2012) provides some illustrative global indicators for these priorities which have to be operationalised for use on diets and food production on a national scale to assess the social sustainability of diets. In this study, a proof-of-concept assessment based on the Oxfam doughnut concept was made using some illustrative indicators from social life cycle assessment (Table 2).

First- and second-order interactions between different social priorities and between social priorities and environmental impacts (Dearing et al., 2014) were neglected and only priorities with a very direct coupling to food production were included. Furthermore, priorities relevant for food production and not affected by the *type* of food produced, but rather external societal and political systems, e.g. gender and social equality, were also excluded. Hence, analysis of the social foundation for the ECOLEFT diets revolved around food security, employment (including safe working conditions) and voice (with emphasis on freedom of expression). Exclusion of the income priority required careful consideration, since farm income is highly dependent on the type of products produced and the market situation for these. However, since the scenarios in this study were of a long-term explorative nature, discussing the income possibilities for farmers and food industries in producing these diets in prevailing economic systems was deemed not to be very relevant. Current political systems governing much of the profitability in European food production show several serious policy inconsistencies (e.g. subsidised livestock and sugar production, when consumption of these needs to decrease for environmental and health reasons). Hence, drastic changes to the prevailing economic system are needed to obtain true sustainability.

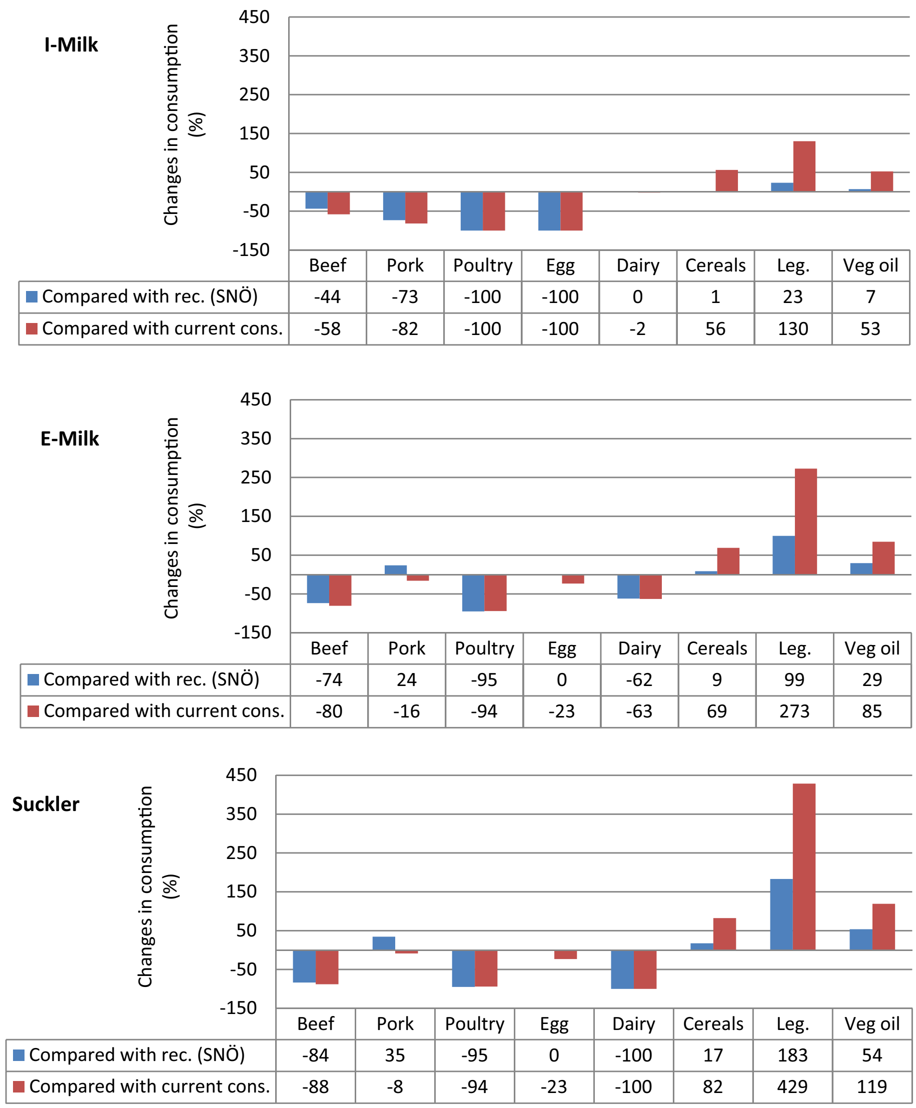
To identify existing social sustainability indicators that mapped to the Oxfam doughnut social priorities included, a literature review was performed to identify the social indicators used in major frameworks for social life cycle assessment, i.e. UNEP (2009) and PRé Sustainability (2014). The indicators identified and their Oxfam doughnut priority are summarised in Table 2. The assessments performed are outlined in Supplementary Material S2.

Results and discussion

The diets

The amounts of protein-rich foods consumed in the three different ECOLEFT diets are shown in Table 3, while Fig. 2 illustrates the change in intake from recommended and current levels.

In all ECOLEFT diets, meat consumption was reduced substantially, from the 10 servings per week currently consumed to four servings per week in the E-Milk and Suckler diets and two servings per week in the I-Milk diet. Consumption of plant-based protein in the form of cereals and legumes increased to replace meat consumption, and in the E-Milk and Suckler diets also to replace decreased or excluded consumption of dairy. For diets not to



I-Milk

	Beef	Pork	Poultry	Egg	Dairy	Cereals	Leg.	Veg oil
Compared with rec. (SNÖ)	-44	-73	-100	-100	0	1	23	7
Compared with current cons.	-58	-82	-100	-100	-2	56	130	53

