TRansition paths to sUstainable
legume-based systems in Europe

Summary of Consequential Life Cycle Assessment

Work Package: 5

Deliverable: 5.4 (D32)

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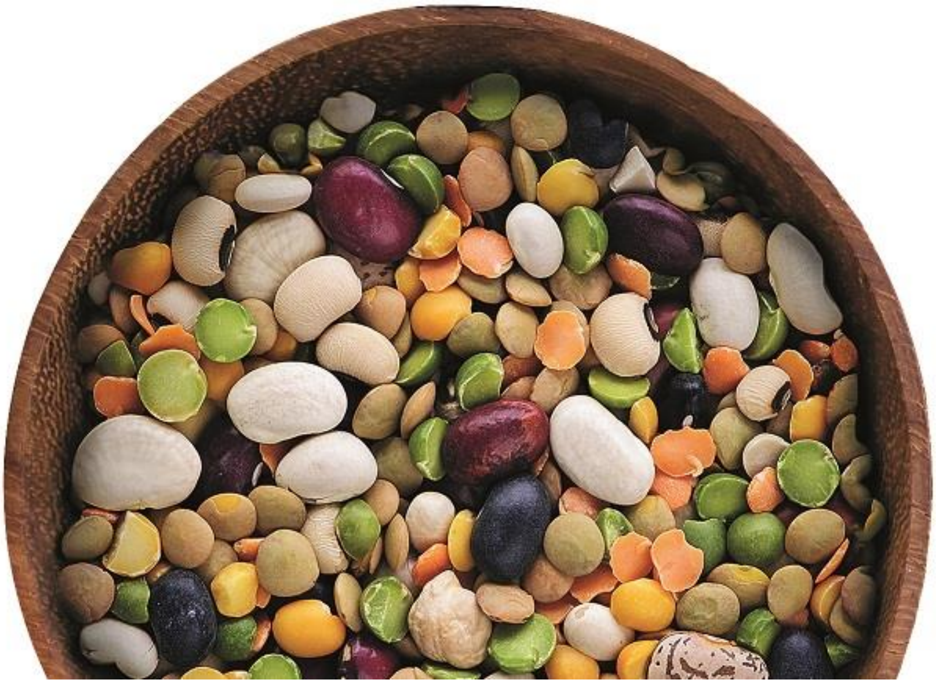

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Deliverable Description & Contributors

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- **Deliverable Description:** This report summarises the consequential life cycle assessment undertaken in WP5 to identify the net environmental effects associated with a transition towards higher legume inclusion in European diets.

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1. Introduction

1.1. Work package 5 objectives

The aim of this work package (WP) is to provide a coordinated Life Cycle Assessment (LCA) of the environmental impact of legume production and processing coupled with a nutri-economic analysis of legume-enriched diets for feed and food. This WP answered the following overarching questions.

- What is the environmental footprint of animal feed and food produced from legumes, considering nutrient cycling and break-crop effects in legume-rotations across major EU agro-climatic zones?
- What are the optimum legume-enriched diets/food choices for improving health, that decrease the environmental footprint –including indirect effects incurred during supply chain transitions -and reduce direct costs to the consumer?

The specific objectives of this WP are as follows.

- Produce a practical report outlining the LCA methodology to be used in TRUE.
- Assess, using attributional LCA, the environmental footprints of legume products, and benchmark against conventional alternatives.
- Assess the European diet in terms of environmental burden and nutrient quality.
- Assess how increasing the proportion of legumes and legume products in the European diet may increase the beneficial nutrient content of diet/food choice but decrease their environmental impact, accounting for rotation and land use effects associated with supply chain transitions. This report.
- Calculate the combined environmental, health and purchase costs of diet/food choices and assess if increasing the proportion of legumes and legume products in these may increase the affordability and environmental sustainability of healthier diets.

1.2. Purpose of this Report

This report provides a summary of the consequential LCA (cLCA) undertaken in WP5 to assess the environmental effects of a *transition* towards a healthier diet containing more legume products. The rationale for this work is to develop a fuller picture of the direct and indirect effects associated with dietary transitions, including agronomic effects, and changes in land requirements that could result in significant land use change. Costa et al. (2021) demonstrated the potential agronomic benefits associated with the integration of legumes into conventional rotations. A recent review found that such effects are not explicitly considered in most attributional LCA studies, which may result in an underestimation of the environmental benefits that could be attributed to legumes in Europe (Costa et al. 2020). The latest footprint studies undertaken in the TRUE project (Saget et al. 2020; Saget et al. 2021; Saget et al. 2021) indicated much lower "carbon opportunity costs" (CoC) for legume substitutes of popular meat-based products, indicating high potential for positive land use change associated with diet transitions incorporating more legume foods.

Thus, there is a need for a cLCA representing both crop rotation and wider land CoC effects, as well as direct e.g. livestock production emission avoidance, associated with diet change in Europe. In this report, methodology and results are summarised for a cLCA of bovine (milk & beef) product substitution by soy milk grown and pea protein balls produced from European soybeans and peas, respectively. These products were chosen owing to the high potential for environmental impact reduction from beef substitution (Eshel et al. 2014), and the complex interaction between milk and beef production systems. During the final stages of TRUE, a wider cLCA was initiated for scenarios where legume-based foods substitute traditional products that are overconsumed, so as to better align with the latest recommendations for an environmentally-sustainable and healthy diet (Willett et al. 2019). Completion of this wider cLCA depends on further data input from collaborators outside of the TRUE project; nonetheless, **Appendix 1** provides a summary of the Methodology developed to date, which provides further evidence to support conclusions on the wider environmental effects of legume-substitution contained in this report.

2. Methodology

2.1. Prelude: Attributional Life Cycle Assessment case studies

2.1.1. Goal, scope, and boundary definition

The case studies presented in this section are comparative attributional LCAs of legume-based products and their traditional counterparts. While more information on the methods can be found in the published articles, this section presents an overview of published studies with the following comparisons:

- pasta made of chickpeas or wheat (Saget et al. 2020);
- burger patties made with pea protein and other plant-based ingredients or beef (Saget et al. 2021);
- protein balls made with pea protein or beef (Saget et al. 2021); and,
- mayonnaise made with chickpea cooking water or egg yolk (Saget et al. 2021).

Company data were collected to produce the life cycle inventories of the legume-based foods. The LCAs were modelled in the open-source software OpenLCA (GreenDelta 2019). System boundaries were from cradle to fork for all products, excepted for the mayonnaise for which the boundaries stopped at the factory gate or to gate. Agri-footprint v. 3.0 (Durlinger et al. 2017) and Ecoinvent v. 3.6 (Wernet et al. 2016) databases were used. A mass-based functional unit was applied to compare all products, followed by a second functional unit aiming to capture basic nutrient density (except for the mayonnaise). The Nutrient Density Unit (NDU) proposed by (Van Dooren 2016) takes into account energy, protein, dietary fibre, and fatty acid contents of a given mass of each food.

2.1.2. Food footprints

Results of the attributional LCAs in which innovative legume-based foods were compared with their traditional alternatives performed within the TRUE project are recorded in **Error! Reference source not found.**. It can be deduced from the Table that additional processing required for legumes in these case studies, and the addition of other ingredients, legume-based foods present an overall significantly lower environmental impact than the traditional foods across most categories, with lower acidification, greenhouse gas emissions, marine and terrestrial eutrophication, and

respiratory inorganics burdens. The only exception was for the mayonnaise, where transport burdens and electricity required for aquafaba processing resulted in a higher overall environmental impact for the legume-based mayonnaise (though this effect was specific to the production location, and would differ with a low-carbon energy source and more efficient supply chain configuration). Trade-offs in environmental burdens were identified for other products, including greater resource and photochemical ozone formation burdens than their traditional counterparts. Normalising the environmental burdens into global person equivalents as per the Product Environmental Footprint (PEF) recommendations (European Commission 2018) showed that these trade-offs were minimal when compared with the categories across which the traditional foods had a higher environmental impact. Notably, land use burdens were significantly higher for the animal-based foods than the legume-based foods, in accordance with other studies (Alandia et al. 2020; Poore and Nemecek 2018). Legume yields were identified as a potential area for improvement, to lower the land occupation of these products compared with cereal-derived products that benefit from the higher yields of cereal crops (which have undergone much more intensive breeding).

As shown in **Error! Reference source not found.**, the environmental benefits of the legume-based foods were further extended when using the NDU as a functional unit, although trade-offs remained across the land use impact category for the pasta comparison, and for "resource use minerals and metals" for the burger comparison, with the Brazilian beef burger having a significantly lower burden for this particular category (owing to extensive production with low inputs). Freshwater ecotoxicity and cancer human health were also significantly lower for the Irish beef burger than for the vegetarian patties. Larger environmental advantages for legume-based products when using the NDU instead of the simple serving-based functional unit suggest that the innovative legume-based foods assessed across these case studies provide more nutrition (or at least a larger quantity of nutrients) at a lower environmental cost. Therefore, these legume-based foods hold significant potential to play a key role in the sustainable transition towards healthier diets with lower environmental impact.

