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Supplementary information

Halting European Union soybean feed imports favours ruminants over pigs and poultry

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Halting European Union soybean feed imports favours ruminants over pigs and poultry

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Supplementary Materials

Sensitivity analysis

Model sensitivity to parameters and assumptions deemed likely to have a large impact on results was tested in sensitivity analyses. The results are described below and summarised in Supplementary Figure 1.

S1.sens1

Lifting constraints on maximum herd size

Lifting the constraint on maximum herd size per country, which was originally limited to not exceed herd size in the baseline, had a large impact on the potential protein supply from EU livestock, e.g. in scenario S1 total protein supply from animal-source food then exceeded the supply in the baseline, a 38% increase compared with the original S1 scenario. However, this relied on a dramatic restructuring of the EU livestock sector. Egg production increased almost four-fold compared with the baseline (Supplementary Figure 1c). Raw milk supply was also larger than in the baseline (Supplementary Figure 1d), mainly as a consequence of increased numbers of sheep and goats. Pig meat production decreased dramatically (Supplementary Figure 1a). The increased protein supply in that scenario led to a 3 Mha decrease in demand for cropland outside the EU compared with the original S1 scenario (Supplementary Figure 1h), since use of land required for soybean to replace animal-source protein in human diets was avoided. While this sensitivity analysis showed that animal-source protein supply could be increased while avoiding soybean imports, further reducing land demand abroad, it would rely on drastic consumption changes or increased international trade and a less diverse EU livestock sector than in the original S1 scenario.

S1.sens2

Edible fraction of pig and poultry meat increased

We relied on literature values to find the fraction of carcass weight that is edible meat. The values reported ranged from 0.59 to 0.75 for pig meat[1-5] and 0.55 to 0.80 for poultry meat[2-6]. For beef[1,3-5,7] the variation is smaller (range 0.64-0.72). In this sensitivity analysis, we tested whether increasing the edible fraction of pig and poultry meat, thereby making that production more favourable, affected the observed favouring of ruminants in the optimisation model. The highest values available were therefore used for pig and poultry meat (i.e. 0.75 and 0.80, respectively), while default values were kept for ruminant meat. The results showed no reallocation of feed resources from ruminant toward pig and poultry meat production (Supplementary Figure 1d-e). The conclusion that ruminant production is favourable in utilising available feeds was thus robust to changes in this model parameter. Limited reallocation of feed resources from poultry toward pig meat was observed, however (Supplementary Figure 1a,b). This can be explained by the default edible fraction for poultry meat already being close to the highest value.

S1.sens3

Lifting constraints limiting reallocation of EU grains from one country to another

In the scenarios, cereals and other grains used directly for feed were constrained on country level, so a surplus of these feeds in one EU country could not be reallocated to other EU countries. This was to ensure that the land base for livestock production in any given country would not be reduced compared with the current situation. Lifting this constraint and allowing feed grain to be reallocated between countries resulted in higher utilisation of cereals in the scenario and thus less land was made available for producing protein-rich feeds (4.0 Mha instead of 7.7 Mha). This resulted in a slight reduction in animal-source protein supply (-4%) (Supplementary Figure 1f) compared with the original S1 scenario. This, together with higher utilisation of imported non-EU feed cereals, led to a 0.9 Mha increase in demand for cropland outside the EU compared with the original S1 scenario (Supplementary Figure 1h).

The optimisation model used was designed to maximise protein provision from feed resources currently available in the EU along with feeds introduced in the different scenarios. Therefore it did not explore the complete option space for optimising EU cropland use for efficient protein supply. An approach where all cropland use is optimised would lead to different results, potentially enabling a larger protein supply from animal-source food. However, it would also lead to scenarios deviating further from the current situation in terms of what crops are produced where, and rely on more profound restructuring of EU crop production.