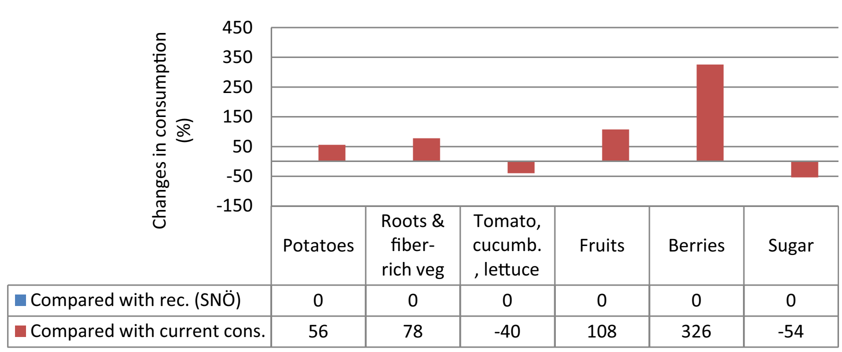
E-Milk

	Beef	Pork	Poultry	Egg	Dairy	Cereals	Leg.	Veg oil
Compared with rec. (SNÖ)	-74	24	-95	0	-62	9	99	29
Compared with current cons.	-80	-16	-94	-23	-63	69	273	85

Suckler

	Beef	Pork	Poultry	Egg	Dairy	Cereals	Leg.	Veg oil
Compared with rec. (SNÖ)	-84	35	-95	0	-100	17	183	54
Compared with current cons.	-88	-8	-94	-23	-100	82	429	119

Fig. 2. Changes in consumption of protein-rich foods and vegetable oil in the different ECOLEFT diets in comparison (as %) with the recommended diet (SNÖ) and the current average diet.



	Potatoes	Roots & fiber-rich veg	Tomato, cucumb., lettuce	Fruits	Berries	Sugar
Compared with rec. (SNÖ)	0	0	0	0	0	0
Compared with current cons.	56	78	-40	108	326	-54

Fig. 3. Changes in consumption of roots, fruits, vegetables and sugar in the ECOLEFT diets in comparison (as %) with the recommended diet (SNÖ) and the current average diet.

exceed the recommended energy content, the daily protein intake was reduced in all ECOLEFT diets compared with current consumption, but was still within the recommended interval (Table 3).

Consumption of potatoes, roots, vegetables, fruits, berries and sugar was similar in all ECOLEFT diets and corresponded to the recommended levels in the SNÖ diet. However, these consumption levels would require considerable changes from the current consumption patterns, e.g. increased consumption of fruit (+108%) and berries (+326%), decreased consumption of sugar (−54%) and also replacement of non-fibre rich vegetables such as tomato and cucumber by more roots, cabbage and onions (Fig. 3). Supplementary Material S6 provides a complete list of all food items in the different diets.

The results showed that for Swedish conditions, a diet based on the principle of limiting livestock production to what can be produced from ecological leftovers would entail yearly per capita meat consumption of 11–21 kg of bone-free meat, which can be compared with the current level of approximately 50 kg. It can also be compared with what other authors have proposed as a sustainable level of meat consumption, e.g. McMichael et al. (2007) propose a target of approximately 25 kg bone-free meat per capita and year based on an 'international contraction and convergence strategy' in which current total global meat consumption is divided evenly on future populations. Davidson (2012) showed that atmospheric N_2O could be stabilised by 2050 if meat consumption in the developed world was cut in half, in combination with also decreasing N_2O emission factors by 50%. Such a reduction for Sweden would imply meat consumption of approximately 25 kg of bone-free meat, i.e. in the same range as suggested by McMichael et al. (2007) and the upper limits presented in this study.

Agricultural production

For the production of the I-Milk, E-Milk and Suckler diets, 58%, 50% and 42% of total agricultural land in Sweden would be used to grow feed for animals (Fig. 4), which is a reduction from the current level of approximately 75%. Due to the country's location, without using some arable land for production of winter feeds, no livestock production would be feasible. The total amount of silage ranged from 912 kton DM/year for the Suckler diet to 2934 kton DM/year for the I-Milk diet (Table S3.3). In the E-Milk and Suckler diets, almost all of the remaining feed was made up of by-products, whereas the feed used in the I-Milk diet included 42% by-products.

For all ECOLEFT diets, 30% of agricultural land would be needed to grow the plant-based foods required. For the I-Milk, E-Milk and Suckler diets, 1.3%, 5.6% and 10% of arable land, respectively, would be needed to grow replacement products (cereals, legumes and rapeseed oil) to maintain the recommended intake of protein and fat despite reduced consumption of animal products.

All ECOLEFT diets would lead to lower proportions of Swedish agricultural land being used for ley and cereals and higher proportions for grain legumes, oilseed crops and other food crops (Fig. 5). This would involve diversification of cropping systems for the production of ECOLEFT diets due to a larger number of crops and more even distribution of different crops on the available land. Cropping system diversification is an important target in developing more sustainable food production systems, since it increases cropping system resilience to pests, diseases and extreme weather events (Kremen and Miles, 2012; Tscharntke et al., 2012).

Fruits (mainly apples) and berries are a major component within the category 'Other food crops'. Upscaling Swedish fruit and berry production to the levels required in the ECOLEFT diets would pose interesting challenges and possibilities for combining fruit orchards and arable crops in agroforestry systems. Agroforestry has the ability to promote a number of functions and services, such as carbon sequestration, prevention of soil erosion, enhanced species and functional diversity with benefits for biodiversity conservation, crop pollination and biological pest control, and potentially improved recreational values (Jose, 2009). Such systems would thus strongly improve the multifunctionality of agricultural landscapes (Van Huylenbroeck et al., 2007).

The E-milk and Suckler diets required 10% and 11%, respectively, of agricultural land to be used for grain legume production, which corresponded to about a 10-fold increase compared with current production. This means that a grain legume crop would be cultivated on average once every 10 years on all agricultural land in Sweden, which is not possible given the soil types and climatic conditions in large parts of the country. Instead, grain legumes would need to be cultivated more often on suitable land in central and southern Sweden. Soil-borne fungal diseases can cause severe problems if grain legumes are grown too frequently in the same field (more often than every 5–7 years for faba beans and peas, depending on soil type; Fogelfors, 2015). The large increase in grain legume production in the E-milk and Suckler diets may thus be difficult to obtain, at least based on current crop varieties and cropping practices. On the other hand, plant breeders are developing early-maturing bean and pea varieties suitable for central and northern Sweden. This, in combination with development of innovative cropping systems – crop rotations optimised for grain legumes, intercropping and sanitary cover crops (e.g. brassicas which can reduce the occurrence of soil-borne fungal diseases) for higher yield stability – may provide the conditions needed for a large increase in Swedish grain legume production.