Table 1. Difference between the environmental score of a single serving of the legume product (Chickpea pasta from Bulgaria, BG, or Spain, ES; Pea Protein Balls, PPB; Veggie Burger, VB; Aquafaba mayonnaise, VEG, from Mexico, MX, or Canada, CA) and the traditional product (Wheat pasta; Meat Balls, MB, from Ireland, IE or Brazil, BR; Beef Burgers, BB, from IE, BR South Africa, ZA, US or France, FR; Egg mayonnaise), based on economic allocation of co-products. Table extracted with permission from (Saget et al. 2021).

	Pasta				Pea Protein Balls		Veggie Burger (VB) patties					Mayonnaise	
Legume Product	Chickpea (BG)	Chickpea(BG)	Chickpea(ES)	Chickpea(ES)	PPB	PPB	VB	VB	VB	VB	VB	VEG (MX)	VEG (CA)
Traditional Product	Wheat (0-s)	Wheat (s)	Wheat (0-s)	Wheat (s)	MB (IE)	MB (BR)	BB (IE)	BB (BR)	BB (ZA)	BB (US)	BB (FR)	EGG	EGG
Acidification	-37%	-33%	-68%	-66%	-95%	-81%	-91%	-50%	-88%	-83%	-80%	21%	-17%
Cancer human health	18%	20%	-2%	-1%	-78%	-99%	80%	-99%	-71%	89%	82%	16%	6%
Climate change	-21%	-17%	-45%	-42%	-85%	-89%	-67%	-77%	-68%	-72%	-71%	80%	13%
Ecotoxicity freshwater	35%	37%	17%	19%	-81%	-100%	185%	-95%	419%	-49%	382%	-7%	-9%
Eutrophication freshwater	-37%	-37%	-50%	-50%	-75%	-63%	-63%	3%	-91%	-55%	50%	134%	-11%
Eutrophication marine	-22%	-6%	-86%	-83%	-96%	-93%	-92%	-87%	0%	-87%	-60%	3%	-7%
Eutrophication terrestrial	-38%	-34%	-76%	-74%	-97%	-87%	-96%	-80%	-94%	-92%	-92%	-9%	-26%
Ionising radiation, HH	-43%	-43%	-46%	-46%	-43%	-43%	-29%	-31%	500%	-4%	100%	153%	2429
Land use	177%	200%	149%	169%	-89%	-97%	-87%	-96%	-98%	-86%	-89%	-11%	-11%
Non-cancer human health	115%	120%	84%	87%	-71%	-100%	-91%	-100%	-78%	-89%	-91%	-3%	-7%
Ozone depletion	-10%	-9%	-25%	-25%	-29%	-41%	36%	-9%	-9%	-17%	-24%	128%	30%
Photochem. ozone form.	8%	11%	-13%	-11%	-82%	-75%	-9%	43%	150%	-23%	67%	46%	6%
Resource use, energy	-25%	-25%	-36%	-36%	-57%	-44%	-29%	8%	0%	-67%	-10%	129%	163%
Resource use mins. &	56%	68%	-55%	-51%	-99%	-23%	-92%	741%	-100%	-100%	-99%	-9%	-11%
Respiratory inorganics	-34%	-31%	-63%	-61%	-96%	-82%	-91%	-58%	-88%	-86%	-80%	6%	-11%
Water scarcity	-30%	-30%	-40%	-40%	-74%	-37%	-71%	-2%	-26%	-93%	NA	-4%	389%

Green shading means that the legume product has a significantly (p<0.05) lower burden than the traditional product, red significantly higher, and white non-significant. (0-s) = no straw harvest; (s) = 80% straw harvested (allocation).

Table 2. Difference between the environmental score of one nutrient density unit of the legume product (Chickpea pasta from Bulgaria, BG, or Spain, ES; Pea Protein Balls, PPB; Veggie Burger, VB) and one nutrient density unit of the traditional product (Wheat pasta; Meat Balls, MB, from Ireland, IE or Brazil, BR; Beef Burgers, BB, from IE or BR), based on economic allocation of co-products. Figure extracted with permission from (Saget et al. 2021).

	Pasta				Protein balls		Burger patties	
Legume Product	Chickpea(BG)	Chickpea(BG)	Chickpea(ES)	Chickpea(ES)	PPB	PPB	VB	VB
Traditional Product	Wheat (0-s)	Wheat (s)	Wheat (0-s)	Wheat (s)	MB (IE)	MB (BR)	BB (IE)	BB (BR)
Acidification	-75%	-74%	-86%	-85%	-97%	-86%	-95%	-78%
Cancer human health	-54%	-53%	-62%	-61%	-84%	-99%	-88%	-99%
Climate change	-69%	-68%	-78%	-77%	-88%	-91%	-79%	-86%
Ecotoxicity freshwater	-47%	-47%	-54%	-54%	-87%	-100%	76%	-97%
Eutrophication freshwater	-75%	-75%	-80%	-80%	-78%	-67%	-83%	-50%
Eutrophication marine	-69%	-63%	-95%	-94%	-97%	-95%	-94%	-91%
Eutrophication terrestrial	-76%	-74%	-90%	-90%	-98%	-90%	-97%	-88%
Ionising radiation, HH	-78%	-78%	-79%	-79%	-61%	-61%	-56%	-58%
Land use	9%	17%	-2%	5%	-92%	-98%	-92%	-98%
Non-cancer human health	-16%	-14%	-28%	-27%	-80%	-100%	-95%	-100%
Ozone depletion	-65%	-64%	-71%	-70%	-49%	-59%	-18%	-45%
Photochem. ozone formation	-58%	-57%	-66%	-65%	-86%	-80%	-75%	-60%
Resource use, energy carriers	-71%	-71%	-75%	-75%	-69%	-60%	-56%	-34%
Resource use mins. & metals	-39%	-34%	-82%	-81%	-99%	-45%	-95%	415%
Respiratory inorganics	-74%	-73%	-85%	-85%	-97%	-87%	-94%	-75%
Water scarcity	-73%	-72%	-77%	-77%	-82%	-56%	-83%	-42%

Green shading means that the legume product has a significantly ($p<0.05$) lower burden than the traditional product, red significantly higher, and white non-significant. (0-s) = no straw harvest; (s) = 80% straw harvested (allocation).

2.2. Consequential Life Cycle Assessment case studies

2.2.1. Goal, scope, and boundary definition

Following the attributional LCAs presented in the previous section, a cLCA was conducted to understand the environmental impact and land implications of shifting product consumption within a regular diet based on simple substitution of animal-based products with plant-based products in Germany, specifically replacing dairy milk and meatballs for soy milk and pea balls, respectively. The target audience for this study comprises researchers and policymakers with an interest in the transition to more sustainable food systems. Two functional units were addressed: (i) the production of 1 liter of soy milk (ii) the production of 100g portion of pea-balls. It was considered that soy milk replaces skimmed milk, while pea protein balls replace beef meatballs, and a 1:1 mass basis.

Modelling was undertaken in Open LCA v1.9 (GreenDelta 2006), using Ecoinvent v.3.5 database for background data (Moreno-Ruiz et al. 2018). The Life Cycle Impact Assessment (LCIA) was performed using the method recommended by the European Commission - Product Environmental Footprint (PEF) guidelines (European Environmental Bureau, Pro-, and Commission 2018). This method was selected because it is comprehensive and aligns with the aim to harmonise European environmental footprint studies. The method recommends the calculation of 16 environmental impact categories. The human toxicity categories were not reported in detail because (i) there were no primary or secondary data about crop protection applications for the rotations, and (ii) of high uncertainty related to these categories, classified as interim categories within the PEF method (European Environmental Bureau, Pro-, and Commission 2018).

Legume crops necessary for the soy milk and the pea balls are assumed to be integrated into existing Germany rotations due to the recent efforts to increase legume production and consumption in Europe.