S1.sens4

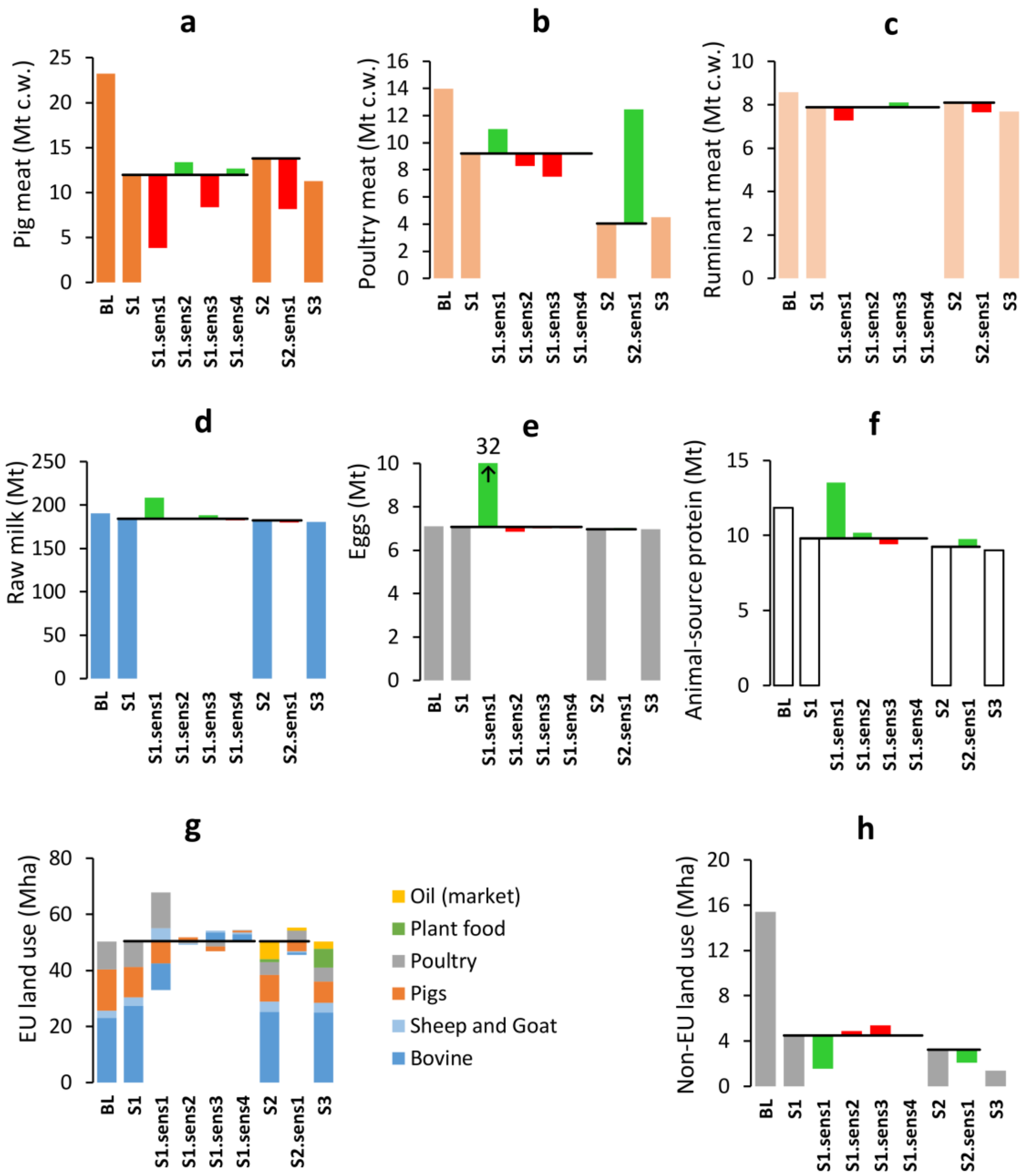
Using unadjusted CAPRI feed rations

The feed rations used in this study were sourced from the CAPRI-model. However, inclusion of roughage feeds were adjusted prior to running the model (see methods section). The sensitivity of the model to these adjustments were tested for scenario S1. Using the unadjusted CAPRI feed rations only marginally affected model results and did not change any of the main conclusions of the results. Since the unadjusted feed rations generally contained more roughages, EU land use for feed production increased in the baseline from 50 Mha to 54 Mha as compared to using the adjusted rations (Supplementary Figure 1g). Only very marginal changes were observed for non-EU cropland use (Supplementary Figure 1h) and animal-source protein supply (Supplementary Figure 1f) compared to the original S1 scenario.

S2.sens1

Lifting constraints on maximum inclusion of rapeseed meal in pig and poultry diets

Maximum inclusion of rapeseed and sunflower seed meals was limited for pigs and poultry in the model. However, developments in plant breeding have reduced the presence of anti-nutritional substances in rapeseed meal and higher inclusion rates have been tested without adverse effects on animal health and productivity[8]. Model sensitivity to these constraints was therefore tested for scenario S2 (EU vegetable oil scenario), which was likely to be most sensitive to this constraint. The analysis showed that poultry meat was limited by the constraint and lifting it led to reallocation of rapeseed meal mainly from pigs to poultry (Supplementary Figure 1a-b) due to more favourable feed conversion ratios. Lifting the constraint led to a 6% increase in total edible protein from animal-source food (Supplementary Figure 1f) and subsequently a 1 Mha reduction in demand for land outside the EU for soybean and vegetable oil production (Supplementary Figure 1h). In scenario S2, the weighted average inclusion of rapeseed meal was 15% and 9% of dry matter in pig and poultry rations, respectively, which changed to 12% and 20%, respectively, when constraints were lifted.

