The role of livestock in a sustainable diet: a land use perspective

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Supplementary Material S1 *Supplementary information*

Description of vegan diets

The diet composition used as a reference in this study is based on an average of the vegan diet composition of three studies (Supplementary Table S1): Van Dooren et al. (2013), Meier and Christen (2012) and Risku-Norja et al. (2009). These three studies describe western vegan diets that meet common recommendations for a healthy diet. The diet in the Dutch study of Van Dooren et al. (2013) meets the Dutch Dietary Guidelines and is highly comparable to the vegan adjustments of USDA food patterns. In this vegan diet, milk is replaced by soy drinks and extra legumes are included to ensure adequate protein intake. The German study of Meier and Christen (2012) based diet recommendations on the USDA food patterns because in Germany there were no official guidelines for vegan diets. In this vegan diet, milk is also replaced by soy drinks. We assumed that the soy-based milk contains 12.5% soybeans. The Finnish diet of Risku-Norja et al. (2009) was nutritionally balanced in terms of reasonable daily intakes of carbohydrates, fats and protein. In the Finnish study an oat-based milk was introduced, corresponding to 100 grams extra oat per person per day.

Supplementary Table S1. *Average composition of the vegan, based on three papers: Van Dooren et al. (2013), Meier and Christen (2012) and Risk-Norja et al. (2009).*

Product group	Van Dooren et al. 2013	Meier and Christen 2012	Risku-Norja et al. 2009	Average g/d
Vegetables	400	245	268	304
Legumes	21	154	17	64
Fruit	200	250	362	271

Bread	210			70
Cereal grains	53	295	404	251
Potatoes	105	107	250	154
Nuts and seeds		26		9
Vegetal oils, margarine	45	27	49	40
Sugar		32	60	31
Plant-based drinks	450	732		49
Meat replacer	43			14

Land use of vegan diet

The land use of the vegan diet described by Van Dooren et al. (2013) was 792 m^2 and for the vegan diet described by Meier and Christen (2012) 1052 m^2. No estimate of land use was given for the vegan diet described by Risku-Norja et al. (2009). Nevertheless, the calculations of land use were based on high yields in developed countries. If we account land use of the average vegan diet (see Supplementary Table S1) based on global average yields, land use will be 0.13 ha per person. Global average yields are based on Monfreda et al. (2008) and are presented in Supplementary Table S2. Adopting this 0.13 ha as average land use of a vegan diet and we know that 0.16 ha of arable land and permanent cropland is available per person, it seems possible to feed the world human population a vegan diet in 2050. Note: the world population is projected to reach 9.7 billion by 2050 (UN, 2015). We, however, want to make some remarks related to the assumption of land use. First, the estimation of the land use does not include food waste. In case 10% of our food is wasted we need 0.14 ha and 0.16 ha in case of 30% food waste (see below for information related food waste). Second, in addition to crop production for human food, arable land and permanent cropland are needed for other functions such as the production of clothes. Third, these vegan diets are formulated based on health recommendations and, therefore, do not represent the total feed intake e.g. do not include (luxury) snacks and drinks. Hence, total feed intake probably results in a higher land use. Fourth, there are large variations in estimating the area available for crop production and pasture. Ramankutty et al. (2008), for example, indicated that there were 1.5 billion ha of cropland (95% confidence range of 1.22-1.71) and 2.8 billion ha of pasture (95% confidence range of 2.36-3.00) worldwide available in 2000. Finally, when leftover streams are used to produce animal source food (ASF), part of the products in the vegan diet e.g. soy milk or legumes can be replaced by the produced ASF resulting in a reduced land use.

Supplementary Table S2*. Global average yields based on Monfreda et al., 2008.*

Product group	Ton/ha/harvest
Cereals	3.1
Oil crops	2.4
Forage	17.6
Pulses	1.1

Roots and tubers	17.7
Fruit	10.5
Vegetables	17.1
Fiber	1.7
Sugar crops	56.8
Three nuts	1.2
Other crops	6.7

Assessing the amount of available co-products and food waste

To calculate the amount of co-products and food waste available, we first determined the main product(s) used in each product group, based on Gustavsson et al. (2011). For each main product we determined the production process to determine the co-products related to the production of the main product. We based this on documentation reports of Feedprint (Vellinga et al., 2013). Supplementary Table S3 shows the co-products that become available during the production of the average vegan diet. The availability of specific co-products depends on the assumptions made for the main products. For example, we assumed that the main product used in the product group ‘vegetal oils and margarine’ is soybean oil. However, in Europe sunflower seed and rape seed are the main products while soybean is the main product in North America, Oceania and industrialised Asia. Our results, related to the amount of pork will change, in case we assume sunflower oil is used, because of the higher fat content of sunflower seeds and the lower nutritional value of sunflower seed meal compared to soybeans and soybean meal.

