

# Saving land to feed a growing population: consequences for consumption of crop and livestock products

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## Abstract

**Purpose** The expected increase in demand for food raises concerns about the expansion of agricultural land worldwide. To avoid expansion, we need to focus on increasing land productivity, reducing waste, and shifting human diets. Studies exploring diet shifts so far have ignored competition for land between humans and animals. Our objective was to study the relation between land use, the share of animal protein in the human diet, population size, and land availability and quality. **Methods** We used linear programming to determine minimum land required to feed a population a diet with 0–80 % of the protein derived from terrestrial domestic animals. Populations ranged from 15 million to the maximum number of people that could be supported by the system. The agricultural system in the Netherlands was used as illustration, assuming no import and export of feed and food. Daily energy and protein requirements of humans were fulfilled by a diet potentially consisting of grain (wheat), root and tuber crops (potato, sugar beet), oil crops (rapeseed), legumes (brown bean), and animal

protein from ruminants (milk and meat) and monogastrics (pork).

**Results and discussion** Land is used most efficiently if people would derive 12 % of dietary protein from animals (% PA), especially milk. The role of animals in such a diet is to convert co-products from crop production and the human food industry into protein-rich milk and meat. Below 12 % PA, human-inedible products were wasted (i.e., not used for food production), whereas above 12 % PA, additional crops had to be cultivated to feed livestock. Large populations (40 million or more) could be sustained only if animal protein was consumed. This results from the fact that at high population sizes, land unsuitable for crop production was necessary to meet dietary requirements of the population, and contributed to food production by providing animal protein without competing for land with crops.

**Conclusions** A land use optimization model including crop and animal production enables identification of the optimal % PA in the diet. Land use per capita was lowest at 12 % PA. At this level, animals optimally consume co-products from food production. Larger populations, furthermore, can be sustained only with diets relatively high in % PA, as land unsuitable for crop production is needed to fulfil their food demand. The optimal % PA in the human diet depended on population size and the relative share of land unsuitable for crop production.

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## 1 Introduction

Global food demand is projected to increase by 60 % by 2050 (Alexandratos and Bruinsma 2012), because of a growing

world population and increasing wealth. This increased demand for food has raised concerns about environmental impacts related to expansion of agricultural land worldwide (Foley et al. 2011). Pressure on land increases not only because of future food demands but also because of land degradation (Stringer 2008) and increasing demands for biofuels (OECD/FAO 2014), biomaterials, housing, and infrastructure.

Currently, agriculture already occupies about 38 % of the terrestrial surface of the Earth, divided among 1.5 billion ha of cropland and 3.4 billion ha of pastures (Alexandratos and Bruinsma 2012). Meeting the food demand projected for 2050 may require an additional 0.2 to 1 billion ha of land under agriculture (Tilman et al. 2011). This additional land will include land of relatively low fertility and productivity and will be partly located in currently forested or protected areas (Alexandratos and Bruinsma 2012; Foley et al. 2011; Ramankutty et al. 2002). Converting such forested lands to agricultural land conflicts with the need for nature preservation (Royal Society of London 2009; Smith et al. 2010; World Bank 2007) and leads to adverse environmental effects (DeFries et al. 2004; Gerber et al. 2013; Millennium Ecosystem Assessment 2005; Pielke et al. 2002).

There is considerable agreement, therefore, that humans should minimize further expansion of agricultural land. Limiting global land expansion for food production, however, requires a combination of interventions on the production and consumption side (Foley et al. 2011). Proposed strategies include increasing yields on underperforming lands (Van Ittersum et al. 2013), reducing waste (Papargyropoulou et al. 2014), and shifting human diets (Stehfest et al. 2009; Wirsenius et al. 2010).

Studies exploring the potential contribution of dietary shifts generally conclude that (i) a vegan diet requires the least land (Hallström et al. 2015) and (ii) that land use decreases when ruminant meat is replaced by monogastric meat (Stehfest et al. 2009; Wirsenius et al. 2010). These studies, however, do not consider the competition between humans and animals for land. Animals fed with cereals, for example, directly compete with humans for land. No matter how efficiently produced, direct consumption of cereals by humans is ecologically more efficient than consumption of animal-source food produced by animals fed with these cereals (Foley et al. 2011; Godfrey et al. 2010). Compared to pigs or poultry, ruminants generally consume less feed that can be consumed directly by humans (De Vries and De Boer 2010; Vellinga et al. 2009). Ruminants, however, can still compete with humans for land, as some of the world's grasslands are also suitable for production of arable crops (Suttie et al. 2005). To limit global land use for food production, therefore, we should consume livestock products from systems that use land that is unsuitable or less suitable for crop production and/or that use co-products from food production (Van Zanten et al. 2015). The objective of this study, therefore, was to identify which factors influence the relation

between land use, the share of animal protein in the human diet, population size, and land availability and quality. We determined the minimum amount of land used to feed a growing population a diet varying in the percentage of the protein derived from terrestrial domestic animals. The agricultural system in the Netherlands was used as case-study, assuming no import and export of feed and food.