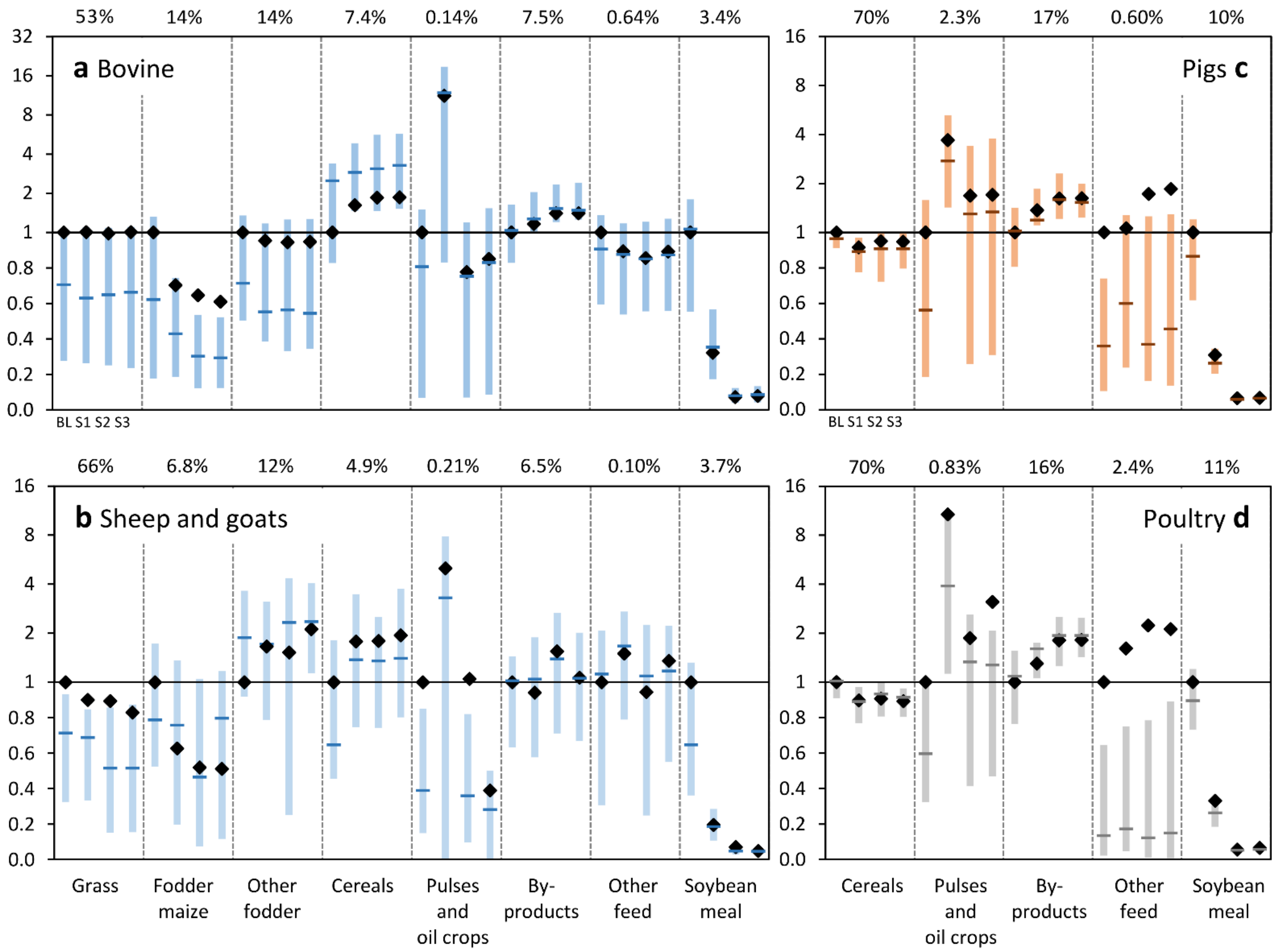


Supplementary Figure 1. (a-e) EU production of animal-source food under the original scenarios and in sensitivity analyses (indicated as deviations from the original scenarios).(f) Edible protein supply from animal-source food. (g, h) EU and non-EU cropland use, respectively.

