TRansition paths to sUstainable legume-based systems in Europe

Open Access Database for Life Cycle Analysis

Work Package: 5

Deliverable: 5.3 (D31)

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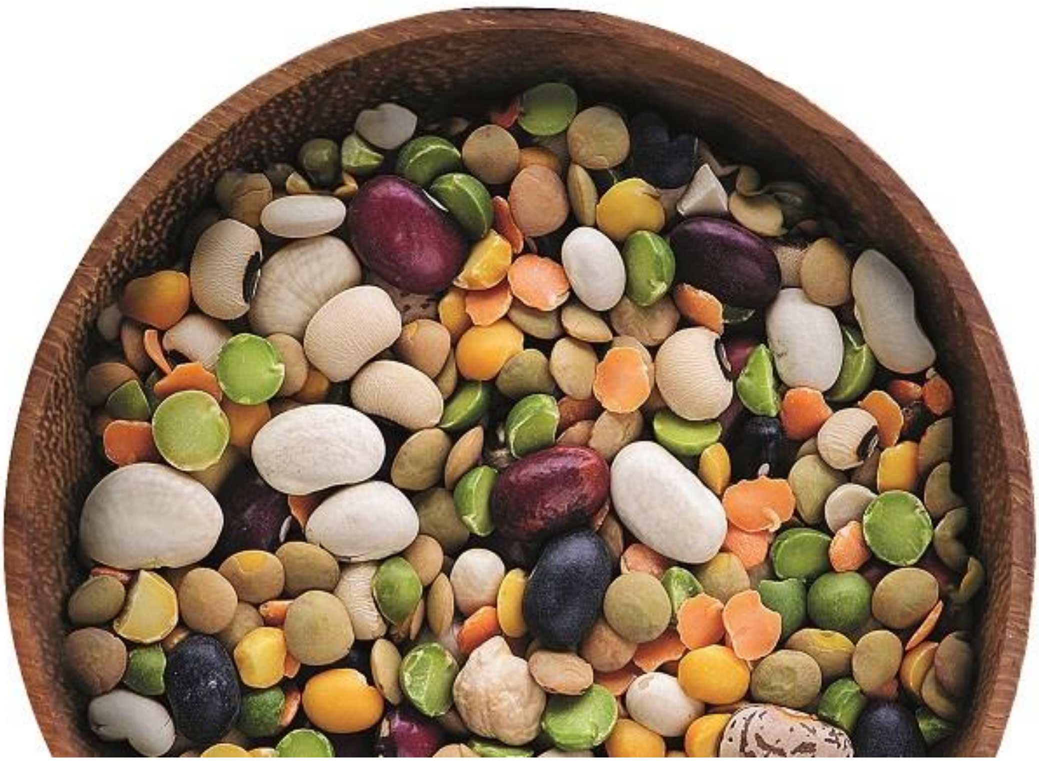

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Deliverable Description & Contributors

- **Due date**: 31th March, 2020
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- **Nature of deliverable**: Report
- **Dissemination level**: Public

- **Deliverable Description:** This Deliverable describes the building and use of an Open Access Life Cycle Assessment (LCA) database. The database is collated on the project database (Work Package (WP) 2) and will be accessible via the project website (WP1). This data will allow access to a unique collection of processes and emission factors for specific legume crops and legume-based food and feed products and associated value chains. The legume crops assessed include: faba- and common-abeans, chickpeas, soybean, lupin and peas cultivated across three different European biogeographical regions (Atlantic/Boreal, Continental and Mediterranean). Additionally, LCA results are also presented for three novel legume-based food products: chickpea pasta plus gin made from neutral spirit derived from distilled peas, and pea-protein balls.

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- **Key words:** Life Cycle Assessment, database, Open Access, legumes, food

Contents

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Executive Summary

Life Cycle Assessment (LCA) is a vital tool to evaluate the environmental impact and resource efficiency of food- and feed-value chains. The approach accounts for environmental burdens (e.g. Green House Gas (GHG) emissions), and resource use at all stages from production through distribution to consumption and disposal. This Deliverable report describes a MS Excel Open Access Database (TRUE Project D5.3) and summarises environmental footprints across 16 different environmental impact categories for important grain legume crops, specifically: peas, faba beans and common beans, chickpeas, lupin and soybean. Also, for three novel legume-derived food products, specifically: chickpea pasta; pea-protein balls; and alcoholic beverage, gin, made from neutral spirit derived from distilled peas. The database contains information on major inputs and outputs for the crop systems, and entire inventories of all inputs and outputs for the grain legume derived products. D5.3 provides researchers and other stakeholders with access to attributional LCA (environmental footprint) data for major grain legume crop species and is applied for novel legume-based products and value chains.