## 2 Material and methods

This study was based on a land use optimization model created in General Algebraic Modelling System (GAMS) version 24.2.

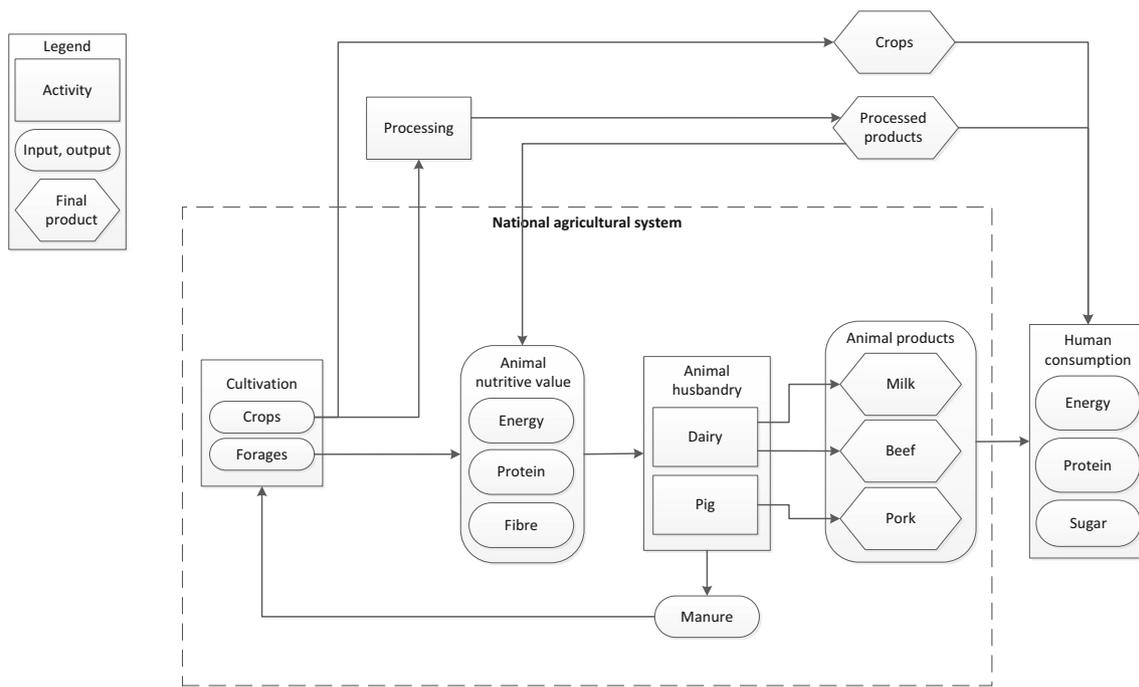
### 2.1 System definition

The system in our case study consisted of production, processing, and consumption of food in the Netherlands as a standalone system (Fig. 1). The objective of this system was to produce human-edible energy and protein for domestic use. The model estimated the land area required to feed populations ranging from 15 million (close to the current population size) to the maximum number of people that could be supported by the system. Within this range, we increased population size by steps of five million people. As we approached the maximum number of people, we increased population size with steps of 0.1 million people. Daily per capita requirements were defined as 2000 kcal and 57 g protein (EFSA 2009; EFSA 2012). Total sugar intake was limited to the maximum recommended intake level of 90 g per capita per day (EFSA 2009). We estimated land use for human diets varying in the percentage of the protein derived from terrestrial domestic animals ("protein derived from animals" or PA) between 0 % PA (a vegan diet) to 80 % PA. Within this range, we increased % PA by steps of 5 % (and by steps of 1 % where relevant). Land use was determined for cultivation of crops and forages.

### 2.2 Crop production system

The current Dutch agricultural area of  $1842 \times 10^3$  ha (CBS 2013) represented the maximum available area for production of crops and forages. This area consists of clay soils ( $839 \times 10^3$  ha), sandy soils ( $779 \times 10^3$  ha), and peat soils ( $224 \times 10^3$  ha) (Lesschen et al. 2012). Clay and sandy soils can be used for cultivation of crops and forages, whereas peat soils were assumed to be suitable only for cultivation of grass, since most of these are too wet for competitive crop production. For the fact that they are marginal for crop production, peat soils represent so-called marginal lands in this study.

Crops included in the modeling represented the following major groups: grains, root and tuber crops, oil crops, and



**Fig. 1** Diagram of the system

legumes (Electronic Supplementary Material I). In each food crop group, the arable crop with the largest cultivated area in the Netherlands was chosen (LEI and CBS 2012). Grains were represented by wheat, root, and tuber crops by potatoes and sugar beets, oil crops by rapeseed, and legumes by brown beans. Seven crop rotations were adopted from Van Ittersum et al. (1995), the length of rotations varying from 1 to 6 years (Electronic Supplementary Material I). Crop yields were based on current Dutch averages. To compute the annual yield of each crop within a rotation, we multiplied the crop's yield with its frequency in the rotation (i.e., years of cultivation in a rotation divided by total years of rotation). In the harvested crop, we distinguished the main crop product and human-inedible products (i.e., wheat straw, sugar beet tops and tails, and rapeseed straw). Wheat and maize stubble, potato haulms, sugar beet leaves, and bean straw were left on the field as source of soil organic carbon. We lowered actual yield levels by 7 % for potatoes, 5 % for beans, and 2 % for wheat and rapeseed to account for production of seeds and seedlings (PPO 2009; PPO 2012). Hence, seed and seedling production was already accounted for in crop yields in our calculations ( $Y_{i,j,t}$ ). In addition to crops, we considered production of maize silage and grass as forage for dairy cattle. We assumed no effects on yields of climatic differences across the Netherlands (Van Wart et al. 2013).