Supplementary results

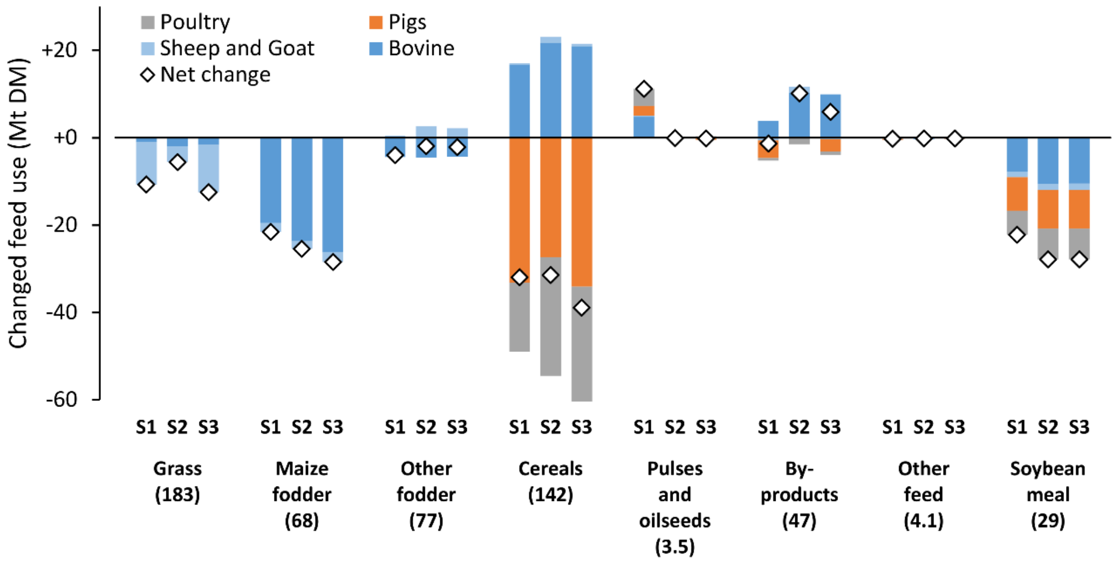
Feed rations and use

In scenarios S1-S3, inclusion of soybean meal in animal feed rations was reduced. In order to maintain nutritional adequacy of livestock diets, inclusion of other feed components was adjusted. For monogastric animals (pigs and poultry), this involved reduced inclusion of cereals and higher inclusion of pulses and protein-rich by-products (Supplementary Figure 2c,d). Inclusion of cereals in monogastric animal diets was reduced because the pulses and by-products replacing soybean meal in the scenarios generally contain less protein per unit energy. For ruminants, inclusion of maize silage was reduced and, perhaps counterintuitively, inclusion of cereals was increased (Supplementary Figure 2a,b). This is likely due to replacement of fodder maize with cereals with a higher protein:energy ratio, which allowed for lower inclusion of the protein-rich feeds that were of limited supply in the scenarios.



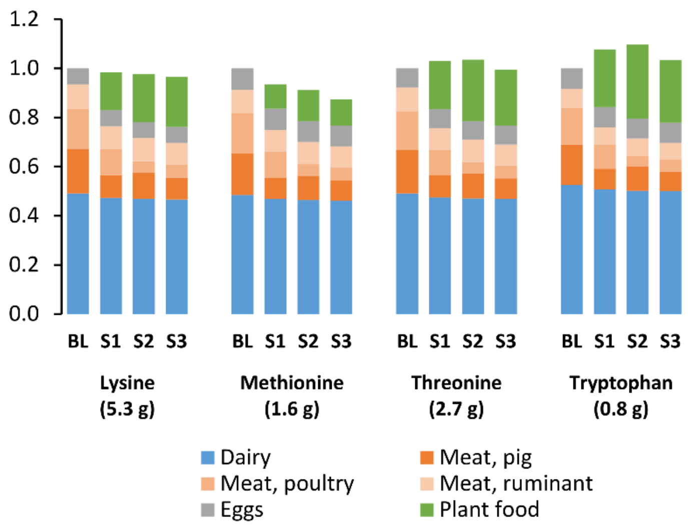
Supplementary Figure 2. Composition (% of dry matter) of feed rations under the different scenarios for (a) cattle, (b) sheep and goats, (c) pigs and (d) poultry, normalised to the EU weighted average ration in baseline (BL) (shown on top of each panel). Diamonds show the EU weighted average, horizontal lines the median ration composition and vertical bars the variation including 50% of EU countries (25-75th percentile). Diamonds may appear above the 75th percentile in cases where one or more countries with a large number of animals also has a large inclusion of that feed in animal diets. For each feed, the inclusion is presented from left to right for the BL, S1, S2 and S3 scenarios. Note that the scale on the horizontal axis changes from linear for values <1 to logarithmic for values >1.

These changes in animal feed rations, together with changes in animal numbers, led to reduced total use of cereals and maize fodder and reallocation of feeds between different animal categories (Supplementary Figure 3). Protein-rich by-products, such as rapeseed and sunflower seed meal, were reallocated from pigs and poultry to ruminants, while e.g. low-grade potatoes and vegetables were not fully utilised in the scenarios due to their low energy and protein density. In scenario S1, use of pulses for animal feeding was increased almost four-fold, but from relatively low inclusion in the baseline. Rapeseed oil production introduced in scenarios S2 and S3 led to increased total use of by-products in the form of rapeseed meal.