Supplementary Table S3*. Co-products of the annual production of the average vegan diet for one person as described in Supplementary Table S1.*

Co-products, fresh basis	kg/ person/year
Molasses	2
Potato cuttings	2
Potato peels	1
Potato starch, dried	1
Soybean hulls	9
Soybean meal	55
Sugar beet pulp	15
Wheat bran	19
Wheat germ	3
Wheat middlings	20
Total	129

During the processing and consumption of food, about one third is wasted according to the FAO (Gustavsson et al. 2011). In developed countries people throw away 95-115 kg food per year. Food is spilled mainly when production exceeds consumers demands and during the consumption stage when people throw food away which is still suitable for human consumption. In developing countries 6-11 kg of food is wasted (compared with the 95-115 kg in developed countries). This is mostly due to e.g. technical limitations and limited available infrastructure. To reduce the environmental impact it is essential to reduce the amount of food wasted as all food waste results in a loss of resources and unnecessary environmental impact. Nevertheless, it is unlikely to entirely prevent waste of food and, therefore, we assumed that a part of our food will always be wasted. These products can be used as livestock feed. In order to estimate the amount of food waste available for livestock we assumed that 10% of the vegan diet (Supplementary Table S1) is wasted (Supplementary Table S4).

We assume that the co-products and waste products of the vegan diet are fed to pigs (see main paper for explanation). However, some co-products and waste products are less suitable for pigs, because of their low digestibility in monogastrics or because of limitations of the feeding system. We, therefor, did not take those products (vegetables, raw potatoes and fruit) into account.

Supplementary Table S4*. The amount of food waste available for animal production, based on the assumption that 10% of the average vegan diet is (Supplementary Table S1) wasted.*

Food waste	kg /person/ year
Apples	10
Bread meal	3
Potato chips	3
Potatoes	3
Soybeans	6
Sugar	1
Soy oil	2
Vegetables	11
Wheat flour	10
Total	46

Assessing the nutrient content of co-products and waste products used as pig feed

To estimate the nutrient content (Supplementary Table S5) of one kg of feed based on co-products and food waste, a commercial linear programming tool (i.e. Bestmix®, Adifo, Maldegem, Belgium) with CVB (2010) database of feed ingredients was used. The diet composition was for almost 99% based on the use of the co-products and waste products in the available ratio (Supplementary Tables S3 and S4). One percent was left to add a premix to provide minerals and vitamins, including limestone and salt.

***Supplementary Table S5**. Diet and nutritional composition of pig feed, based on the use of co-products (Supplementary Table S3) and waste products (Supplementary Table S4) in the available ratio on product basis (with the exception of wet products, which were recalculated to a DM content of 880 g/kg).*

Ingredients	**%**	Nutrient content, g/kg	
Soybean meal RC<45 RC<480	37.0	Dry matter content	880
Wheat middlings	13.9	Net energy, MJ	8.27
Wheat bran	13.4	Lysine (SID[2])	12.7
Wheat feed flour	7.0	Methionine (SID)	3.3
Soybean hulls RC 320-360	6.5	Cysteine (SID)	3.4
Sugar beetpulp <100	5.3	Threonine (SID)	8.0
Soybeans heat treated	3.8	Tryptophan (SID)	2.9
Wheat grem	2.2	Phosphorus	6.2
Potato cut pre fried	2.2	Crude protein	261
Bread meal	2.0	Crude fat	48
Sugar beet molasses	1.7	Crude fibre	76
Salt	1.3		
Oil (soy)	1.1		
Potato starch (dried)	0.8		
Sugar	0.9		
Premix[1]	0.4		
Potato peels steamed	0.5		

1 Including 500 FTU of microbial phytase to enhance phytate degradation and phosphorus digestibility
2 SID, standardised ileal digestible

Assessing the amount of protein from pigs fed with co-products and waste products

In order to calculate the amount of protein from pig meat we used the energy and lysine required to produce a growing pig of 116 kg calculated by Van Zanten et al. (2015). In addition, feed is needed for piglet production. Piglet production includes rearing gilts and sows and their piglets needed for the production of finishing pigs. The energy and lysine for growing pigs, piglets, gilts and sows in the required ratio as based on Van Zanten et al. (2015) is summarised in Supplementary Table S6.