To determine total dry matter production (ton DM) of harvested product  $j$  ( $Q_j$ ), we multiplied the land area allocated to crop rotation  $i$  on land type  $l$  ( $X_{i,l}$ ) by the fresh matter yield of harvested product  $j$  from the same crop rotation and land type ( $Y_{i,j,t}$ ), and by the dry matter content of harvested product  $j$

( $DM_j$ ), then summed across rotations ( $i=1,7$ ) and land types ( $l=1,3$ ; Eq. (1)).

$$Q_j = \sum_{i=1}^7 \sum_{l=1}^3 X_{i,l} \times Y_{i,j,t} \times DM_j \quad (1)$$

### 2.3 Processing of crops

Harvested products (e.g., rapeseed) were divided into food and feed products (e.g., oil and meal) following ratios of dry matter output and dry matter input of various processing steps (Electronic Supplementary Material II). These dry matter output/input ratios were calculated from fresh matter output/input ratios (Mattsson et al. 2001; Vellinga et al. 2013) and dry matter contents of food (RIVM 2013) and feed products (PDV 2011). To determine dry matter production of food or feed product  $k$  ( $Q_k$ ), we multiplied production quantities of harvested product  $j$  assigned to process  $m$  ( $Q_{j,m}$ ) with the output/input ratio of product  $k$  produced from harvested product  $j$  in process  $m$  ( $C_{j,m,k}$ ) (Eq. (2)). Processes that do not divide one product into multiple products (e.g., ensiling of grass and heating of beans) were assigned an output/input ratio of 1.

$$Q_k = Q_{j,m} \times C_{j,m,k} \quad (2)$$

We converted production quantities of human-edible products into available energy, protein and sugar, using nutrient contents of products found in the Dutch nutrient database NEVO (RIVM 2013). Similarly, for animal feeds (see

Sect. 2.4), we converted production quantities into nutrients using feed tables (PDV 2011).

## 2.4 Animal production system

We included two animal production systems with contrasting abilities to use marginal land. We chose pig production as representative for monogastrics, a system that derives its feeds from land suitable for cultivation of crops, and dairy production as representative for ruminants, able to use marginal land. We chose these systems as within the group of monogastrics and ruminants, pork and dairy products are the largest contributors to protein in the human diet (PPE/PVV 2013; RIVM 2011).

Production levels of animals were based on Dutch averages. We modeled pig and dairy production based on animal production units (PUs) per animal place per year. One pig PU consisted of 3.3 fattening pigs, 0.12 sows, and 0.07 gilts (Electronic Supplementary Material III). One pig PU produced 171 kg pork per year, which corresponds to 1475 MJ and 55 kg human-edible protein per year. Net energy requirements per pig PU (equivalent to the weighted sum of net energy requirements (PDV 2012) for fattening pigs, sows and gilts) totaled 9901 MJ per year (Electronic Supplementary Material IV). The diet of one pig PU had a minimum of 16 % and a maximum of 18 % crude protein (Bikker 2014; Devendra and Clyde Parris 1970) and a digestibility coefficient of at least 80 % (Bikker 2014). Grass, maize silage, straw, sugar beet tops and tails, and sugar factory lime were excluded from consumption by pigs (Bikker 2014). We applied additional restrictions to create a plausible diet (Electronic Supplementary Material V).

One cow PU consisted of a dairy cow and its replacement stock, i.e., 0.31 heifers aged 1–2 years, and 0.34 calves aged 0–1 year (Electronic Supplementary Material VI). Surplus calves were excluded from our analysis. One cow PU produced 8502 kg fat-and-protein-corrected-milk and 74 kg meat per year, both derived only from the milking cow, corresponding to 22,775 MJ, 303 kg human-edible protein and 383 kg total sugar per year (Electronic Supplementary Material VI). Net energy requirements for one cow PU (equivalent to the weighted sum of net energy requirements (PDV 2012) for the milking cow, replacement heifer, and calf) totaled 51,977 MJ and 606 kg intestinal digestible protein per year (Electronic Supplementary Material VII and VIII). Rumen degradable protein balance had a lower limit of 0 and an upper limit of 200 g per cow per day (Dijkstra 2014). To assure sufficient structure in the diet, the structure value of the diet (PDV 2012) was at least 1 per kg DM. Maximum feed intake capacity was limited to 14.9 saturation values per day for dairy cows, 3.2 for replacement heifers, and 5.9 for replacement calves (PDV 2012). Sugar factory lime was excluded from consumption by

cows. We applied additional restrictions to create a plausible diet (Electronic Supplementary Material V).