Supplementary Figure 3. Total use of different feeds in the scenarios, expressed as change from total use of that feed in the baseline (shown in brackets). Coloured bars show increased (positive) or decreased (negative) use per livestock category and diamonds show the total change in feed use. S1 = feed crops scenario, S2 = oil crops scenario, S3 = food crops scenario.

Supply of essential amino acids

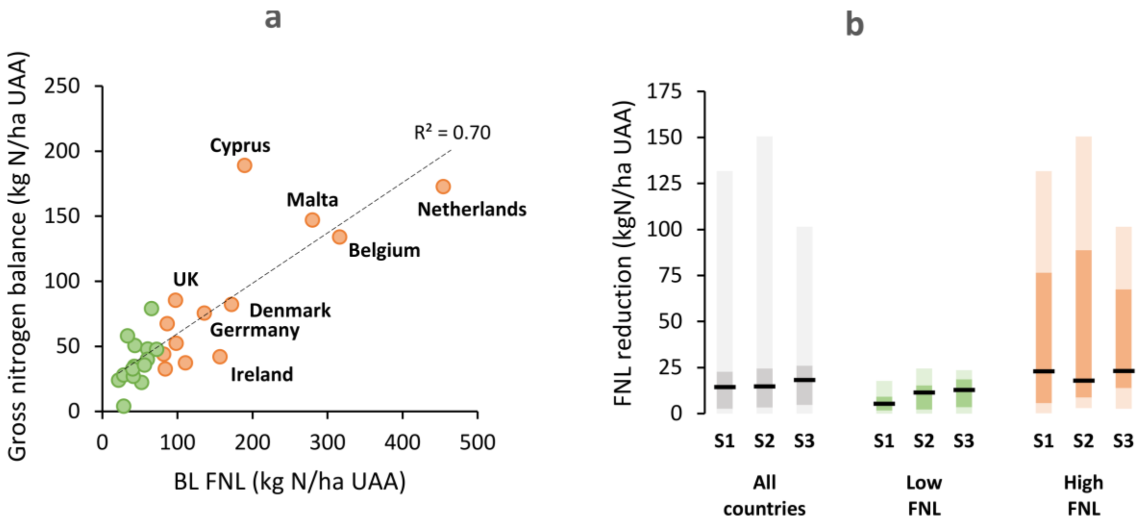


Supplementary Figure 4. Essential amino acids in edible parts of animal-source foods produced in the EU and in plant foods that compensated for reduced edible protein and fat supply from animal-source foods in the scenarios. The supply of amino acids is normalised to the supply in the baseline (shown in brackets). BL = baseline, S1 = feed crops scenario, S2 = oil crops scenario, S3 = food crops scenario.

Feed use nitrogen load

Our analysis showed that all scenarios are likely to reduce nitrogen surpluses, especially in EU countries currently with large surpluses (Supplementary Figure 5). There was a clear link between FNL and gross nitrogen balance for EU countries (Supplementary Figure 5a). This indicates that lower FNL can improve the nitrogen balance and mitigate eutrophication and other environmental impacts related to excess nitrogen. In scenarios S1-S3, the EU average FNL declined by 17-22% due to reduced feed use and livestock production. In countries where FNL is currently high (i.e. countries with a high risk of nitrogen surplus), the decline was greater (Supplementary Figure 5b). These countries

(e.g. the Netherlands, Belgium, Denmark, Germany) currently cause the greatest emissions of nitrogen to air and water per unit area in the EU[9].



Supplementary Figure 5. (a) Gross nitrogen balance for 2012-2015 according to Eurostat as a function of baseline (BL) feed use nitrogen load (FNL). Green dots represent countries with low FNL (≤EU median) and orange dots countries with high FNL (>EU median). (b) Reduction in FNL under scenarios S1-S3 for all (n=27), low (n=14) and high (n=13) FNL countries. Horizontal lines show the weighted average FNL reduction for the group, dark shaded bars include 50% of countries in the group (25-75th percentile) and light shaded bars show the maximum and minimum values.

Supplementary discussion

Model assumptions and limitations

The intensity of EU livestock production was assumed to remain unchanged in the scenarios assessed, and thus animal diets would need to satisfy the same nutritional requirements as current EU livestock production systems. It is not obvious that the current high-input, high-output livestock systems in most EU countries are the most efficient when the quality of available feeds are reduced. For example, van Hal et al.[10] demonstrated that when only non-food-competing feeds are used, less intensive livestock systems are preferable to high-yielding systems where nutritional needs are greater. Introducing further flexibility in our model could allow for changes in livestock production intensity, and thereby nutritional requirements, potentially enabling greater EU production of animal-source food than shown here. However, the effect on our scenarios, where only one feed source was removed (i.e. imported soybean), is likely not as great as that observed by van Hal et al.[10], where all food-competing feeds were excluded from livestock rations.