The E-milk and Suckler diets would reduce the area used for ley production, which could be a disadvantage since perennial legume–grass leys in particular are valuable for soil fertility and carbon sequestration. On the other hand, if the land not used for food production were to be used for bioenergy purposes, approximately 25% of the agricultural land in the E-milk and Suckler diets

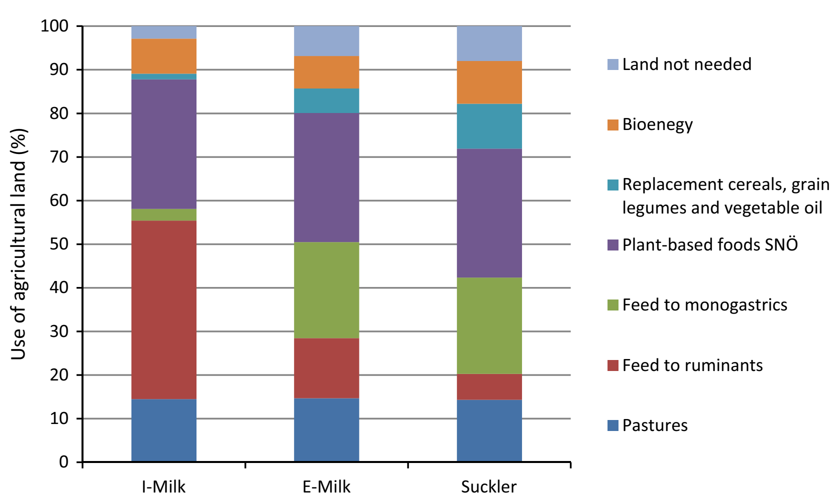


Fig. 4. Use of land for different purposes, as a percentage of total agricultural land, for the different ECOLEFT diets.

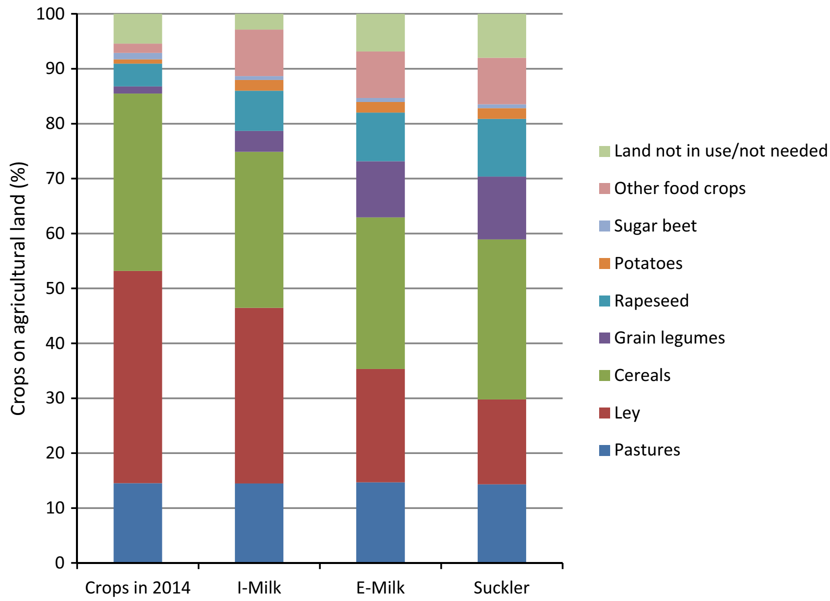


Fig. 5. Crops grown on agricultural land, as a percentage of total agricultural land, in 2014 (SBA, 2014a) and for the different ECOLEFT diets.

Table 4
Yearly per capita outputs and environmental impact from the different ECOLEFT diets.

	Boundary condition for yearly diet	I-Milk diet	E-Milk diet	Suckler diet
Outputs		Diet described in Section 'The diets' 165 kg surplus milk 0.0064 ha spare land	Diet described in Section 'The diets' 0.015 ha spare land	Diet described in Section 'The diets' 0.018 ha spare land
Climate impact (excl. land use changes)	Zero net emissions	0.62 ton CO_2e	0.43 ton CO_2e	0.36 ton CO_2e
Biosphere integrity	All semi-natural pastures and arable land preserved	All semi-natural pastures and arable land preserved	All semi-natural pastures and arable land preserved	All semi-natural pastures and arable land preserved
Nitrogen cycle	6.5 kg N added	12.8 kg N added	12.7 kg N added	13.2 kg N added
Phosphorus cycle	0.65 kg P added	2.3 kg P added	2.1 kg P added	2.3 kg P added
Land system change	Max 0.21 ha used	0.204 ha (0.186 ha in Sweden 0.018 ha for imports)	0.195 ha (0.177 ha in Sweden 0.018 ha for imports)	0.193 ha (0.175 ha in Sweden 0.018 ha for imports)

could still be used for ley production, with biomass from leys as feedstock for e.g. biogas conversion.

In this study, we chose to produce pig meat on the remaining by-products after egg and cattle production. The main by-products left from the I-Milk scenario were whey and bakery waste, which fit well into pig diets. In the E-Milk and Suckler scenarios, the variation in residual by-products that could be used for other livestock was large, since the number of cattle was smaller and their nutritional requirements were lower due to the more extensive production systems. These by-products made it possible also to include poultry in the production system. It was decided to produce eggs and keep the male chicks sorted out at hatching to be reared for meat. It can be argued that this is an inefficient use of feed resources, since cockerels require about twice the amount of feed to reach the same slaughter weight as broiler chickens (Leenstra, 2013). Nevertheless, in the present study all available human food resources were valued and this option was chosen instead of discarding the male chicks as pet feed or substrate for biogas and instead producing broiler chickens for meat.