2.2.2. Agriculture rotation data

The linear programming model (Economic Farm Emission Model, EFEM) was run at the University of Hohenheim to identify conventional crop rotations likely to be replaced by legume-modified rotations incorporating soybean cultivation. EFEM is a comparative static linear optimisation model,

which maximises farm gross margins. It operates in a bottom-up approach, which can be used at farm level as well as at regional level. In this study typical farms are addressed without regional upscaling (Figure 1). The model consists of a farm type module and a production module. The general classification of these farm types is based on the farm typologies of the Farm Accountancy Data Network (FADN) of the EU Commission (EU-FADN – DG Agri, 2018). The capacities of the typical farm models are based on average single farm data of the FADN and create restrictions for the optimisation process. The main part of the model is the production module. It unites all relevant agricultural production operations of the crop and livestock production. EFEM distinguishes different production activities on arable land and grassland, which can be used as food or feed. The different production processes vary in fertilisation and plant production intensities and soil treatment as well. In this study, EFEM was extended by new legume cultivation and feed consumption systems. Policy regulations and plant cultivation restrictions are also included in EFEM, *e.g.,* crop rotation, upper-limit usage of organic fertiliser, and equating of humus balance constraints. The values of relevant input data, such as producer prices, factor prices, and yields, are based on three-year averages to compensate for annual variability. The considered variable costs are exogenous parameters in the model that are derived from FADN data for the selected regions on NUTS2 level. A detailed description of EFEM is presented in Krimly et al. (2016) and Petig et al. (2018).

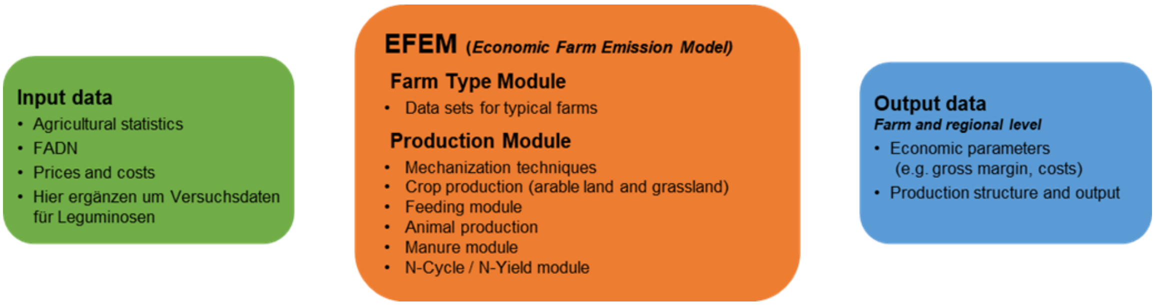

Figure 1. Structure and data sources for EFEM, used to model typical and modified rotations, and the (displaced) dairy and suckler-beef farm systems.

Under the scenario DE21Cro2, the introduction of 1 kg of fresh matter (FM) of soybean, displaces 2.2 kg FM of wheat, 1.4 kg FM of maize and 1.3 kg FM of silage maize. Under the scenario DE40Cro1, the introduction of peas in the rotation displaces 1.4kg FM of barley, 1.4 kg FM of maize and 1.2 kg FM of silage maize. Therefore, when pea or soybean are introduced, these crops are displaced and need to be produced somewhere else. This forms the initial economic input used to parameterise the cLCA.

2.2.3. Beef and Dairy Systems data

In addition to new soybean cultivation (above), the milk and beef substitution scenarios obviously involve the avoidance (displacement) of milk and beef production. It is assumed that this avoidance also arises in Germany, in response to (future) market and policy signals related to climate neutrality objectives. Two statistically representative dairy and suckler-beef farms were assessed, based on input data from the EFEM model described above. Animal emissions were modelled according to the Farm LCA tool (Styles et al. 2015), adapted in Costa et al. (2021). The dairy farm is a typical grass and maize based dairy farm located in Baden-Württemberg, where a large share of German dairy production is based. The details of this system can be observed in Table 3. Although there are more extensive grass-based systems in Germany, this type of farm was selected to represent the most common production system. The dairy farm comprises 139 milking cows, 35 calves and 35 heifers for rearing, and exports 8000 litres of milk *per* milking cow *per* year, alongside 93 surplus calves. In addition to feed provided from the farm, 9 t of soybean meal are consumed *per* year.

Table 3. Key characteristics of the statistically representative German dairy farm used to model the effects of avoided cow milk production.

	Cultivated area	N input	Use as feed		yield	
	ha	kg N / ha	%	t FM / ha	% Dry mass	t DM / ha
Arable land (total)	**70.0**					
Winter cereals	24.4	200	3	7.8	86	6.7
Spring cereals					86	
Corn					86	
Silage maize	29.0	156	100	45	35	15.8
Clover Grass	12.3	100	82	85	14	11.9
Rapeseed	4.2	200	0	4.2	91	3.8
Catch crops	14.5					
Permanent grassland	**75.0**	**100**	**100**			**6.4**

The beef farm is also located in Baden-Württemberg and represents a typical suckler beef farm in the German middle mountain region. The system information is described in Table 4, and comprises 20 suckler cows, 9 fattening bulls and 3 heifers. Six heifers are sold annually, and 16.5 t of cereal-based feed is imported to the farm.

Table 4. Key characteristics of the statistically representative German suckler-beef farm used to model the effects of avoided beef production.

	Cultivate	**N**			**yield**	
	ha	**kg N /ha**	**Use as feed (%)**	**t FM / ha**	**% Dry mass**	**t DM / ha**
Arable land (total)	**4.00**					
Winter cereals	**1.20**	160	100	6.3	0.86	5.418
Spring cereals	**0.75**	100	0	5.4	0.86	4.644
Corn	**0.20**	186	0	10.6	0.86	9.116
Silage maize	**0.50**	180	100	39.2	0.35	13.72
Clover Grass (on arable	**1.25**	180	100	65	0.14	9.1
Rapeseed	**0.10**	220	0	3.9	0.91	3.549
Catch crops	**1.00**					
Permanent grassland	**26.00**	**100**	**100**			**4.8**

The dairy system produced milk as a main product and calves and meat from cow slaughter as co-products. When the production of the main product (milk) is avoided under alternative (i), the co-products are also avoided. However, it is assumed that there is no reduction in the market demand for those co-products (calves that are designated for suckler systems and meat). Therefore, those co-products need to be compensated by the unconstrained market. Data from ecoinvent v3.7 consequential were used to assess the impact of the market for weaned calves and for cattle for slaughtering.

2.2.4. Soybean and Dairy milk Processing data

Data for soymilk processing production was taken from Pandy (2018). During processing of soymilk, Okara is generated. This co-product can be designated to livestock feed. Therefore, marginal feed is avoided *i.e.,* barley (marginal feed for energy) and soybean meal (marginal feed for protein). To identify the quantity of soymeal and barley avoided, a linear optimisation was conducted considering the values of energy and protein of each crop. The values of energy and protein from

Okara were taken from López (2018), while the soymeal and barley values were extracted from Feedpedia.

Data for the pasteurisation from raw milk was taken from Agrybalyse. Since the baseline scenario considers skimmed milk, if skimmed milk consumption is avoided (substituted) by soy milk, the co-product (fat) is also avoided and needs to be replaced by the market alternative, since the demand of fat remains unaltered. According to FAO statistics and increased production over the past decade, milk fat is most likely to be replaced by vegetable oil *i.e.,* palm oil from Malaysia, a determining product (Schmidt 2008).

2.2.5. Beef meatball and Pea protein ball processing data

Life cycle activities associated with processing of pea protein balls and beef balls were taken from Saget et al. (2021). The additional ingredients, such as onions, were included in the model using the ecoinvent consequential database. The transportation, refrigeration and distribution of both pea balls and meatballs were not included in the study.

2.2.6. Consequential assumptions and land balance

Before the increase in soybean milk production, the typical systems are arable rotations and dairy farms. Two scenarios were considered in the modelling following an increase demand in soymilk, with reference flows based on production of 1 litre of soymilk. The soybean introduction into the arable rotations displaces maize, wheat, and silage maize, whilst the milking farm activities are all avoided. In the first scenario (Figure 2), the crops displaced from the arable rotation need to be compensated by cultivation on spared dairy arable area, and by the market. End of dairy farm production spares grassland and avoids emissions related to cows, but also reduces demand for the following feed crops: clover-grass, silage maize, and wheat. Avoided silage requirements are larger than the amount of silage displaced from the rotation, and the net spared area is converted to maize and wheat (to compensate for their displacement from the arable rotation). Additional wheat displacement is compensated from the market, along with milk co-products *i.e.*, beef live weight (LW) from culled cows and calves. In this scenario, the spared dairy grassland is entirely available for conversion to forest (0-100% of this area afforested, represented using an average carbon gain from Searchinger et al. (2018)).