## 2.5 Manure production and application

Nutrient (i.e., nitrogen and phosphorus) excretion by animals was computed as the difference between nutrient intake and nutrients retained in animals and their products. Nutrient intake was computed based on information about feed intake and nutrient content of feed ingredients (PDV 2011). Nutrient retention in growing pigs was computed from nutrient concentrations in body tissue (Groenestein et al. 2008) and production data (Electronic Supplementary Material III), and totaled 9.4 kg N and 2.0 kg P per pig PU per year. Nutrient retention in milk and body tissue of culled cows and growing young stock was computed from nutrient concentrations in body tissue and milk (RVO 2010) and production data (Electronic Supplementary Material VI), and totaled 50.1 kg N and 9.64 kg P per cow PU per year.

In line with European Union (EU) legislation, application of manure to crop and grassland was limited to 170 kg nitrogen from animal manure per hectare per year (RVO 2014). Additionally, we restricted total nitrogen application from manure and artificial fertilizer to the sum of crop- and soil-type-specific maximum nitrogen application rates allowed by EU legislation. The nitrogen fertilizer replacement value of manure was set at 60 % (RVO 2014). Moreover, we restricted total phosphate application to the sum of soil-type-specific maximum phosphate application rates for grass and arable land (RVO 2014). These rates depended on the phosphate levels of the soil, as determined by Schoumans (2007).

## 2.6 Losses

We accounted for losses of food crop products, meat, and milk by applying loss fractions (Gustavsson et al. 2011) during postharvest handling, storage, processing, packing, distribution, and consumption. We assumed that at most 21 % of total food crop product losses could potentially be used as feed (Soethoudt and Timmermans 2013). We assumed 5 % postharvest handling and storage losses for wheat straw, sugar beet tops and tails, and rapeseed straw. In addition, we accounted for conservation and feeding losses for crop products allocated to animals. We assumed conservation losses of 4 % for moist concentrates, 5–10 % for potato peel, silage maize, and beans, 15–17.5 % for grass silage and potatoes, 20 % for straw, and 25 % for sugar beet tops and tails (Remmelink et al. 2012). Feeding losses were 2 % for dried concentrates, 3 % for moist concentrates, and 5 % for roughages (Remmelink et al. 2012). No losses were assigned to fresh grass, as fresh grass yields represented net production (i.e., intake) by animals.

**Table 1** Characteristics of the reference situation and, assessed in sensitivity analyses, alternative situations

Sensitivity	Reference situation	Alternative situations
Soil type	12 % peat soils, 46 % clay soils, 42 % sandy soils	A: 5 % peat soils, 50 % clay soils, 45 % sandy soils B: 40 % peat soils, 30 % clay soils, 30 % sandy soils
Yield	Average Dutch yields under current practices	20 % lower yields on sandy soils and 50 % lower yields on peat soils compared to the reference situation
Meat content	No predefined requirements for meat consumption	Meat constitutes at least 50 % of dietary protein from animals

## 2.7 Objective function

The linear-programming model allocated crop products to humans or animals based on an objective function to minimize land use for all crop rotations  $i$  on all land types  $l$  ( $X_{i,l}$ ) (Eq. (3)) while meeting energy and protein requirements of the human population.

$$\text{Min} \sum_{i=1}^7 \sum_{l=1}^3 X_{i,l} \quad (3)$$

## 2.8 Sensitivity analysis

We explored the impact of changes in the share of different soil types, in crop and forage yields and in the share of protein from meat in the animal protein consumed on final results of land use and human dietary composition (Table 1)

**Changes in share of different soil types** In the reference situation, land consisted of 46 % clay soils, 42 % sandy soils, and 12 % peat soils. To determine the impact of decreasing the share of marginal land (peat soil), we studied a situation in which land consisted of 50 % clay soils, 45 % sandy soils, and 5 % peat soils (less peat). To determine the impact of increasing the share of marginal land, we studied a situation in which land consisted of 30 % clay soils, 30 % sandy soils, and 40 % peat soils (more peat). **Changes in crop and grass yields** To determine the impact of differences in relative productivity of clay, sand, and peat soils, we decreased yields on sandy soils by 20 % and on peat soils by 50 %.

**Changes in meat content of the diet** In the reference situation, we did not set requirements for meat consumption. One possible outcome, therefore, was that PA could come mainly from milk. To determine the impact of meat consumption, we forced meat (pork and/or beef) to constitute at least 50 % of PA, as this is the current situation in the Netherlands (RIVM 2009).