In this study, we only included feed sources commonly used in EU livestock production and did not introduce any novel feed sources such as insects or algae. Using insects to tap into unutilised resources such as food waste has received increasing attention in the scientific literature[11,12]. However, production of insects to replace soybean meal is still in a preliminary phase and, in order to become a sustainable feed source, ‘waste’ streams (e.g. food waste or manure) should be used to produce the insects and changes in EU legislation are required[13]. Using novel techniques to access currently underutilised resources could increase the level of livestock production without imported soybean compared with results presented here.

To calculate land use from soybean cultivation, we used national yields averaged over the period 2014-2016. However, yields vary within countries and reduced soybean demand will likely affect the least productive regions first, which would result in a larger difference in land use between the baseline and our scenarios. For example in Brazil regional yields vary by roughly ±10%[14] around the national average, while in the US yields range from -26% to +17%[15] of the national average for the 10 states with largest harvested soybean area. Another source of uncertainty is the selected reference years. In the period 2010-2016, annual Brazilian soybean yields varied from 2.6 to 3.1 t/ha, with an average for the 2014-2016 period of 2.9 t/ha[16].

For the land use calculations we used a consequential approach where e.g. soybean meal bore the full land use from soybean cultivation and reduced production of the associated soybean oil was handled by assuming additional production of the marginal oil traded on global markets (i.e. palm oil). An alternative approach is to use allocation based on e.g. economic value to handle by-products. In that case, the full land use from soybean cultivation would be split between the meal and oil based on their respective economic value. This would yield different results. However, when studying large-scale changes allocation can yield biophysically unfeasible results, as mass and energy balances are not preserved[17] and as it is implicitly assumed that soybean oil production could continue even though soybean meal production is reduced, which is not possible. Our approach rests on the assumption that demand for one of the co-products is the sole driver of production, while in reality a complex mix of economic and policy drivers often determine production, where the latter may be affected through e.g. lobbying by different stakeholders.

Inclusion of food legumes in the scenarios more than doubled dietary iron supply, but it should be noted that in meat some iron is in haem form, while in other animal- and plant-source foods iron is only found in non-haem form, which has lower bioavailability to humans[18]. The USDA FoodData Central, on which we relied for nutrition data, also reports relatively high iron content of soybean compared with other sources. Assuming 30% bioavailability for haem iron, 5% for non-haem iron and that 40% of the iron in meat is in haem form, all scenarios still supplied more bioavailable iron than the baseline. This was still true when assuming half the iron content of soybean and other pulses compared with values in the USDA FoodData Central. Dietary changes in line with the scenarios presented here would therefore with high confidence increase the supply of bioavailable iron to EU diets.

The average requirements for vitamin A are given in terms of retinol equivalents (RE) in the EU dietary reference values[19], while in the data source we used for nutrition data (USDA FoodData Central) vitamin A is expressed as retinol activity equivalents (RAE)[20]. RAE assumes lower bioavailability of dietary provitamin-A carotenoids[20] and thus results in lower values, especially for plant-source foods. Using RE instead would have resulted in a greater vitamin A supply from the additional plant-source foods introduced in the scenarios. We decided to use RAE in order to avoid overestimating the contribution of plant-source foods to vitamin A supply.

The calculation of nutrients supplied from animal-source foods and supplementary plant-source foods was based on the raw edible fraction (i.e. excluding bones, eggshells etc.), but did not account for changes in nutrient composition during processing and cooking. The fraction wasted post farm-gate or animal-source food exported from the EU was also not accounted for. However, the net trade balance for animal-source food is relatively limited, with around 10%, 6% and 2% of milk, meat and eggs produced being exported from the EU, according to FAOSTAT[21]. The majority of animal-source food produced is thus consumed within the EU and nutritionally sustains the EU population. Reliable estimates on the fraction of animal-source food that is wasted are currently lacking. A global assessment of food losses and waste estimated that in Europe, around 20% of meat and 10% of milk are lost or wasted after leaving the farm[22]. For meat, part of these losses refer to trimmings during slaughter, which were accounted for in the edible fraction used in this study. Due to lack of reliable data on food waste, we chose not to include it in our calculations. Therefore comparisons of nutrients present in animal-source food to population nutrient requirements must be made with caution.

We relied on trade data for 2014-2016 to estimate where in the world demand for cropland would decline with cessation of soybean imports for feed to the EU. However, soybean is traded on a volatile global market where geopolitical events can influence trade flows, e.g. the current US-China trade war is causing exports of US soybean to China to plummet[23]. Simultaneously, the US passed Brazil as the main supplier of soybean to the EU in the first months of marketing year 2018/19[24]. Trade flows did however recover the following year, putting Brazil back as the number one supplier of soybean to the EU. Nonetheless, selected reference years influences the extent to which reduced non-EU cropland demand can affect cropland demand in deforestation-prone regions, although we argue that total global demand for soybean is the primary driver of deforestation.