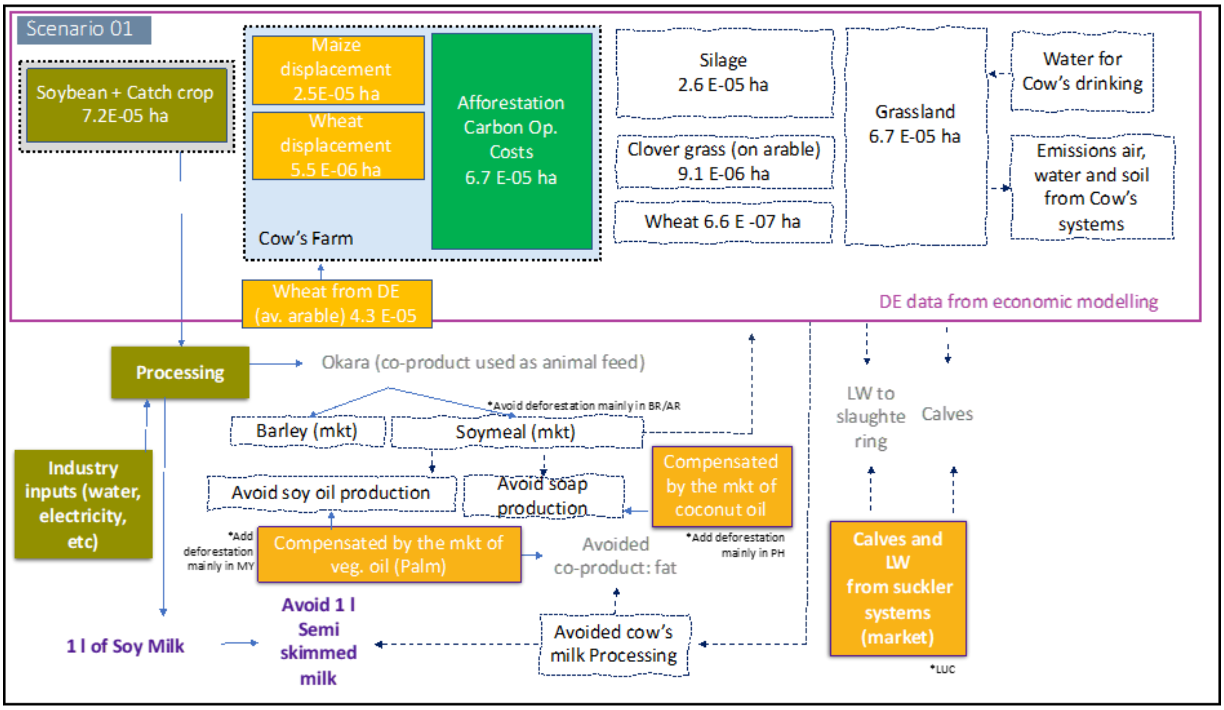

Figure 2. Scenario 1. Soybean cultivation displaces grain cultivation on the arable farms and on the avoided dairy farm. Some wheat, live weight, and calves need to be compensated by market alternatives.

In the second scenario, the additional wheat displaced is not compensated by the average market dataset, instead it is assumed that part of the spared dairy grassland is converted into wheat and the remainder is available for afforestation (Figure 3), of which 0-100% is afforested in sensitivity analysis. There remains the necessity to compensate LW and calves with market alternatives. LUC represents where there is a Land Use Change and a gain or loss of carbon.

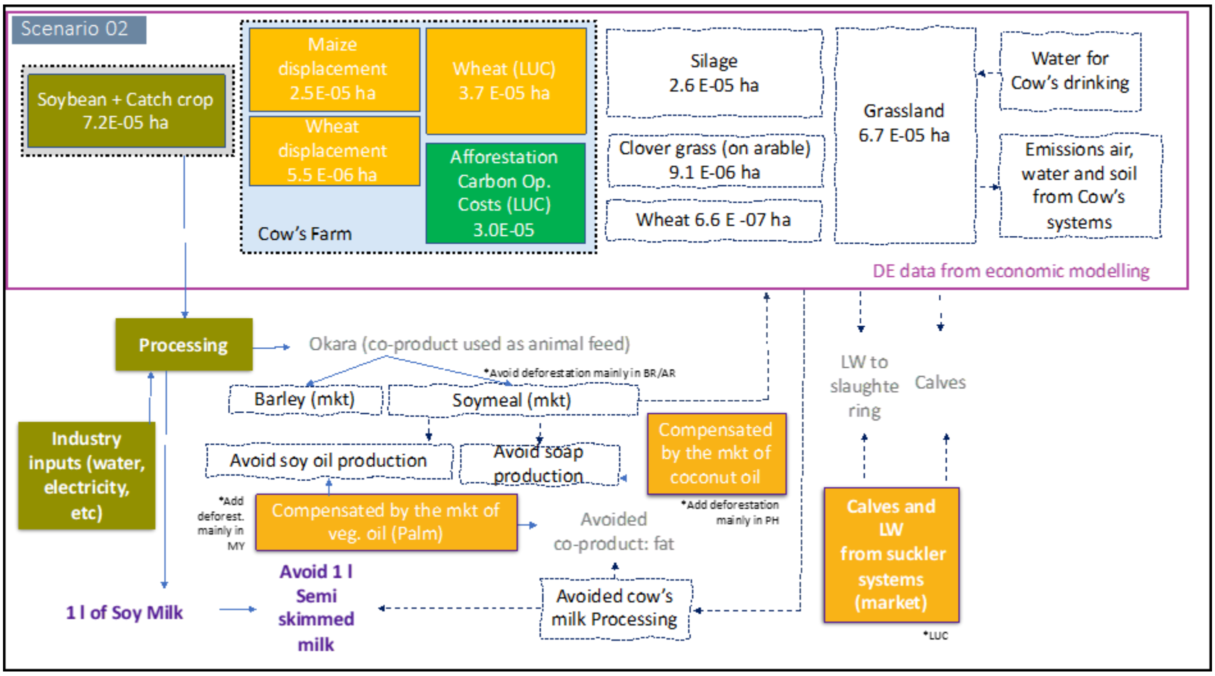

Figure 3. Scenario 2. Soybean cultivation displaces grain cultivation on the arable farms and on the avoided dairy farm. Some wheat production is displaced onto spared dairy grassland, whilst live weight, and calves need to be compensated by market alternatives.

For the pea protein balls, only one scenario is considered (Figure 4). The baseline before the pea protein balls are produced and consumed is represented by two main systems: (i) a suckler beef farm associated with annual cropland for cattle feed production, as well as a large area of permanent grassland; (ii) an arable cropping system. The introduction of pea cultivation into the arable rotation displaces barley, maize, and silage production previously used to produce cattle feed. The remaining spared arable land, and spared grassland, is available for conversion to forestation (0-100% afforested in sensitivity analysis).

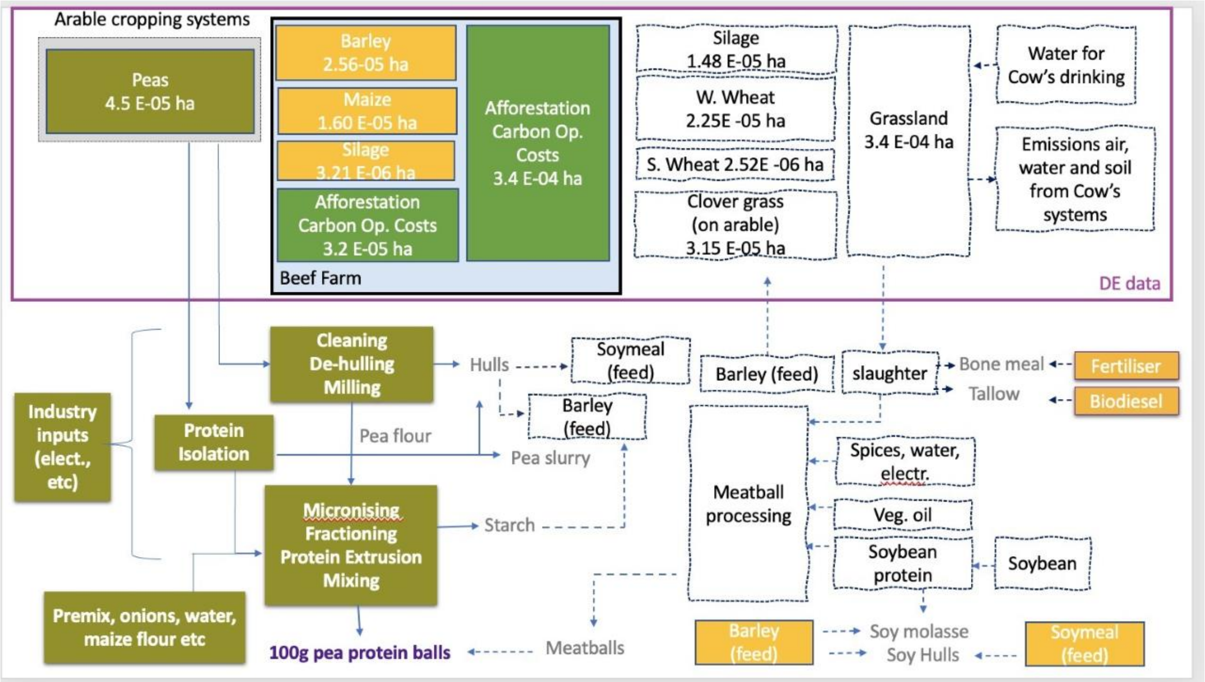

Figure 4. Beef meatball substitution with pea protein balls, where pea cultivation replaces cultivation of cereals used for beef cattle feed, sparing large areas of arable and grassland for afforestation.