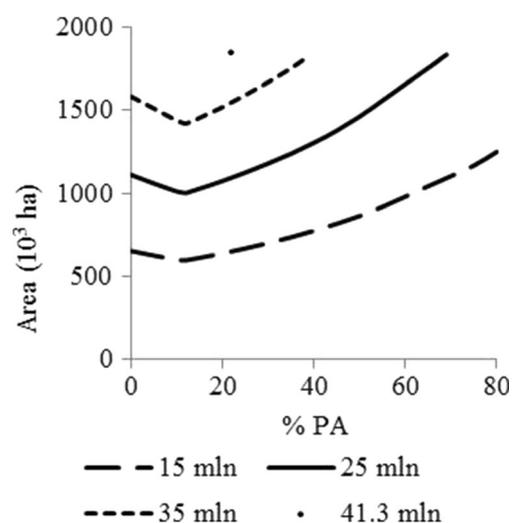
## 3 Results

### 3.1 Land use

#### 3.1.1 Reference situation

The relation between the minimum amount of land needed to feed a specific population and the percentage of the protein derived from animals (% PA) in the diet was nonlinear (Fig. 2). As % PA increased, land use initially decreased up to about 12 % PA, and subsequently increased. Diets with about 12 % PA, therefore, systematically had the lowest land use. Furthermore, as population size increased, the possible range of % PA in the diet became more narrow. This implies that larger populations could not be supported by a vegan diet or a diet containing a high % PA.

The amount of land needed per capita increased as population size increased (Table 2). Per capita land use increased with population size because high yielding soils, i.e., clay soils, were cultivated first, followed by sandy soils (Fig. 3). This order follows from the generally higher yields at rotation level on clay soils than on



**Fig. 2** Minimum land ( $10^3$  ha) needed for feeding the total population with diets varying in percentage of dietary protein from animals (% PA) in the reference situation. *mln* million

**Table 2** Per capita land use index for diets varying in percentage of dietary protein from animals (% PA) and various populations in the reference situation

% PA	Population (mln)			
	15	25	35	40
0	100	102	104	
10	92	93	94	
15	94	94	95	96
20	98	99	100	100
30	107	108	109	
40	119	120		
50	132	134		
60	150	152		
70	169			
80	191			

Index=100 for a diets with 0 % PA and a population of 15 million people

*mln* million

sandy soils. As population size increased, therefore, the relative contribution of lower yielding soils increased, explaining the increase in per capita land use (Table 2 and Fig. 3).

Food production on clay soils was sufficient to feed a population of 15 million people a diet with 0–25 % PA. In the range from 30 to 60 % PA, in addition to clay soils, sandy soils were used for the production of silage maize, as silage maize had higher yields on sandy soils than on clay soils. If PA exceeded 60 %, sandy soils were predominantly used for the production of crops, as all clay soils were fully used. Feeding a population of 35 million, however, required all clay soils and most of the sandy soils, even at low % PA. From 15 % PA upward, in addition to clay and sandy soils, peat soils were used to produce grass (see Electronic Supplementary Material X for diet composition per cow PU). Diets with more than 39 % PA were not feasible.

### 3.1.2 Impact of changes in share of different soil types

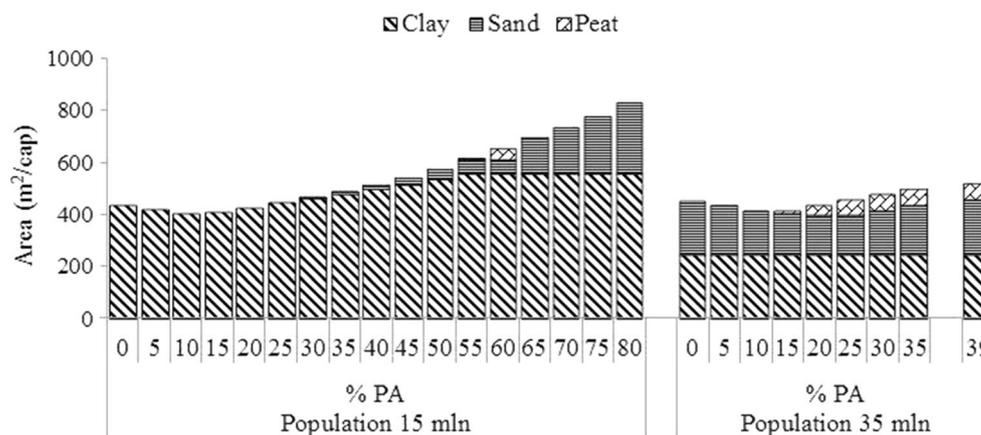
Decreasing the share of peat soils (i.e., from 12 % in the reference situation to 5 %) increased the maximum number of people that could be fed from the land, whereas increasing the share of peat soils (i.e., from 12 % in the reference situation to 40 %) decreased the maximum number of people that could be fed from the land (Fig. 4). This difference in the number of people that can be fed can be explained by the higher productivity of clay and sandy soils than peat soils. Furthermore, in the situation with a smaller share of peat soils, the maximum number of people (i.e., 43.6 million) consumed diets with about 15 % PA, whereas in the situation with a larger share of peat soils, the maximum number of people (i.e., 31.5 million) consumed diets with about 44 % PA. In other words, when population size increases in a region with a larger share of marginal land, this population can be supported only if a relatively high percentage of its protein comes from animal sources. Moreover, a vegan diet is only feasible for smaller populations in such a situation, i.e., larger populations can only be sustained when animal protein is consumed. The feasible share of animal protein in the human diet, therefore, depends on the population size in combination with the share of marginal land.