Some by-products are limited to certain species due to the chemical composition of the feed, such as fibre and fat content. Fibrous by-products are more suitable as feed for ruminants, since the ability to digest fibre is limited in pigs and poultry, whereas the use of fat-rich by-products is limited in ruminant diets due to the sensitivity to lipids of rumen microbiota. In addition, by-products often need to be supplemented with cereals in order to fulfil the nutritional requirements of monogastric diets. The use of by-products in pig diets was maximised in this study, but only approximately 35% of the pig diet could consist of by-products and the rest needed to be cereals and grain legumes. Therefore a large proportion of arable land (22%) was used for monogastric feeds in the E-Milk and Suckler scenarios. In a strict sense, this (as well as feeding cereals to dairy in the I-Milk scenarios to boost milk yield) violates the principle of restricting livestock production to ecological leftovers, but without these supplements it would not have been possible to raise any monogastrics on the available by-products, so the principle was stretched to allow for some cultivation of animal feed on arable land. Producing livestock on purely ecological leftovers, i.e. not using any arable land for feed, is impossible in a high-latitude country such as Sweden, since winter feed for grazing animals needs to be cultivated.

An alternative use of some of the by-products would be to refine them into human foods, e.g. whey protein. Another alternative could be to use food waste as pig feed, but this is prohibited within the EU (2011) due to the risk of contamination and infection. Another important consideration is the aim to decrease food waste within the food chain and it is therefore not a sustainable option to count on food waste as a resource for pig feed.

Environmental impact

The environmental impacts from production of the ECOLEFT diets are summarised in Table 4. For land use, production was well within the planetary boundaries and considerably lower than the land use of the current Swedish diet (0.34 ha per capita and year; Röös et al., 2015). For all ECOLEFT diets there was some spare land available after the food needed in the diets and the energy needed in agriculture were produced (I-Milk: 64 m^2 per capita; E-Milk: 154 m^2 per capita; Suckler: 180 m^2 per capita).

Regarding climate impact, the production of all diets gave rise to emissions of greenhouse gases, mainly methane from ruminant digestion and nitrous oxide from soils (Figure S7.1 in Supplementary Material). These emissions varied between 0.36 and 0.62 ton CO_2e per capita and year for the ECOLEFT diets (Table 4). When soil carbon changes in arable land used to grow ley and annual crops were included, the climate impact increased to 0.44–0.66 ton CO_2e per capita and year due to soils losing carbon, mainly through reduced ley cultivation (Fig. S7.1).

Using spare land to sequester carbon through forest plantation could offset some of the climate impact from the production of the diets. Including carbon sequestration in forests on spare land and carbon sequestration in fruit orchards gave a yearly climate impact of 0.30–0.57 ton CO_2e for the diets (Fig. S7.1).

Through improved management practices and breeding programmes that lead to less nitrous oxide emissions from soils in the case of plant production and less methane emissions from ruminants in the case of animal production, greenhouse gas emissions from soils and animals could be decreased (Martin et al., 2010; Snyder et al., 2014). A reduction in these emissions by 50% reduced the climate impact of the diets to 0.12–0.26 ton CO_2e (Table S7.1). Thus, a reduction of more than 50% was needed to bring the climate impact of the Suckler diet down close to zero, while for the other two diets even larger reductions were needed.

However, it should be noted that although the ECOLEFT diets did not meet the very strict climate boundary of not allowing any net emissions, the climate impact from production of all ECOLEFT diets was less than half that from production of the current diet (excluding carbon sequestration and reductions in methane and nitrous oxide) which was estimated to 1.9 ton CO_2e (Röös et al., 2015). The climate impact of the diets can be compared with emission pathways compatible with limiting global warming to 2°, e.g. a yearly global emission allowance of 20 Gton CO_2e in 2050 as in the IPCC AR5 RCP2.6 scenario (IPCC, 2014). Production of the three diets took up 28% (I-Milk), 20% (E-Milk) and 16% (Suckler) of the per capita emissions space of 2.2 ton CO_2e. Hence, all the ECOLEFT diets could be considered to be in line with this emissions pathway.

The planetary boundaries for nitrogen and phosphorus cycles were clearly exceeded in all scenarios (Table 4). However, the nitrogen and phosphorus inputs in the ECOLEFT diets were considerably lower than in the production of current diets, which requires substantially more land (0.34 ha per year; Röös et al., 2015). Producing the ECOLEFT diets with the current Swedish crop production systems would thus pose severe challenges regarding plant nutrient use in order to stay within the planetary nitrogen and phosphorus boundaries. Precision agriculture, better crop rotations and efficient use of catch crops and new crop varieties with improved nutrient use efficiency are promising tools that can help maintain high crop yields with reduced fertiliser inputs. However, as nitrogen inputs have to be decreased by half and phosphorus inputs by two-thirds for all diets to stay within the boundaries, more efficient nutrient recycling from society back to agriculture is crucial.

When comparing the environmental impact it must be kept in mind that apart from providing nutritionally similar diets, the three scenarios provided different additional outputs (Table 4). The I-Milk diet delivered an additional 165 kg of milk per capita yearly (2.2 million tons in total) that can be exported from Sweden, while production of the E-Milk and Suckler diets saved more land that can be used to sequester carbon and produce bioenergy, produce more food or other biomass, or e.g. for nature conservation. If the milk produced in the I-Milk scenario is assumed to replace other similar milk production on a 1:1 basis elsewhere, the climate impact of the I-Milk scenario would be reduced by approximately 30%. If the milk replaces some other less efficient milk production, the climate impact of the I-Milk diet would be reduced even more. However, if the exported milk increases global total milk consumption by adding more milk to the market, no such reductions can be claimed. Hence, it is not possible without further modelling or scenario analysis to establish the environmental impact of the diets alone. Clearly, however, a diet which causes less climate impact and leaves more land available for other purposes has a greater chance of causing less environmental damage on an absolute scale.