Animal production and slaughterhouses produce animal wastes and by-products (so-called C1, C2 and C3 category materials). These materials are processed into pet food/animal feed, fat, biofuels, and fertilisers. The life cycle inventory of the treatment of C1, C2 and C3 materials are obtained from a detailed life cycle assessment for DAKA, which is the dominant rendering company in Denmark (Schmidt and Trolle 2020).

3. Results

3.1. Soy milk

Excluding potential afforestation of spared grassland, displacing cow's milk with soymilk results in no overall change to GHG emissions (Table 5) in scenario 1, because significant savings of 0.82 kg CO_2e *per* litre milk arising from avoided dairy production are offset by wheat, LW (beef) and calf displacement (Figure **5**). These latter effects cumulatively increase emissions by 0.87 kg CO_2e. We highlight that displacement of surplus calf production associated with dairy systems means that a larger suckler herd is needed in Germany, generating substantial emissions. This "leakage" effect of dairy-calf displacement has previously been shown for dairy intensification transitions (Styles et al. 2018), but not, as far as we are aware, for diet transitions. Such leakage could be avoided if beef demand was dramatically reduced to a level that could be satisfied by dairy-beef production. For scenario 2 (Figure 6), emissions actually increase overall following the switch to soy milk, because of higher burdens associated with production of wheat on the international market (linked with indirect LUC).

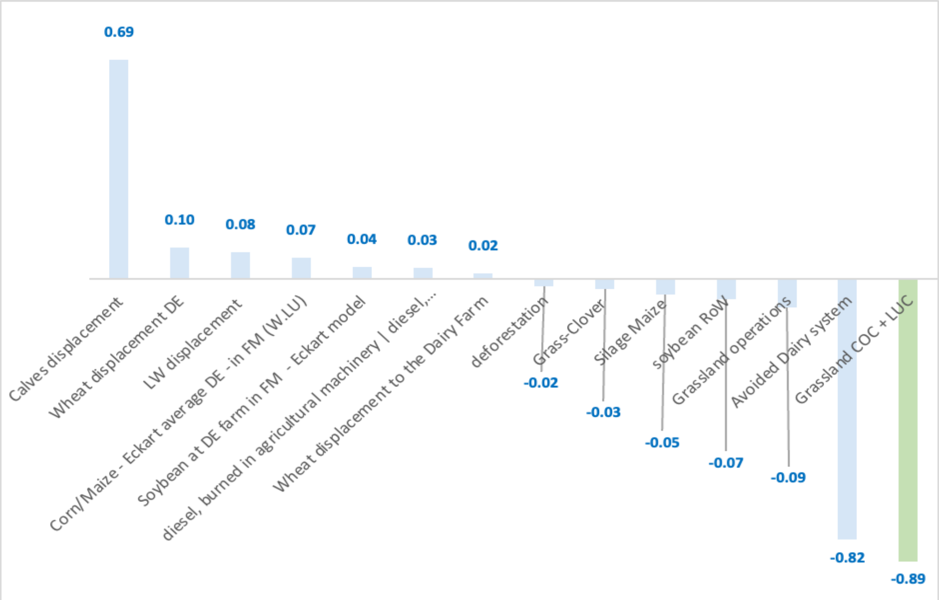

Figure 5. Milk scenario 1 results, expressed as net GHG balance (kg CO_2 eq.) per litre of soy milk produced, in aggregate (right) and per main incurred or displaced process.

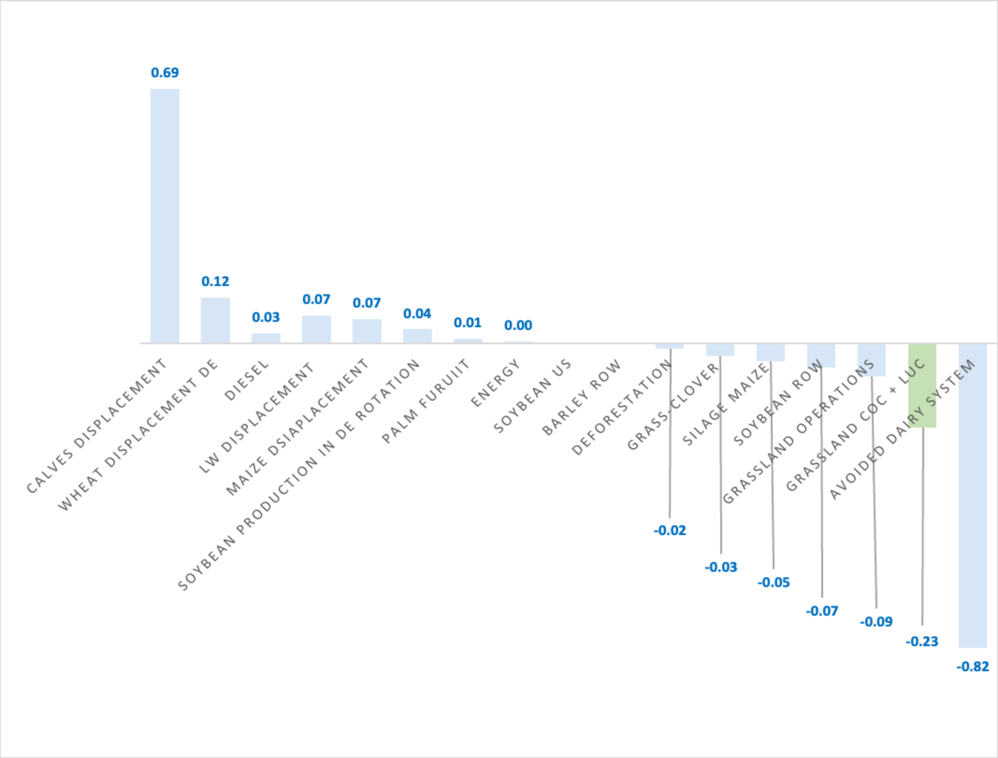

Figure 6. Milk scenario 2 results, expressed as net GHG balance (kg CO2 eq.) *per* litre of soy milk produced, in aggregate (right) and *per* main incurred or displaced process.

Nonetheless, for both scenarios, afforestation of the spared grassland area can lead to significant net GHG savings overall, ranging from a maximum of 0.23 kg CO2e *per* kg milk for scenario 2 to 0.89 kg CO2e *per* kg milk for scenario 1 (Table 5).

Table 5. Summary (aggregate) results for milk scenarios, based on different levels of afforestation on land spared from food production

% spared area afforested	**Scenario 1 (kg CO2e *per* litre milk)**	**Scenario 2 (kg CO2e *per* litre milk)**
0	0	0.17
25	- 0.22	0.07
50	- 0.45	- 0.03
75	-0.67	-0.13
100	- 0.89	- 0.23

TRUE is a Research & Innovatin Action funded by the European Commission
Horizon 2020 programme under Grant Agreement number 727973.

3.2. Pea protein balls

Results are more clear-cut for pea protein balls substituting beef meat balls. Tentative preliminary results displayed in Table 6 show that, even before accounting for possible afforestation of spared land, substitution of beef can avoid 2.8 kg CO2e *per* 100 g serving of meat balls. In fact, in addition to sparing 3.4 m^2/yr of grassland from beef production (*per* 100 g serving), pea cultivation occupies a smaller area of arable land than would otherwise be required to produce the cereal portion of the suckler-beef herd's diet. Thus, up to 3.7 m^2/yr is spared *per* 100 g portion of pea balls, resulting in a GHG saving of up to 7.71 kg CO2e *per* portion (Table 6).

Table 6. Summary (aggregate) preliminary results for the beef substitution scenario, based on different levels of afforestation on land spared from food production.

% spared area afforested	Results (kg CO2e per 100 g beef)
0	-2.80
25	-4.03
50	-5.26
75	-6.49
100	-7.71

4. Discussion and conclusions

The modelling undertaken here demonstrates that a dietary shift towards more legumes could result in substantial GHG emission savings if increased plant-protein intake leads to reduced consumption of beef. The same situation is likely to arise for other meat, products, though to a less dramatic extent. When meat is replaced, large areas of land can also be spared. Afforestation of this land can more than double net GHG mitigation.