Feed use nitrogen load

Sharp increases in soybean and other feed imports during the past half-century have contributed to livestock production becoming specialised and concentrated to livestock-dense regions[25]. Nitrogen and phosphorus embedded in

in feed imports flow into livestock-dense regions with insufficient land for spreading the manure, leading to nutrient surpluses that affect regional air, soil and water quality[25,26]. In our scenarios, reduced livestock numbers and FNL were more pronounced in countries where the nitrogen balance is currently high, indicating that livestock density would need to decline in these countries in order to reverse EU soybean import dependency. This would potentially be helpful in mitigating negative effects of nutrient surpluses. However, nutrient pollution is often an effect of livestock concentrations in small regions within a country, so reduction of livestock numbers in general is not always sufficient to alleviate such problems. For this reason, adoption of practices such as manure processing technologies (i.e. anaerobic digestion, gasification, composting)[27], manure redistribution[28] and manure separation into solid (rich in P) and liquid (rich in N) fractions[29] might be needed to reduce pollution problems at sub-national level.

Supplementary tables

Supplementary Table 1. Inclusion of roughages (% of dry matter) in the feed rations of ruminant animals used in this study, and unadjusted values directly derived from the CAPRI model. Both EU weighted averages and the medians of EU countries are presented. Numbers in brackets show the difference after adjustments. For comparison, values from the GLEAM model for Western Europe[30] are also shown

	CAPRI (unadjusted)		CAPRI (this study)		GLEAM[30]
	EU	Median	EU	Median	Western Europe
Dairy cows					**Dairy cattle**
Total roughage	82	73	76 (-6)	66 (-8)	75
Grass	56	47	49 (-6)	35 (-13)	50
Maize	16	4	15 (-1)	6 (+1)	-
Other	10	5	11 (+1)	5 (0)	-
Other cattle and buffalo					**Beef cattle**
Total roughage	90	85	86 (-4)	81 (-4)	76
Grass	65	54	56 (-9)	44 (-10)	50
Maize	13	8	13 (+1)	10 (+2)	-
Other	13	16	17 (+4)	17 (+1)	-
Sheep and goats					**Small ruminants** (beef/dairy)
Total roughage	86	83	85 (-1)	83 (0)	90/67
Grass	61	45	66 (+5)	47 (+2)	67/44
Maize	7	8	7 (-1)	5 (-2)	-
Other	17	24	12 (-5)	22 (-2)	-

Supplementary Table 2. Animal species-dependent constraints on nutritional characteristics of feed rations used to ensure that rations in the scenarios were of equal nutritional quality to the baseline feed rations

Animal	Parameter	Constraint
Cattle, buffalo, sheep and goats	Metabolisable energy (ME)	≥ ME in baseline ration
	Digestible crude protein (DCP)	≥ DCP in baseline ration
	Total feed intake (as fed)	≤ Total feed intake in baseline ration
Pigs	Net energy (NE)	≥ NE in baseline ration
	Digestible crude protein (DCP)	≥ DCP in baseline ration
	Total feed intake (as fed)	≤ Total feed intake in baseline ration
	Lysine	≥ Lysine in baseline ration
	Methionine	≥ Methionine in baseline ration
	Rapeseed meal	≤ 15% of NE
	Sunflower seed meal	≤ 10% of NE
Poultry	Apparent metabolisable energy N-corrected (AMEn)	≥ AMEn in baseline ration
	Crude protein (CP)	≥ CP in baseline ration
	Total feed intake (as fed)	≤ Total feed intake in baseline ration
	Lysine	≥ Lysine in baseline ration
	Methionine	≥ Methionine in baseline ration
	Rapeseed meal	≤ 10% of AMEn
	Sunflower seed meal	≤ 20% of AMEn

Supplementary Table 3. Assumed losses of feed during storage, handling and feeding

Feed	Losses (%)
Grains	5
Oil meals	5
By-products (dry)	5
By-products (wet)	15
Grass from permanent grasslands*	0
Crops harvested green (other than grass from permanent grasslands)	20
Fodder roots	15

*Grass from permanent grasslands was defined in the model rations as grass consumed by animals, so no losses apply to this category.