### 3.1.3 Impact of changes in crop and grass yields

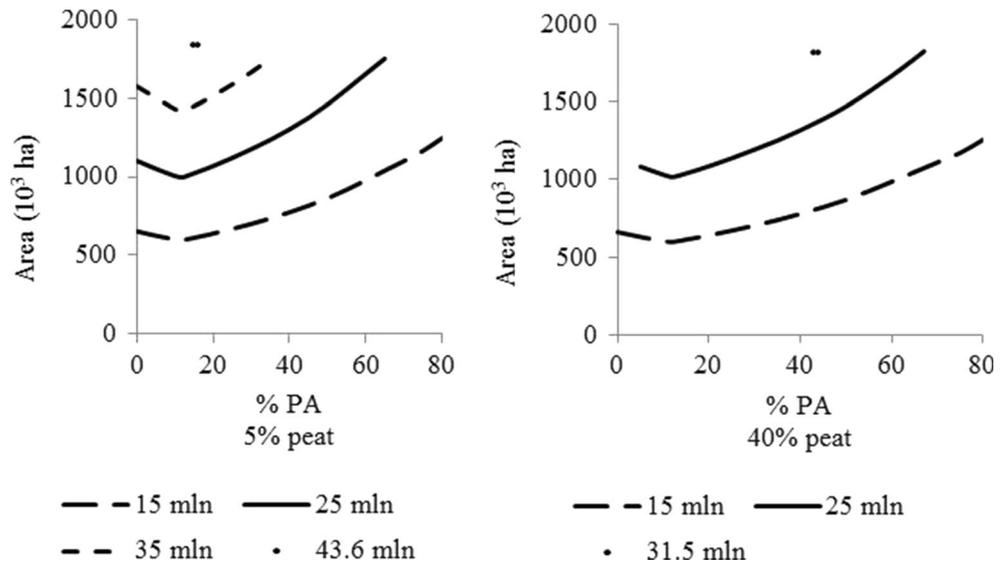
Decreasing crop yields on sandy and peat soils did not increase per capita land use compared to the reference situation as long as % PA was less than 30 %, because only clay soils were used in that range to feed a population of 15 million in both the reference and alternative situation (Fig. 5). When % PA was 30 % or more, per capita land use increased relatively quickly compared to the reference situation (Fig. 3), because of the lower availability of highly productive land.

We expected decreasing crop yields on sandy soils to result in higher land use on these soils compared to the reference

**Fig. 3** Land use ( $m^2$ /capita) per soil type for diets varying in percentage of dietary protein from animals (% PA) and populations of 15 million (*left*) and 35 million (*right*) people in the reference situation. For a population of 35 million people, 39 % PA was the last feasible option. *mln* million



**Fig. 4** Minimum land ( $10^3$  ha) needed for feeding the total population with diets varying in percentage of dietary protein from animals (% PA) in alternative situations with 5% (*left*) and 40% (*right*) of total land area underlain by peat soils. *mln* million



situation, under high population pressure or high % PA. For a population of 15 million, this was indeed the case for diets with 50 % PA and more (Fig. 5). For diets containing less than 50 % PA, however, sandy soils were not used in the alternative situation. This resulted from the relatively small difference in yield of maize silage between clay and sandy soils in the reference situation. After reducing yields by 20 % on sandy soils, yield of maize silage was higher on clay soils, which postponed the use of sandy soils to a higher % PA.

To feed 35 million people, more sandy soils were used than in the reference situation, due to their lower yields. From 20 % PA upward, sandy soils were fully used and peat soils were needed to produce animal protein. The maximum feasible % PA for this population was lower than that in the reference situation.

### 3.2 Consumption of animal protein

#### 3.2.1 Reference situation

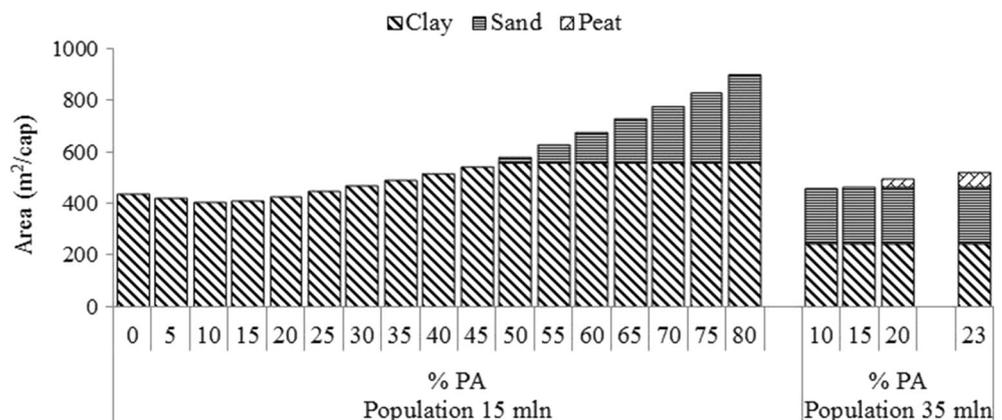
When % PA was less than 10 %, daily protein intake per capita equaled the recommended intake level of 57 g, but this

recommended level was often exceeded when % PA exceeded 10 % (Fig. 6) (see Electronic Supplementary Material IX for human diet composition). Our simulations also show that animal protein was mainly provided by milk (fixed ratio of protein from milk and beef of 14:1) (Fig. 6), which is due to higher protein productivity of dairy cows than of pigs (De Vries and de Boer 2010).