When legumes replace dairy products, the picture is more complicated. Dairy systems produce milk, beef, and surplus calves for beef fattening. Dairy-beef production is considerably more efficient than suckler-beef production (Nguyen, Hermansen, and Mogensen 2010). Thus, whilst milk substitution can reduce emissions from dairy systems, it may also displace beef production to less efficient suckler systems, unless demand can be dramatically reduced. This suggests that legume incorporation into European diet should focus on meat, rather than dairy, replacement in the first instance. Nonetheless, significant net land sparing can still arise from substitution of cow’s milk, and if this land is afforested, that could lead to net GHG savings. This highlights the importance of complementing diet change strategies with land use planning to deliver effective carbon dioxide removals on spared land, in line with IPCC recommendations (IPCC 2019).

Preliminary modelling undertaken for wider diet change in line with EAT-Lancet recommendations (Appendix 1) indicates that such a shift would involve a large reduction in primary production of food and feeds (Figure A2). Land sparing is therefore likely to make a considerable contribution to potential GHG mitigation for such a transition, too. Avoidance of livestock production (emissions), and the potential to substitute synthetic N fertiliser application at scale (Costa et al. 2021) are likely to deliver large GHG emission savings even before possible carbon sequestration *via* afforestation is considered. These results will be confirmed as soon as remaining rotation data become available to complete the modelling.

In summary, the following conclusions can be drawn from this novel cLCA modelling:

- Substitution of beef by pea-derived protein can result in large GHG savings, of up to 2.8 kg CO2e *per* 100 g serving.
- Associated land sparing of up to 3.7 m^2.yr *per* serving could support further mitigation via afforestation, more than doubling total GHG mitigation *per* serving.
- Substitution of cow's milk with soy-based milk does not lead to significant GHG savings owing to the displacement of dairy-beef production to less efficient suckler-beef herds.
- Nonetheless, land sparing by cow's milk substitution could lead to overall GHG mitigation if spared grassland is afforested, especially if beef consumption is simultaneously reduced.
- Legumes can play an important role towards realisation of the EAT-Lancet diet, support considerable land sparing, livestock emission avoidance and synthetic fertiliser displacement.
- Combining legume-driven diet transitions with land use planning to maximise carbon dioxide removals (*e.g.,* via afforestation) could play a key role in achieving climate neutrality by 2050.

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4. Appendices

Appendix 1

Goal & Soap

We performed a cLCA of a diet change scenario in Europe in which legume-based foods substitute traditional products that are over-consumed, so as to better align with the latest recommendations for an environmentally-sustainable and healthy diet (Willett et al. 2019). This report aims to answer the following question:

- What is the environmental impact associated with a change in the current European diet, with a substitution of popular foods for legume-based alternatives, to better align with the EAT Lancet recommended diet?

Legume-based alternatives were chosen that mimic popular foods in order to facilitate the transition towards a sustainable EAT Lancet diet. These include pea gin, faba bean beer, chickpea pasta, soymilk, pea protein balls, and tofu – for which attributional LCA studies were undertaken as part of the TRUE project (Leinhardt et al. 2019; Saget et al. 2020; 2021). A key novelty from this study lies in the integration of *changes* in crop rotations, as these can play a significant role in the environmental performance of a system. Thus, we performed a cLCA from cradle to fork integrating agricultural rotation changes and diet change (Figure A1).

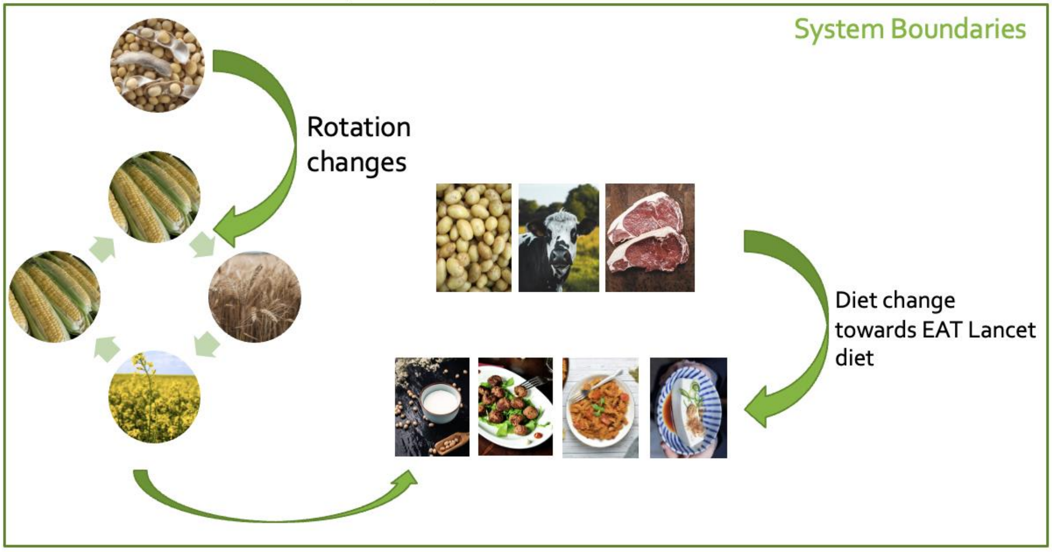

Figure A1: Schematic diagram of the cLCA study.

EAT-Lancet Diet

The EAT Lancet report classifies foods under different categories, including “tubers or starchy vegetables”, “protein sources”, and “whole grains”. Sub-categories can be found in these categories, such as “beef, lamb and pork”, “legumes”, and “eggs” in “protein sources”. The legume-based product attributional LCAs performed during the TRUE project were selected and amounts of legumes in grams were matched with foods that the EAT Lancet recommends to reduce the consumption of in Europe: chickpea pasta (Saget et al. 2020) with potatoes and pea protein balls (Saget et al. 2021) with beef. In addition, Ecoinvent processes of tofu and soymilk were added to replace beef and milk, respectively (Wernet et al. 2016). The summary of these substitutions can be found in Table A1, and the European-level commodity replacement required annually was recorded in Figure A2. The highest range of legume consumption in the EAT Lancet diet was opted for. It was assumed that lamb consumption was not reduced, with all the red meat reduction taking place in the beef subcategory. The European population number was extracted from (Eurostat 2021b). The additional demand for soy in tofu and soymilk was assumed to be produced in Europe. The inputs for cattle were extracted from the Agri-footprint v.3 process of PEF-compliant Irish beef (Durlinger et al. 2017).

Table A1: Changes in European diet modelled to better meet the EAT Lancet diet.

	EAT Reference		European current intake	Difference EAT vs current						European level	
	Macronutrient intake, g/day	Caloric intake, kcal/day	Macronutrient intake, g/day	Percentage difference	Macronutrient intake, g/day	Corresponding products modelled in the clca	Substitution product	Product/ ingredient replacement, g/day	Remaining difference with EAT, g/day	Product/ ingredient replacement, ton/day	Remaining difference with EAT, ton/day
Tubers or starchy vegetables											
Potatoes and cassava	50	39	200	400%	-150	**potatoes**	chickpea pasta	-84	-68	-37534	-30311
						protein balls (potato starch)		1.7		751	
Dairy foods											
Whole milk or derivatives	250	153	309	123%	-59	**dairy milk**	soy milk	-59	0	-26276	0
Protein sources											
Beef and lamb	7	15	30	433%	-23	**meatballs (70% beef)**	protein balls	-17	0	-7455	0
							tofu	-17		-7455	
Legumes	150	284	21	14%	129						
Dry beans, lentils, and peas	100	172	14	14%	86	protein balls (pea protein isolate)		1	0	488	0
						protein balls (pea protein fractionated)		1		445	
						chickpea pasta		84		37534	
Soy foods	50	112	7	14%	43	soy milk (soy)		7	27	3250	12208
						protein concentrate)		-1		-365	
						tofu (soy)		9		4142	
Additional products											
Corn						protein balls (cornflakes)		1			
Onion						protein balls (onion)		2			
						meatballs (onion)		0		6.33E+02	