Supplementary Table 4. Assumed edible fraction of food items produced

Food item	Edible fraction	Source
Raw milk	0.9	Own estimate based on raw milk production and feed rations used in this study
Cattle and buffalo meat	0.695	Clune et al.[31]
Sheep and goat meat	0.66	Clune et al.[31]
Pig meat	0.59	Clune et al.[31]
Poultry meat	0.77	Clune et al.[31]
Eggs	0.99	Own estimate accounting for the weight of eggshells
Soybean	0.8	Wilkinson[32]
Other pulses	0.8	Wilkinson[32]
Vegetable oil	1	Own estimate

Supplementary Table 5. Food items used in the study and their division into different cuts/subcategories, with corresponding USDA FoodData Central food ID codes used to access the nutritional composition of the food. Where multiple food IDs are presented, the average value was used

Food item	Cut/sub cat.	Fraction	USDA FoodData Central food ID
Meat			
Bovine meat	Chuck	0.29	13786, 23137, 23143, 23093, 13809, 13815, 23122, 23128, 23053, 23057, 23059, 23108, 23102
	Loin	0.16	23336, 23342, 23388, 23281, 23001, 23005, 13909, 23290
	Rib	0.09	23192, 23236, 13838, 13147, 13850, 13824
	Round	0.22	13868, 23330, 23061, 23055, 23063, 13883, 13891
	Thin cuts	0.19	13803, 13970, 23217, 23224
Sheep and goat meat	Loin	0.16	17023
	Rib	0.12	17029
	Shoulder	0.24	17055
	Leg	0.28	17011
	Misc.	0.20	17007, 17224
Pig meat	Belly	0.21	10005
	Spareribs	0.06	10088
	Loin	0.24	10020
	Ham	0.27	10008
	Picnic	0.10	10074
	Shoulder	0.11	10080
Poultry meat	Legs	0.33	5075
	Breast	0.35	5057
	Back	0.20	5048
	Wings	0.11	5100
	Fat	0.01	5047
Eggs	-	-	1123
Milk			
Cattle milk	-	-	1211
Buffalo milk	-	-	1108
Sheep and goat milk	Sheep	0.54	1109
	Goat	0.46	1106
Plant-source food			
Soybean	-	-	16108
Broad bean	-	-	16052
Peas	-	-	16085
Vegetable oil	-	-	4582

Supplementary Table 6. Daily requirements of the nutrients studied here and demographic data used to calculate the requirements of the average EU citizen. Where age groups in the demographic data did not match age groups used for the intake recommendations, the closest intake value was used

				Energy requirements*			Average Requirement (AR)						Adequate Intake (AI)
Age group	Gender	Population in group	Body weight	Energy	Fat (lower)	Fat (upper)	Protein	Iron	Calcium	Zinc	Vitamin A	Riboflavin	Vitamin B_{12}
		%	*kg*	*MJ*	*g*	*g*	*g*	*mg*	*mg*	*mg*	*µg RE*	*mg*	*µg*
<5	F	2.5	9	5.7	54	62	7	5	540	3.6	205	0.5	1.5
	M	2.6	9	6.2	59	67	7	5	540	3.6	205	0.5	1.5
5-9	F	2.6	22	6.7	36	63	16	8	680	5.4	280	0.7	2.0
	M	2.7	22	7.2	39	68	16	6	680	5.4	280	0.7	2.0
10-14	F	2.5	40	8.4	45	79	29	7	960	8.9	480	1.1	3.5
	M	2.6	40	9.1	49	86	29	8	960	8.9	480	1.1	3.5
15-19	F	2.6	57	9.5	51	90	39	7	960	9.9	490	1.4	4.0
	M	2.7	64	11.9	64	113	45	8	960	11.8	580	1.4	4.0
20-29	F	6.0	66	9.0	49	85	44	7	860	9.2	490	1.3	4.0
	M	6.2	79	11.2	61	106	52	6	860	10	570	1.3	4.0
30-39	F	6.7	66	8.7	47	82	44	7	750	9.2	490	1.3	4.0
	M	6.8	79	10.8	58	102	52	6	750	10	570	1.3	4.0
40-49	F	7.3	66	8.6	46	81	44	7	750	9.2	490	1.3	4.0
	M	7.3	79	10.7	58	101	52	6	750	10	570	1.3	4.0
50-59	F	7.0	66	8.5	46	80	44	6	750	9.2	490	1.3	4.0
	M	6.8	79	10.5	57	99	52	6	750	10	570	1.3	4.0
60-69	F	6.1	66	7.8	42	74	44	6	750	9.2	490	1.3	4.0
	M	5.5	79	9.6	52	91	52	6	750	10	570	1.3	4.0
70-79	F	4.5	66	7.7	42	73	44	6	750	9.2	490	1.3	4.0
	M	3.6	79	9.5	51	90	52	6	750	10	570	1.3	4.0
>80	F	3.4	66	7.7	42	73	44	6	750	9.2	490	1.3	4.0
	M	1.9	79	9.5	51	90	52	6	750	10	570	1.3	4.0
	EU weighted averages:												
	F	51	59	8.2	46	78	39	6.5	770	8.8	465	1.23	3.8
	M	49	69	10	56	95	46	6.2	772	9.4	530	1.22	3.7
	F+M	**100**	**64**	**9.1**	**50**	**86**	**43**	**6.4**	**771**	**9.1**	**497**	**1.22**	**3.7**

* PAL=1.6, moderately active

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