Social impact

Inclusion of social impacts for agricultural systems at this national and dietary scale is new and the assessment here serves only as an example of how social impacts could be included. The study did not define boundaries for all social aspects and this issue should be further explored in future work.

For the indicator on provisioning of adequate nutrition for a fair number of people, similar to the biodiversity boundary, this was considered in the set-up of the scenarios as an absolute criterion. All scenarios needed to produce diets fulfilling nutrient recommendations for a fair amount of people (Section 'ECOLEFT diets for Sweden'). For the indicators on employment (Table 5) the calculations were made only for the parts that differed between the scenarios and thus the results are presented in relative numbers.

The results reflect the fact that having more animals within the agriculture system generally increases the number of working hours and also increases the number of accidents among farm workers. Accidents are clearly a negative social impact, while an increased number of working hours can be positive (leading to increased employment opportunities) or negative (implying greater labour intensities), depending on the perspective. Greater use of pesticides involves more contact with chemical substances, but the toxicity also depends on the type of substance used and on training and safety procedures in pesticide management. The increased toxicity impact in the E-milk and Suckler scenarios is due to the greater areas of annual crops (Fig. 5). Future improvements of animal management and cropping systems might decrease risks of accidents and pesticide use. For example, intercropping grain legumes and cereals reduce weed pressure (Jensen et al., 2015) and thereby the need for herbicides.

Regarding the social and cultural acceptability of diets, it is difficult to claim that something is true for a whole nation, as dietary preferences differ greatly between social groups, gender, geographical areas, etc. (Debevec and Tidavar, 2006). Sweden has a

Table 5
Results on the employment indicators including number of working hours, accidents to farm workers and toxicity for farm workers (relative to scenario I-Milk).

Indicator	Scenario		
	I-Milk	E-milk (%)	Suckler (%)
No. of working hours (per yr)	–	−19	−30
Accidents for farm workers (per yr)	–	−26	−43
Toxicity for farm workers (kg active substance/yr)	–	+10	+15

long history of eating meat (Metzger, 2005), although the kind of meat has differed, and of consuming dairy products, although mainly of long-lasting milk products rather than fresh milk. The high consumption of fresh milk in Sweden is hence an outcome of fierce marketing by the dairy industry rather than of long-standing traditions (Jönsson, 2005).

All ECOLEFT diets contained considerably lower amounts of meat than current consumption patterns. However, meat would still be included in the diet several times a week, which should fulfil the cultural requirements for upholding Swedish traditions like eating ham and meatballs. The Suckler diet might have the lowest cultural acceptability currently due to its total lack of dairy products. The lack of eggs in I-Milk would also be a major change. However, diets and food habits change rapidly in society, and whether the ECOLEFT diets can be deemed socially acceptable depends very much on the time frame. Reducing meat consumption to these levels is currently probably highly challenging for large consumer groups, but with an increasing trend for more plant-based diets stimulated by targeted transition pathways (Schösler et al., 2012) and efficient policy instruments influencing attitudes towards consumption of animal products, this could potentially change rapidly.

Policy relevance of the ECOLEFT diets

Many studies have discussed and highlighted the need for rapid transition to sustainable food systems (Godfray et al., 2010; Foley et al., 2011). General consensus is beginning to emerge on the main measures needed, which are: closing the yield gap in developing countries, increasing resource use efficiency, reducing waste and reducing livestock product consumption. Vegan, vegetarian or low-meat diets have the potential to reduce greenhouse gas emissions and land use (Van Kernebeek et al., 2014a). In this study we advanced knowledge on fair sustainable diets by connecting consumption, i.e. the food products constituting the diets, with the products that can most efficiently (based on different viewpoints) be produced based on available resources and inherent couplings in the food production system, e.g. the amounts of meat and milk produced in the dairy sector. Although global trade will undoubtedly be increasingly important to provide food security for growing urban populations, several reasons for more regionalised food systems have been reported (Donald et al., 2010). These include increasing resilience, enhancing governance of local communities, increasing the diversity of cropping systems and closing nutrient loops. Whether a possible need for regionalised food systems emerges from conscious policy interventions and planned actions from consumers and businesses, or is forced upon us by external political decisions or weather events, investigating efficient and low-impacting regional agricultural systems by modelling studies like the present analysis can be valuable preparation.

The Oxfam doughnut concept contains minimum requirements for very basic needs. Although Raworth (2012) recognises that sustainable development envisions people prospering beyond these boundaries, she also emphasises that priority should be given to delivering these basic needs to all, based on the extent of deprivation and extreme inequality in the world. However, in Western societies and in those societies currently transforming their eating habits into Western patterns, it is quite possible that diets containing as little livestock products as the ECOLEFT diets are not currently socially acceptable, although they are based on the Oxfam doughnut social foundation (providing a nutritionally adequate diet to a 'fair' number of people). As long as the production of 'wanted/demanded' diets stays within the environmental ceiling of the planetary boundaries, higher consumption of animal products is not problematic. However, as shown in this study, consumption of animal products in line with the ECOLEFT diets already struggled to stay within the planetary boundaries. These examples show how designing sustainable diets inevitably comes back to ethical considerations. Further development of the concepts presented in this paper into a truly sustainable 'doughnut diet', including the aspect of animal welfare, could be valuable in making such ethical discussions more concrete, more complete and based on empirical evidence. Such a framework could be used for evaluating diets based on the principle of ecological leftovers and other diets based on different perspectives and could add valuable knowledge in the discussion of sustainable diets.