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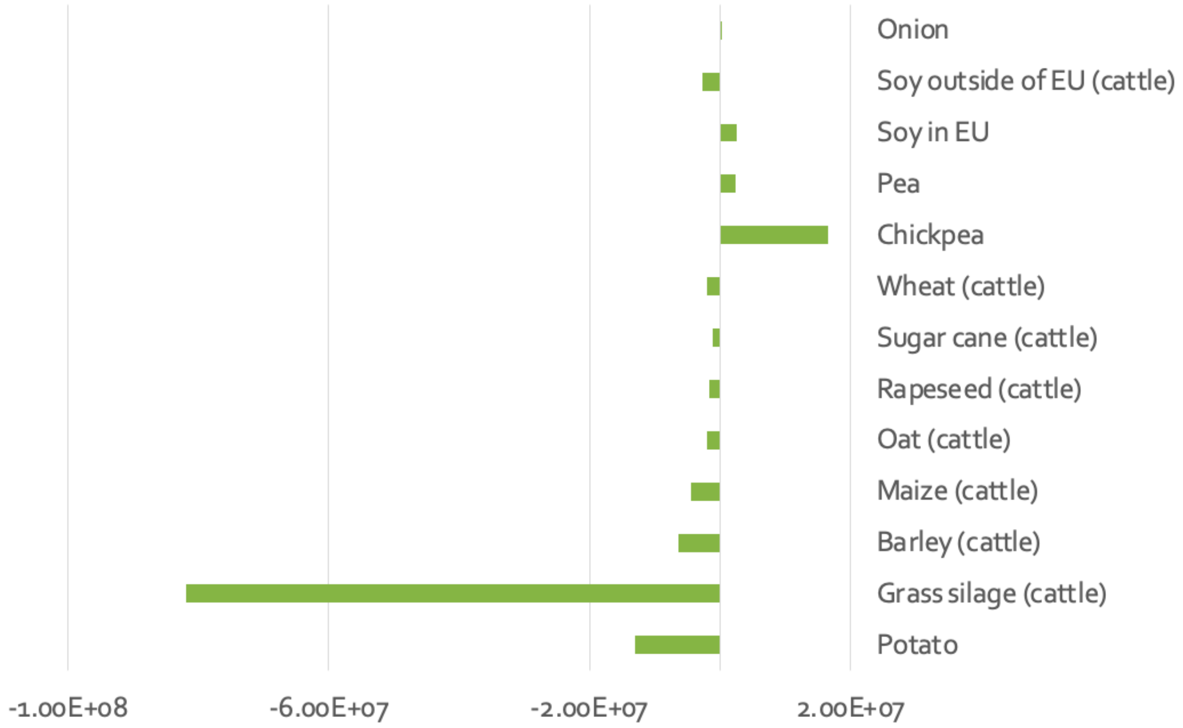


Figure A2: European-level commodity replacement required to match the diet change modelled in tonnes *per* year.

Rotation and land use changes

To determine which European countries were most likely to present agricultural rotation changes matching the product substitutions, future predictions were determined from the average annual growth rate of area harvested of the crops that need to be reduced (calculated with average area harvested (2010-2019) per European country), and from the average annual growth rate of production amount increase of the crops that need to be increased (calculated with average quantity produced (2010-2019) per European country) in FAOSTAT (FAOSTAT n.d.). Countries that appeared in both searches were selected, and from this list available rotation data were matched (Table A2). In total, 51 rotation changes from a baseline to a legume-introduced one were collected.

Table A2. Countries with rotation data matching the diet change modelled

	Crop reduction						Crop increase			
Country	**Potato**	**Barley**	**Maize**	**Oat**	**Rapeseed**	**Wheat**	**Dry peas**	**Soybean**	**Chickpeas**	**Broad beans**
Romania	potato	barley		oat			dry peas	soybean	chickpeas	
Serbia	potato		maize					soybean		
Italy	potato		maize	oat		wheat		soybean	chickpeas	broad beans
Bulgaria		barley			rapeseed		dry peas	soybean	chickpeas	broad beans
Austria		barley			rapeseed	wheat		soybean		
Germany			maize	oat	rapeseed	wheat	dry peas	soybean		broad beans
Sweden				oat						broad beans
United Kingdom	potato				rapeseed	wheat	dry peas			broad beans

Main assumptions

Consumer use modelling

It was assumed that preparation of products at the consumer house was done for two servings at a time, as the average household size in Europe is estimated at 2.3 individuals *per* household (Eurostat 2021a). For products that required to be stored in the fridge, it was assumed that they stayed in for one day. Following the PEF guidelines, cooking on stove required 1 kWh/h use (European Commission 2018). Cooking oil used at the consumer's house was excluded, as it was assumed to be equivalent across the products compared.

Potato modelling

The potato transport mode and distance were the same as for the chickpea pasta chain to ensure comparability. This transport model followed the PEF-recommended distances and modes from supplier to factory, factory to retail (only intracontinental transport modelled), and retail to final client (European Commission 2018). Following the Agribalyse process of "Potato, boiled/cooked in water, processed in FR | Chilled | PP | Boiling | at consumer", the edible fraction of a potato was set as 0.97, and the raw-to-cooked fraction as 0.70 (ADEME 2020). The amount of water used to clean the harvested potato was extracted from Parajuli et al. (2021), and the amount of electricity used to clean the harvested potato was assumed to be the same as to clean the same quantity of chickpeas, due to lack of data. Potatoes are consumed boiled for simplicity. The water and electricity amounts used to boil the potatoes was extracted from the Agribalyse process "Potato, boiled/cooked in water, processed in FR | Chilled | PP | Boiling | at consumer" (ADEME 2020). Quantity and type of packaging for potatoes were extracted from the Agribalyse process "Potato, peeled, raw, processed in FR | Chilled | PP | at packaging" (ADEME 2020). It was assumed that one serving was 80g raw potato, as for the pasta. Energy required to bring the water to boil was excluded in both pasta and potato, as they are the same.

Choice of rotations

Linear optimisation was performed with the Simplex method in the Python Scipy package to determine what amount of each rotation would better reach the desired reduction of certain crops and increase of others, to meet as closely as possible the required European-level commodity replacement. Rotations were then combined with post farm-gate steps, and the changes modelled in the OpenLCA v. 1.10.3 software (GreenDelta 2019) using the Ecoinvent v.3.7.1 consequential database (Wernet et al. 2016). Results will provide recommendations to policy makers as potential effects of European diet substitution with an inclusion of legumes in rotations and foods.

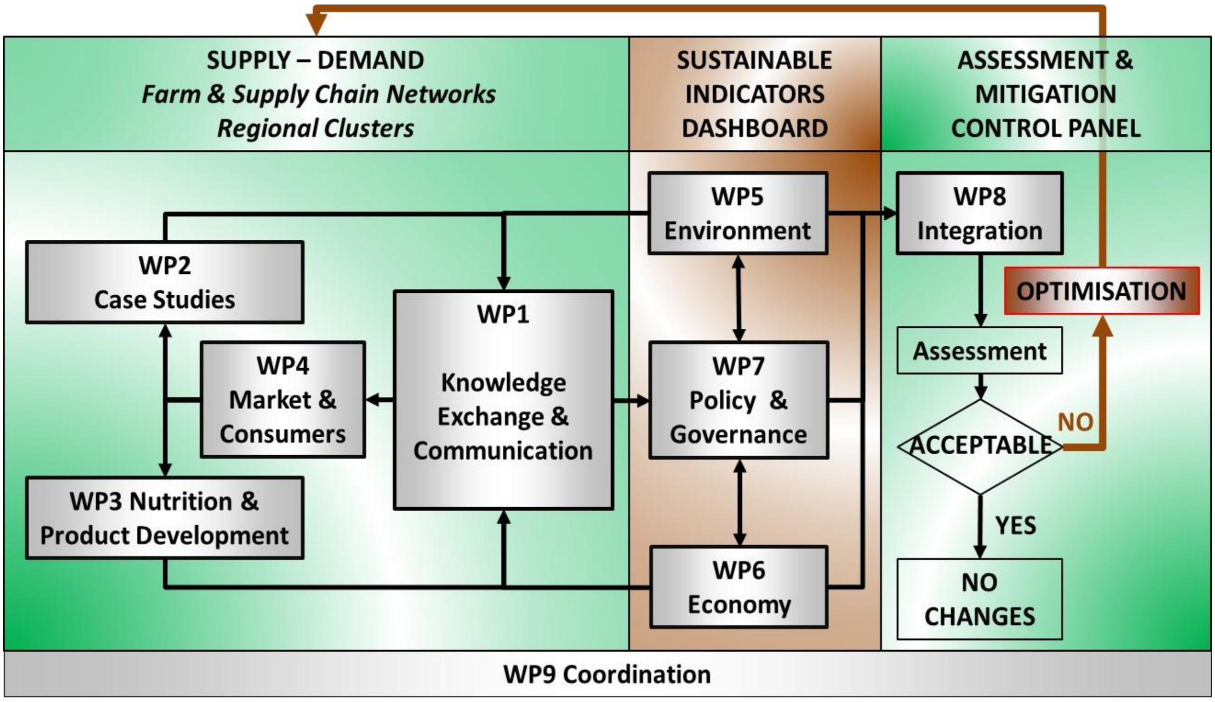
Appendix 2: Background to the TRUE-Project