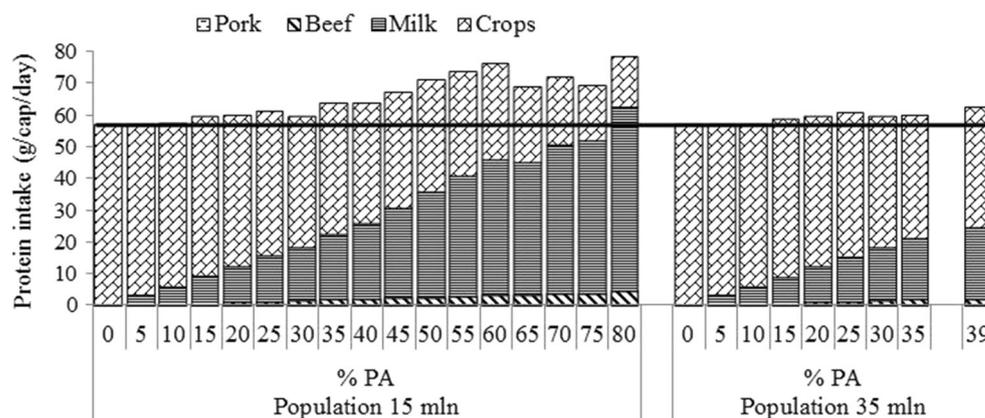
#### 3.2.2 Impact of changes in meat content of the diet

When requiring that at least 50 % of the dietary protein of a population of 15 million came from meat (in our model, beef or pork), the percentage of dietary protein from pork gradually increased from about 2 % (i.e., PA=5 %) to about 37 % (PA=80 %) (Fig. 7), at the expense of dietary protein from milk in particular. Land use in this alternative scenario, therefore, is slightly higher than that in the reference scenario. Hence, replacing dietary protein from milk with that from meat implies that we can eat less protein derived from animals. For a population of 35 million people, maximum % PA in the diet decreased to 35 % (Fig. 7), compared to 39 % in the reference

**Fig. 5** Land use ( $m^2/capita$ ) per soil type for diets varying in percentage of dietary protein from animals (% PA) and populations of 15 million (*left*) and 35 million (*right*) people in the alternative situation with 20 % lower yields on sandy soils and 50 % lower yields on peat soils compared to the reference situation. For a population of 35 million people, 23 % PA was the last feasible option. *mln* million



**Fig. 6** Per capita protein intake (g/day) from crops, milk, beef, and pork for diets varying in percentage of dietary protein from animals (% PA) and populations of 15 million (*left*) and 35 million (*right*) people in the reference situation. For a population of 35 million people, 39 % AP was the last feasible option. The *horizontal line* indicates the daily protein requirement of 57 g/cap. *mln* million



situation (Fig. 6) (see Electronic Supplementary Material XI for diet composition per pig PU).

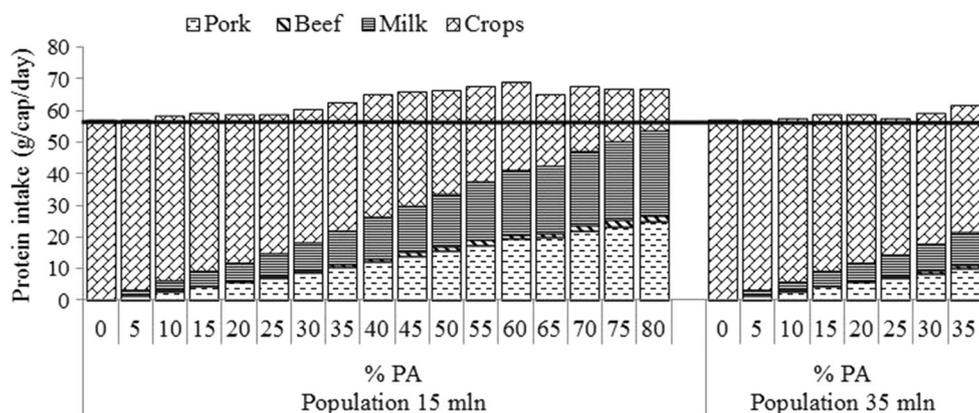
#### 4 Discussion and conclusions

Our model provides insights into relations between land use, the share of animal protein in the human diet, population size, and land availability and quality. We demonstrated that at lower population sizes, consumption of about 12 % of dietary protein from animal source foods resulted in the most efficient use of agricultural land. In the range from 0 to 20 % PA, land use remains more or less stable, whereas beyond 20 % PA land use increases more strongly. At the highest population size that could be supported by the land, however, the optimal percentage of dietary protein derived from animal source foods ranged from 15 to 45 %.