Refinement of the method

The method presented here for designing diets based on the concept of ecological leftovers and the evaluation of the sustainability of these diets based on the concept of a safe and just operating space represent an explorative attempt to operationalise a sustainable food system on national level. The method and the concept require major improvement on several levels. On a technical level, the geographical resolution needs to be improved to account for different land types and climate conditions on a more detailed scale than Sweden as a whole. The global per capita land availability of 0.21 ha, that was a result of simply dividing the total land availability on the global population, should include considerations on the productivity of different land types. In this preliminary study, only the major animal species and crops were included, but future models should include all relevant traditional and novel livestock species and crops, including those from the sea and aquaculture. Linear programming techniques could be employed to optimise land use and use of by-products for different applications (Van Kernebeek et al., 2014b). The frameworks and indicators used to assess the sustainability of diets at this level, especially those for defining a social foundation, need development. Furthermore, the usefulness of the concept as a basis for discussion and decision support among different stakeholders in the food system needs to be evaluated.

Conclusions

Using a set of principles based on the concept of 'ecological leftovers' for livestock production, i.e. that arable land should primarily be used for the production of plant-based food for humans and that livestock should be fed biomass not suitable or not wanted by humans, it is possible to design diets using food produced on Swedish agricultural land that fulfil nutritional recommendations and reduce the environmental impact compared with current diets. However, the production of these diets still results in environmental impacts that cause several planetary boundaries to be transgressed. Meat consumption is drastically reduced in all diets. The approach used in this study of letting the ecological resource capacity act as the constraining factor for livestock production is aligned with agroecology principles and efficient use of land to improve food security, and could be useful for discussions about sustainable levels of livestock consumption.

Author contributions

Röös acted as a project manager, was responsible for the design of the study, performed the calculations (apart from those on the animal production systems) and wrote the majority of the manuscript. Patel contributed to the design of the study and the scenarios, performed all calculations and data collection as regards animal production systems and wrote the parts of the manuscript relating to animal production. Spångberg performed the analysis on the social impacts and wrote those parts of the manuscript. Carlsson gave advice on plant production parameters and crop rotations and discussed the results as regards impact on agricultural crop production. Rydhmer initiated the project and contributed as a discussion partner throughout the work. All authors read and contributed to improvement of the complete manuscript, including the Supplementary Material.

Acknowledgments

Our thanks to the strategic research platform Future Agriculture at the Swedish University of Agricultural Sciences (SLU) for funding this research. Thanks also to Professor Thomas Kätterer, SLU, for help with the ICBM model.

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.2015.10.008.