***Supplementary Table S6**. Energy (NE) and digestible lysine required to produce a growing pig of 116 kg, for the required piglet and the related sows and gilts (Van Zanten et al., 2015).*

	Feed intake	NE (MJ) g/kg	LYS g/kg	NE (MJ)	Lysine, g	Lysine/MJ
Growing pig	226	9.59	7.59	2167	1715	0.79
Piglets	30	9.68	11.70	290	315	1.08
Gilt	6.7	9.24	8.99	62	32	0.60
Sow	40	9.06	7.42	362	297	0.82

The results in Supplementary Tables S5 and S6 show that energy is the limiting nutrient. In total 2878 MJ NE is needed to produce one slaughter pig and 1215 MJ NE is available from the composed feed based on co-products and food products. So in total 0.42 pig produced, equal to 49 kg live weight of pig per person per year (0.42 * 116 kg slaughter pig). Using a conversion factor of 0.53 from live weight to edible product and 0.19 from edible product to edible protein (De Vries and De Boer, 2010), an estimated 14 grams of pork protein is available per person per day.

We acknowledge that the energy concentration of the feed (8.27 MJ NE/kg) is relatively low and may limit the energy intake and growth rate of the growing pigs (e.g. Quiniou and Noblet, 2012). Thus, it may be questioned whether growing pigs are able to realise the same growth performance with the feed containing co-products and waste products as growing pigs fed with conventional feed. Nevertheless, feed intake capacity and optimal energy concentration differ between growing pigs, piglets, gilts and sows. Hence, optimizing the diet composition for each of the different groups of pigs and targeted allocation of co-products and waste products can be used to optimise the conversion of feed to pork.

Assessing the amount of protein from ruminants grazing on marginal land

The model of Herrero et al. 2013 was used to calculate the amount of protein available per tropical livestock units (TLU) from marginal lands. Herrero et al. (2013) assessed the global number of TLU over several regions of the world. For each region of the world it was defined whether ruminants systems were 100% grass-based. Supplementary Table S6 shows the % of dairy cattle, beef cattle and sheep and goat per ha on 100% grass-based systems on marginal land worldwide and the related average protein production from milk and meat per TLU. Based on this, we calculated the average amount of protein from milk and meat per TLU produced on 100% grass-based systems on marginal land. Average protein production per TLU was 14.14 kg per year (the factor 0.19 to convert from kg edible meat product to kg protein was used and 0.03 to convert from kg milk to kg protein for dairy cattle and 0.04 for sheep and goats). Livestock density was calculated with the model of Herrero et al. (2013) and was 0.5 TLU per ha on marginal land. The area of marginal land, based on GAEZ, was 1.6 billion ha. Based on the above mentioned assumptions, 3 gram of protein per person per day can be produced in 2050 (((14.14 kg protein per TLU*0.5 TLU per ha*1.6 billion ha)/9.7 billion people*1000)/365 days).

Grazing occurs also in other areas besides marginal lands. Those areas currently used for grazing are to a certain extend suitable for crop production (Alexandratos and Bruisma, 2012). Expanding the area for crop production in these areas will, therefore, lead to a reduction of grazing land. Although these areas are to a certain extend suitable for crop production, they are not yet in use for crop production. We, therefore, made a second calculation in which we assumed all 3.34 billion ha of permanent meadows and pasture are used for 100% grass-based systems. Supplementary Table S7 shows the % of dairy cattle, beef cattle and sheep and goat per ha on 100% grass-based systems on grassland and the related average protein production from milk and meat per TLU. Protein production per TLU was 14.47 kg per year (average of dairy cattle, beef cattle and sheep and goats). Livestock density – 0.5 TLU per ha - was based on the density of TLU on marginal land. Furthermore, Smil (2012) as well assumed that a livestock density of 0.5 TLU per ha is maximal to prevent degraded grasslands due to overgrazing. Based on the above mentioned assumptions, 7 gram of protein per person per day can be produced in 2050 (((14.47 kg protein per TLU*0.5 TLU per ha*3.34 billion ha)/9.7 billion people*1000)/365 days).

Supplementary Table S7. *% of tropical livestock units (TLU) in 100% grass-based ruminant systems with their related protein production*.

	TLU %	Milk protein (kg/tlu/year)	Meat protein (kg/tlu/year	Protein / %TLU kg/TLU
Marginal land				
Dairy cattle	20	17.25	6.32	4.68
Beef cattle	60		6.8	4.08
Sheep and goat	20	15.53	11.13	5.38
Total grassland				
Dairy cattle	5	37.81	7.39	2.24
Beef cattle	86		10.90	9.37
Sheep and goat	9	17.98	13.48	2.86

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