Minimizing land use resulted in per capita land use of 400–800 m<sup>2</sup>/year, values lower than actual land use values reported by Meier and Christen (2013), Terluin et al. (2013), and Van

Oorschot et al. (2012). This implies that humans can use land more efficiently if they would accept austere diets. Diets resulting from our analysis consisted of a limited variety of products because we used proxies for the five major groups of crop production, and for monogastric and ruminant production. We think, however, that including a wider variety of plant-based or terrestrial domestic animal-based products would not have affected our conclusions. Products from fisheries were not considered, as these systems do not use land.

In our results, animal protein in the human diet consisted mainly of milk, and beef was consumed as a co-product of milk production (milk/beef ratio of 14:1). When requiring that at least 50 % of the animal protein consumed should come from meat, pork was added to the human diet. Let us consider, however, what would have happened had we included beef production from suckler beef systems. Suckler cows can exploit marginal lands by producing beef via grazing. Beef from suckler cows, however, would have been included in the human diet only if we had defined minimum requirements for beef consumption, or if marginal lands had been suitable only



**Fig. 7** Per capita protein intake (g/day) from crops, milk, beef, and pork for diets varying in percentage of dietary protein from animals (% PA) and populations of 15 million (*left*) and 35 million (*right*) people in the alternative situation in which meat contributed at least 50 % of PA. For

a population of 35 million people, 35 % PA was the last feasible option. The *horizontal line* indicates the daily protein requirement of 57 g/cap. *mln* million

for grazing of suckler cows. This is because from a land use perspective grazing of dairy cows is preferred to grazing of suckler cows because dairy cows produce animal protein more efficiently (De Vries and De Boer 2010). Furthermore, feed produced on clay or sandy soil is converted more efficiently to animal protein by pigs than by beef cattle. We realize, however, that producing beef or mutton on marginal lands unsuitable for grazing of dairy cattle can be of utmost importance in other areas, and this will result in an increase of per capita land use.

Another important finding of our study is that a vegan diet always required more land than a diet with small amounts of animal protein. In other words, land is used most efficiently if people consume small amounts of animal protein, which is also referred to as the “default livestock diet” (Fairlie 2010). The role of animals in a default livestock diet is to convert co-products from arable production (e.g., straw) and the human food industry (e.g., beet pulp) that cannot be consumed directly by humans into protein-rich milk and meat. When no animal protein is produced, as suits a vegan diet, these human-inedible products are wasted (i.e., not used for food production) or used as a bio-energy source, and additional crops will have to be cultivated to meet nutritional energy and protein requirements of the population. Consequently, larger populations could not be supported by a vegan diet and a population cannot exceed a certain size unless animal protein is consumed.

Larger populations also could not be supported by a diet with a high percentage of protein derived from animal source foods. A population of 35 million people, for example, could not be supported from a diet containing 40 % PA or more. When demand for animal protein exceeds the default livestock diet, additional crops will have to be cultivated, resulting in higher land use. At higher population sizes this land is not available, which limits consumption of high amounts of animal protein, and, thus, the possible percentages of dietary protein derived from animal-source foods decreased. Moreover, at the highest population size that could be supported by the land, the optimal percentage of dietary protein derived from animal source food ranged from 15 to 45 %, the exact value depending on assumed crop yields and the share of marginal land. Peat soils, although relatively productive in the Netherlands, were considered marginal land as they are suitable only for grass production. Also, peat soils are somewhat less productive than clay soils in the Netherlands. Thus, increasing the share of peat soils increased the optimal percentage of dietary protein from animal source foods at the highest population size, but at the same time decreased the maximum number of people that could be fed. In contrast, decreasing the relative share of peat soils, and hence increasing the relative share of arable soils, would increase the number of people that could be fed and lower the optimal percentage of dietary protein from animal source foods at higher population sizes. The optimal percentage of dietary protein

from animals in future diets, therefore, depends on the share of marginal land in the world, together with the productivity of these marginal lands (which is atypically high in the Netherlands). Moreover, the optimal percentage of dietary protein from animals also depends on the type of crops and the extent to which co-products are harvested. A higher availability of co-products for feed would shift optimum land use to higher % PA but also reduce carbon inputs to the soil.

A final important conclusion is that our results contradict results of life cycle assessment (LCA) studies that explored land use of diets differing in the percentage of protein derived from animals. These LCA studies suggest that vegan diets require the least amount of land, followed by vegetarian diets (Hallström et al. 2015; Meier and Christen 2013). Optimization, as employed in our study, accounts for the unsuitability of marginal lands to grow crops, the suitability of animals to use human-inedible products, and the co-production of meat and milk. These aspects are not included in LCA studies, and explain the different results. Our land-use optimization model could be extended to the use of other limited resources such as fossil energy and phosphorous, and the emission of, for example, greenhouse gases.

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