References

Amcoff, E., Edberg, A., Enghardt Barbieri, H., Lindros, A.-K., Nälsén, C., Pearson, M., Warensjö Lemming, E., 2012. Livsmedels- och näringsintag bland vuxna i Sverige. Resultat från matvaneundersökning utförd 2010–11. ("Food and Nutrient Intake Among Adults in Sweden. Results From a Food Survey Conducted in 2010–11."). Swedish Food Agency, Uppsala, Sweden.
Andrén, O., Kätterer, T., Karlsson, T., 2004. ICBM regional model for estimations of dynamics of agricultural soil carbon pools. Nutr. Cycl. Agroecosyst. 70, 231–239.
Bajzelj, 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.
Brook, B.W., Ellis, E.C., Perring, M.P., Mackay, A.W., Blomqvist, L., 2013. Does the terrestrial biosphere have planetary tipping points? Trends Ecol. Evol. 28 (7), 396–401. http://dx.doi.org/10.1016/j.tree.2013.01.016.
Dagevos, H., Voordouw, J., 2013. Sustainability and meat consumption: is reduction realistic? Sustain. Sci. Pract. Policy 9 (2), 60–66.
Davidson, E., 2012. Representative concentration pathways and mitigation scenarios for nitrous oxide. Environ. Res. Lett. 7, 024005.
Debevec, L., Tidavar, B., 2006. Making connections through foodways: contemporary issues in anthropological and sociological studies of food. Anthropol. Notebooks 12 (1), 5–16.
Dearing, J.A., Wang, R., Zhang, K., et al., 2014. Safe and just operating spaces for regional social-ecological systems. Glob. Environ. Change 28, 227–238. http://dx.doi.org/10.1016/j.gloenvcha.2014.06.012.
Donald, B., Gertler, M., Gray, M., Lobao, L., 2010. Re-regionalizing the food system? Camb. J. Regions, Econ. Soc. 3, 171–175.
Elwinger, C., 2013. Foder och fodermedel till värphöns och slaktkycklingar. ("Feeds for Layers and Broilers".). Department of Animal Nutrition and Management, Swedish University of Agricultural Sciences, Uppsala.
Enghardt Barbieri, H., Lindvall, C., 2003. De svenska näringsrekommendationerna översatta till livsmedel. Underlag till generella råd på livsmedels- och måltidsnivå för friska vuxna. ("The Swedish Nutrition Recommendations Translated into Food-Documentation for General Advice on Food and Meal Level for Healthy Adults"). Swedish Food Agency, Uppsala, Sweden.
EU, 2011. Commission Regulation No 142/2011 of the European Parliament and of the Council laying down health rules as regards animal by-products and derived products not intended for human consumption. Official Journal of the European Union, Brussels, Belgium (26.2.2011).
FAO, 2011. Global Food Losses and Food Waste – Extent, Causes and Prevention. Food and Agricultural Organisation of the United Nations, Rome, Italy.
Flysjö, A., Cederberg, C., Henriksson, M., Ledgard, S., 2012. The interaction between milk and beef production and emissions from land use change – critical considerations in life cycle assessment and carbon footprint studies of milk. J. Clean. Prod. 28, 134–142.
Fogelfors, H., 2015. Vår mat. Odling av åker- och trädgårdsgrödor. ("Our Food. The Cultivation of Arable and Horticultural Crops."). Studentlitteratur AB, Lund, Sweden.
Francis, C., Lieblein, G., Gliessman, S., et al., 2003. Agroecology: the ecology of food systems. J. Sustain. Agric. 22, 99–118.
Foley, J.A., Ramankutty, N., Brauman, K.A., et al., 2011. Solutions for a cultivated planet. Nature 478, 337–342.
Garnett, T., 2009. Livestock-related greenhouse gas emissions: impacts and options for policy makers. Environ. Sci. Policy 12, 491–503.
Garnett, T., 2011. Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? Food Policy 36, S23–S32.
Garnett, T., Röös, E., Little, D., 2015. Lean, Green, Mean, Obscene...? What is Efficiency? And is it Sustainable? Food Climate Research Network, University of Oxford, Oxford, UK.
Gerten, D., Heinke, J., Hoff, H., Biemans, H., Fader, M., Waha, K., 2011. Global water availability and requirements for future food production. J. Hydrometeorol. 12, 885–899.
Godfray, C., Beddington, J.R., Crute, I.R., et al., 2010. The challenge of feeding 9 billion people. Science 327, 812–818.
Griggs, D., Stafford-Smith, M., Gaffney, O., et al., 2013. Policy: sustainable development goals for people and planet. Nature 495 (7441), 305–307.
Göransson, L., Lindberg, J.-E., 2011. Nutritional Recommendations and Feed Tables for Pigs (in Swedish). Swedish University of Agricultural Sciences, Uppsala, Sweden, <http://www.slu.se/sv/institutioner/husdjurens-utfodring-vard/verktyg/fodertabeller/fodertabeller-och-naringsrekommendationer-for-gris/> (accessed 2014-08-29).
IPCC, 2007. Climate Change 2007: Synthesis Report (Chapter 5.4) Emission trajectories for stabilisation <http://www.ipcc.ch/publications_and_data/ar4/syr/en/mains5-4.html>.
IPCC, 2014. Summary for Policymakers. In: Climate Change 2014, Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.
Janzen, H.H., 2011. What place for livestock on a re-greening earth? Anim. Feed Sci. Technol. 166–167, 783–796.
Jensen, E.S., Bedoussac, L., Carlsson, G., Journet, E.-P., Justes, E., Hauggaard-Nielsen, H., 2015. Enhancing yields in organic crop production by eco-functional intensification. Sustain. Agric. Res. 4, 38–46.
Jerrentrup, J.S., Wrage-Mönnig, N., Röver, K.-U., Isselstein, J., 2014. Grazing intensity affects insect diversity via sward structure and heterogeneity in a long-term experiment. J. Appl. Ecol. 51, 68–977.
Jose, S., 2009. Agroforestry for ecosystem services and environmental benefits: an overview. Agrofor. Syst. 76, 1–10.
Jönsson, H., 2005. Mjölk – en kulturanalys av mejeridiskens nya ekonomi. ("Milk – An Analysis of the Cultural Aspects of the New Economy of the Dairy Counter"). Doctoral thesis. Brutus Östlings Bokförlag Symposium (ISBN 91-7139-705-1).
Kremen, C., Miles, A., 2012. Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs. Ecol. Soc. 17 (4), 40.
Leenstra, F., 2013. Raising cockerels as part of free range egg production. LowInputBreeds Technical Note 4.6. <http://www.lowinputbreeds.org> (accessed 2014-08-29).
Mace, G.M., Reyers, B., Alkemade, R., et al., 2014. Approaches to defining a planetary boundary for biodiversity. Glob. Environ. Change 28, 289–297. http://dx.doi.org/10.1016/j.gloenvcha.2014.07.009.
Martin, C., Morgavi, D.P., Doreau, M., 2010. Methane mitigation in ruminants: from microbe to the farm scale. Animal 4 (03), 351–365.
McMichael, A.J., Powles, J.W., Butler, C.D., Uauy, R., 2007. Food, livestock production, energy, climate change, and health. Lancet 370 (9594), 1253–1263.
MEA, 2005. Ecosystems and Human Well-being: Biodiversity Synthesis. Millennium Ecosystem Assessment World Resources Institute, Washington.
Metzger, J., 2005. I köttbullslandet – Konstruktionen av svenskt och utländskt på det kulinariska fältet. ("In Meatball Country – Construction of Swedish and Foreign in the Culinary Field"). Doctoral thesis. Akademitryck, Edsbruk (ISBN 91-85445-04-5).
NFA, 2011. Livsmedelsförsörjning i ett krisperspektiv. ("Food Security in a Crisis"). National Food Agency, Uppsala, Sweden.
Norden, 2012. Nordic Nutrition Recommendations. Integrating Nutrition and Physical Activity, 5th ed. Nordic Council of Ministers, Copenhagen, Denmark.
NRC, 1994. Nutrient Requirements of Poultry. National Research Council 9th Edition, National Academy Press, Washington D.C., USA.
Olsen, Y., 2011. Resources for fish feed in future mariculture. Aquacult. Environ. Interact. 1, 187–200. http://dx.doi.org/10.3354/aei00019.
Peters, C.J., Wilkins, J.L., Fick, G.W., 2007. Testing a complete-diet model for estimating the land resource requirements of food consumption and agricultural carrying capacity: the New York State example. Renewable Agric. Food Syst. 22, 145–153.
Pereira, H.M., Ferreir, S., Walters, M., et al., 2013. Essential biodiversity variables. Science 339, 277–278.
PRé Sustainability, 2014. Handbook for product social impact assessment. Version 2.0 – September 2014. <http://product-social-impact-assessment.com/> (accessed 2014-10-10).
Raworth, K., 2012. A Safe and Just Space for Humanity: Can We Live Within the Doughnut? (Oxfam discussion paper) Oxfam, Oxford, UK.
Rockström, J., Steffen, W., Noone, K., et al., 2009. A safe operating space for humanity. Nature 461, 472–475.
Rook, A.J., Dumont, B., Isselstein, J., Osoro, K., WallisDeVries, M.F., Parente, G., Mills, J., 2004. Matching type of livestock to desired biodiversity outcomes in pastures – a review. Biol. Conserv. 119, 137–150.
Röös, E., Karlsson, H., Witthöft, C., Sundberg, C., 2015. Evaluating the sustainability of diets–combining environmental and nutritional aspects. Environ. Sci. Policy 47, 157–166.
Sabaré, J., Soret, S., 2014. Sustainability of plant-based diets: back to the future. Am. J. Clin. Nutr. 100, 4765–4825. http://dx.doi.org/10.3945/ajcn.113.071522.
SBA, 2013a. Sveriges produktion av nötkött och ägg ökar men importen tar ändå marknadsandelar. ("Sweden's Production of Beef and Eggs Increases the Exports is Still Taking Market Shares"). Swedish Board of Agriculture, Jönköping, Sweden.
SBA, 2013b. Nationell strategi för hållbara verksamhetsprogram inom sektorn för frukt och grönsaker 2009–2014. ("National Strategy for Sustainable Operations in the Sector of Fruit and Vegetables 2009–2014"). Swedish Board of Agriculture, Jönköping, Sweden (report 2009:05 (updated 2013)).