TRUE Project Executive Summary

TRUE's perspective is that the scientific knowledge, capacities, and societal desire for legume supported systems exist, but that practical co-innovation to realise transition paths have yet to be achieved. TRUE presents 9 Work Packages (WPs), supported by an *Intercontinental Scientific Advisory Board*. Collectively, these elements present a strategic and gender balanced work-plan through which the role of legumes in determining '*three pillars of sustainabilit*y' – '*environment*', '*economics'* and '*society'* - may be best resolved. TRUE realises a genuine multi-actor approach, the basis for which are three *Regional Clusters* managed by WP1 ('*Knowledge Exchange and Communication',* University of Hohenheim, Germany), that span the main pedo-climatic regions of Europe, designated here as: *Continental*, *Mediterranean* and *Atlantic,* and facilitate the alignment of stakeholders' knowledge across a suite of 24 Case Studies. The Case Studies are managed by partners within WPs 2-4 comprising '*Case Studies*' (incorporating the project database and *Data Management Plan*), '*Nutrition and Product Development'*, and '*Markets and Consumers'.* These are led by the Agricultural University of Athens (Greece), Universidade Catolica Portuguesa (Portugal) and the Institute for Food Studies & Agro Industrial Development (Denmark), respectively. This combination of reflective dialogue (WP1), and novel legume-based approaches (WP2-4) will supply hitherto unparalleled datasets for the '*sustainability WPs*', WPs 5-7 for '*Environment*', '*Economics'* and '*Policy and Governance'.* These are led by greenhouse gas specialists at Trinity College Dublin (Ireland; in close partnership with Life Cycle Analysis specialists at Bangor University, UK), Scotland's Rural College (in close partnership with University of Hohenheim), and the Environmental and Social Science Research Group (Hungary), in association with Coventry University, UK), respectively. These *Pillar WPs* use progressive statistical, mathematical and policy modelling approaches to characterise current legume supported systems and identify those management strategies which may achieve sustainable states. *A key feature* is that TRUE will identify key *Sustainable Development Indicators* (SDIs) for legume-supported systems, and thresholds (or goals) to which each SDI should aim. Data from the *foundation WPs* (1-4), to and between the *Pillar WPs* (5-7), will be resolved by WP8, '*Transition Design',* using machine-learning approaches (*e.g. Knowledge Discovery in Databases*), allied with *DEX* (*Decision Expert*) methodology to enable the mapping of existing knowledge and experiences. Co-ordination is managed by a team of highly experienced senior staff and project managers based in The Agroecology Group, a Sub-group of Ecological Sciences within The James Hutton Institute.

Work Package Structure

Flow of information and knowledge in TRUE, from definition of the 24 case studies (left), quantification of sustainability (centre) and synthesis and decision support (right).

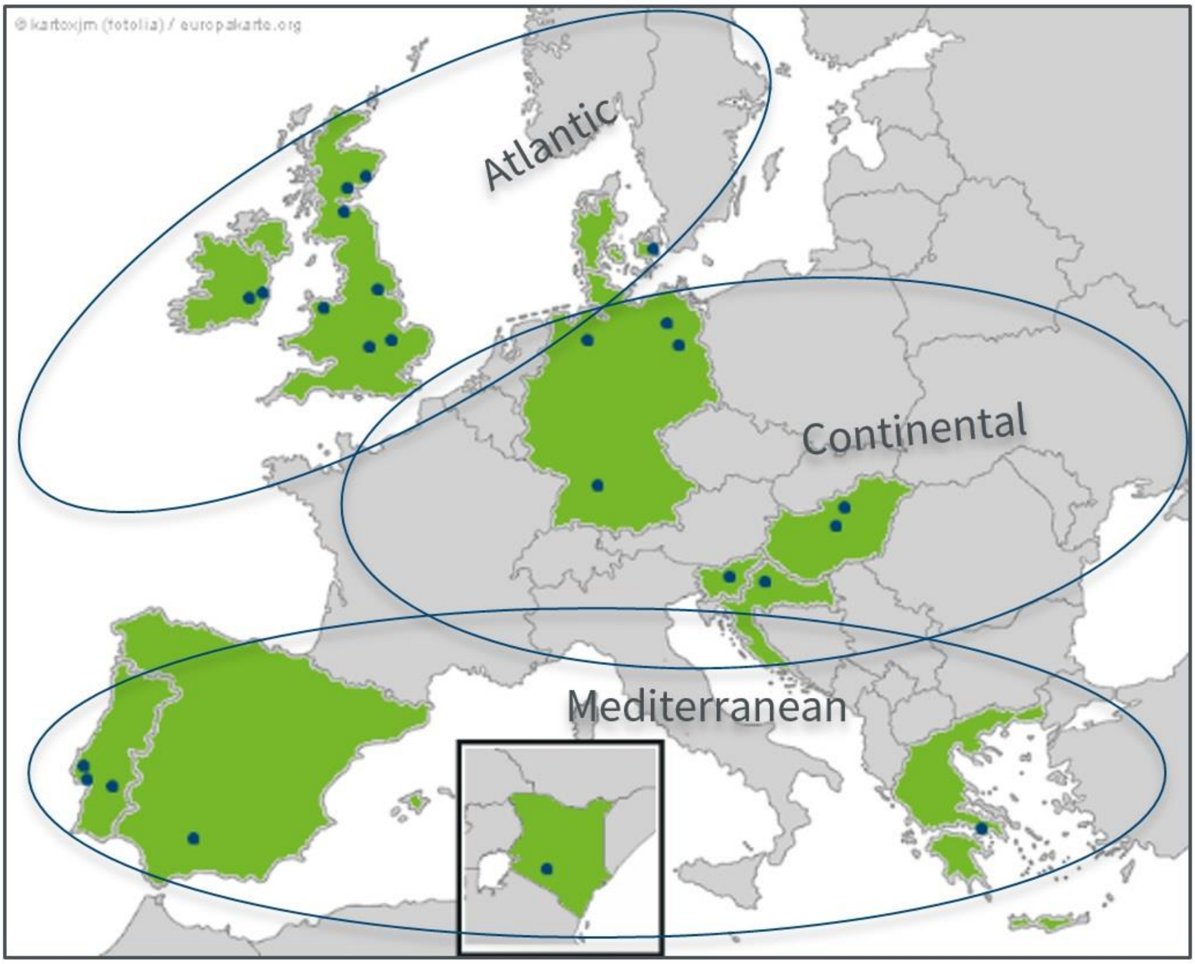


Project Partners

Nº.	Participant organisation name (and acronym)	Country	Organisation Type
1 (C*)	The James Hutton Institute (JHI)	UK	RTO
2	Coventry University (CU)	UK	University
3	Stockbridge Technology Centre (STC)	UK	SME
4	Scotland's Rural College (SRUC)	UK	HEI
5	Kenya Forestry Research Institute (KEFRI)	Kenya	RTO
6	Universidade Catolica Portuguesa (UCP)	Portugal	University
7	Universität Hohenheim (UHOH)	Germany	University
8	Agricultural University of Athens (AUA)	Greece	University
9	IFAU APS (IFAU)	Denmark	SME
10	Regionalna Razvojna Agencija Medimurje (REDEA)	Croatia	Development Agency
11	Bangor University (BU)	UK	University
12	Trinity College Dublin (TCD)	Ireland	University
13	Processors and Growers Research Organisation (PGRO)	UK	SME
14	Institut Jozef Stefan (JSI)	Slovenia	HEI
15	IGV Institut Für Getreideverarbeitung Gmbh (IGV)	Germany	Commercial SME
16	ESSRG Kft (ESSRG)	Hungary	SME
17	Agri Kulti Kft (AK)	Hungary	SME
18	Alfred-Wegener-Institut (AWI)	Germany	RTO
19	Slow Food Deutschland e.V. (SF)	Germany	Social Enterprise
20	Arbikie Distilling Ltd (ADL)	UK	SME
21	Agriculture And Food Development Authority (TEAG)	Ireland	RTO
22	Sociedade Agrícola do Freixo do Meio, Lda (FDM)	Portugal	SME
23	Eurest -Sociedade Europeia De Restaurantes Lda (EUR)	Portugal	Commercial Enterprise
24	Solintagro SL (SOL)	Spain	SME
25	Public Institution for Development of Međimurje REDEA (PIRED)	Croatia	Development Agency

*Coordinating institution

Legume Innovation Networks



Knowledge Exchange and Communication (WP1) events include three TRUE European Legume Innovation Networks (ELINs) and these engage multi-stakeholders in a series of focused workshops. The ELINs span three major biogeographical regions of Europe, illustrated above within the ellipsoids for Continental, Mediterranean and Atlantic zones.

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