SBA, 2013c. Jordbruksstatistisk årsbok 2013 ("Annual Statistics of Agriculture 2013".). Swedish Board of Agriculture, Jönköping, Sweden (report 2009:05 (updated 2013)).

SBA, 2014a. Use of Agricultural Land 2014, Preliminary Statistics. Swedish Board of Agriculture, Jönköping, Sweden (in Swedish) JO 10 SM 1402.

SBA, 2014b. Statistics Database. Consumption of Food 2012. Swedish Board of Agriculture, Jönköping, Sweden.

Scarborough, P., Appleby, P.N., Mizdrak, A., Briggs, A., Travis, R., Bradbury, K., Key, T., 2014. Dietary greenhouse gas emissions of meat-eaters, fish-eaters, vegetarians and vegans in the UK. Clim. Change 125 (2), 179–192.

Schösler, H., Boer, Jd., Boersema, J.J., 2012. Can we cut out the meat of the dish? Constructing consumer-oriented pathways towards meat substitution. Appetite 58, 39–47.

SEPA, 2014. Environmental Objectives. A Rich Diversity of Plant and Animal Life. Swedish Environmental Protection Agency, Stockholm, Sweden, <http://www.miljomal.se/Miljomalen/16-Ett-rikt-vaxt–och-djurliv/> (accessed 2014-11-13).

Smith, P., Gregory, P.J., 2013. Climate change and sustainable food production. Proc. Nutr. Soc. 72 (1), 21–28.

Smith, J., Sones, K., Grace, D., MacMillan, S., Tarawali, S., Herrero, M., 2013. Beyond milk, meat, and eggs: role of livestock in food and nutrition security. Anim. Front. 3 (1), 6–13.

Snyder, C.S., Davidson, E.A., Smith, P., Venterea, R.T., 2014. Agriculture: sustainable crop and animal production to help mitigate nitrous oxide emissions. Curr. Opin. Environ. Sustain. 9–10, 46–54.

Spörndly, R., 2003. Fodertabeller för idisslare. ("Feed Tables for Ruminants") (report 257). Department of Animal Nutrition and Management, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., et al., 2015. Planetary boundaries: guiding human development on a changing planet. Science 347 (6223). http://dx.doi.org/10.1126/science.1259855.

SS, 2000. Land Areas 2000. Statistics Sweden, Stockholm, Sweden, <http://www.scb.se/sv_/Hitta-statistik/Statistik-efter-amne/Miljo/Markanvandning/Markanvandning-enligt-Svenska-MarktackeData-SMD/106160/106167/Marktackedata-2000-riket-/> (accessed 2014-11-26).

SS, 2014. Population Statistics. Statistics Sweden, Örebro, Sweden, <http://www.scb.se/en_/Finding-statistics/Statistics-by-subject-area/Population/Population-composition/Population-statistics/ (accessed 14-12-01).

Tacon, 1995. Feed ingredients for carnivorous fish species: alternatives to fishmeal and other fishery resources. In: Reinertsen, Helge, Haaland, Herborg (Eds.), Sustainable Fish Farming. A.A. Balkema, Rotterdam, the Netherlands.

Tscharntke, T., Clough, Y., Wanger, T.C., Jackson, L., Motzke, I., Perfecto, I., Vandermeer, J., Whitbread, A., 2012. Global food security, biodiversity conservation and the future of agricultural intensification. Biol. Conserv. 151, 53–59.

Tillman, D., Clark, M., 2014. Global diets link environmental sustainability and human health. Nature 515, 518–522.

UN, 2014. World Population Prospects: The 2012 Revision. United Nations Department of Economic and Social Affairs, <http://esa.un.org/wpp/Excel-Data/population.htm>.

UNEP, 2009. Guidelines for Social Life Cycle Assessment of Products. United Nations Environment Programme, Druk in de weer, Belgium, ISBN 978-92-807-3021-0.

Van Kernebeek, H., Oosting, S., Feskens, E., Gerber, P., De Boer, I., 2014a. The effect of nutritional quality on comparing environmental impacts of human diets. J. Clean. Prod. 73, 88–99.

Van Kernebeek, H., Oosting, S., van Ittersum, M., de Boer, I., 2014b. Optimising land use and consumption of livestock products in the human diet with an increasing human population in the Netherlands. In: Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector, San Fransisco.

Van Huis, A., 2013. Potential of insects as food and feed in assuring foods security. Annu. Rev. Entomol. 58, 563–583.

Van Huylenbroeck, G., Vandermeulen, V., Mettepenningen, E., Verspecht, A., 2007. Multifunctionality of agriculture: a review of definitions, evidence and instruments. Liv. Rev. Landsc. Res. 1, 3.

Vidakovic, A., Langeland, M., Sundh, H., Sundell, K., Olstorpe, M., Vielma, J., Kiessling, A., Lundh, T., 2015. Evaluation of growth performance and intestinal barrier function in Arctic Charr (Salvelinus alpinus) fed yeast (Saccharomyces cerevisiae), fungi (Rhizopus oryzae) and blue mussel (Mytilus edulis). Aquac. Nutr. http://dx.doi.org/10.1111/anu.12344.

Vieux, F., Darmon, N., Touazi, D., Soler, L.G., 2012. Greenhouse gas emissions of self-selected individual diets in France: changing the diet structure or consuming less? Ecol. Econ. 75, 91–101.

World Bank, 2014. World Development Indicators Table 3.2. <http://wdi.worldbank.org/table/3.2> (accessed 2014-11-20).