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1. Introduction

Life cycle assessment (LCA) is a vital tool to evaluate the environmental intensity and resource efficiency of food value chains, accounting for environmental burdens (e.g. GHG emissions) and resource use at all stages from production through distribution to consumption and disposal. The basic framework is an iterative procedure involving: (i) system boundary definition; (ii) data collection to quantify relevant inputs and outputs (energy, raw materials, co-products, waste, emissions); (iii) characterisation of inputs and outputs in relation to specific environmental impacts; and (iv) interpretation (with respect to ISO, 2006).

WP5 of the TRUE Project combines statistical data-mining of published literature with data from: past and present EU-funded projects (LEGUME FUTURES, EUROLEGUME, LEGATO); Case Study partners; and, LCA databases (e.g. Ecoinvent v.3.5). The data are used to undertake attributional LCA of legume crops cultivated across major EU biogeographical regions. The Open Access Database described herein provides researchers and other stakeholders with access to attributional LCA (environmental footprint) data for major grain legume crop species and novel grain legume-based products. The LCA data and model approaches described here should be regarded as the building blocks for legume-based value chains and associated LCA studies.

The database described here is currently stored in the TRUE project database (WP2) and is currently available as an Open Access resource on request to the WP5 Leader (Prof. Michael Williams, TCD). It will be made freely available online via the TRUE Project website (WP1) after on-line publication of the peer-reviewed manuscripts which are currently pending. The database exists as a stand-alone MS Excel file containing separate tabs that summarises: (i) key input data (and for products detailed inventories); and (ii) footprint results from 16 different environmental impact categories.

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2. Methodological background

2.1. Life Cycle Assessment

LCA is an approach that aims to quantify the potential environmental impacts of delivering a product or service. The analysis considers all processes arising across all phases of production, use and disposal (ISO 14040, 2006). The Deliverable presented here shows a summary of the interim results of LCAs for major grain legume crop species and products undertaken in TRUE Project WP5. Results are presented for attributional LCA (Rebitzer *et al.*, 2004), with either a 'cradle to farm gate' (crops) or 'cradle-to-consumer' (products) scope.

LCA quantifies potential environmental damage across several impact categories, such as depletion of finite resources, eutrophication of water and other key pollutants and climate change e.g. kg CO_2 equivalents. The LCA results reported here assess grain legume commodities and products across sixteen impact categories (Table 2) as recommended by European guidelines for *Product Environmental Footprints* (European Environmental Bureau, 2018).

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Table 1: Life cycle impact assessment (LCIA) methods used in this study. Adapted from (European Environmental Bureau, 2018).

Impact category	**Indicator**	**Unit**	**Recommended default LCIA method**
Climate change	Radiative forcing as Global Warming Potential (GWP100)	kg CO2 eq	Baseline model of 100 years from IPCC (based on IPCC 2013)
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11 eq	Steady-state ODPs as in (WMO 1999)
Human toxicity, cancer*	Comparative Toxic Unit for humans (CTUh)	CTUh	USEtox model (Rosenbaum *et al.*, 2008)
Human toxicity, non-cancer*	Comparative Toxic Unit for humans (CTUh)	CTUh	USEtox model (Rosenbaum *et al.*, 2008)
Ionising radiation, human health	Human exposure efficiency relative to U235	kBq U235 eq	Human health effect model as developed by Dreicer *et al.*, 1995 (Frischknecht *et al.*, 2000)
Photochemical ozone formation, human health	Tropospheric ozone concentration increase	kg NMVOC eq	LOTOS-EUROS model (Van Zelm *et al.*, 2008) as implemented in ReCiPe 2008
Acidification	Accumulated Exceedance (AE)	mol H+ eq	Accumulated Exceedance (Seppälä *et al.*, 2006, Posch *et al.*, 2008)
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N eq	Accumulated Exceedance (Seppälä *et al.*, 2006, Posch *et al.*, 2008)
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq	EUTREND model (Struijs *et al.*, 2009) as implemented in ReCiPe
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N eq	EUTREND model (Struijs *et al.*, 2009) as implemented in ReCiPe
Ecotoxicity, freshwater*	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	USEtox model, (Rosenbaum *et al.*, 2008)
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq	CML 2002 (Guinée *et al.*, 2002 and van Oers *et al.*, 2002)
Resource use, fossils	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ	CML 2002 (Guinée *et al.*, 2002 and van Oers *et al.*, 2002)
Land use	Soil quality index	Dimensionless (pt)	Soil quality index based on LANCA (Beck *et al.*, 2010 and Bos *et al.*, 2016)
Water use	User deprivation potential (deprivation-weighted water consumption)	m^3 world eq.	Available Water Remaining (AWARE) as Recommended by UNEP, 2016
Particulate Matter	Impact on human health	Disease incidence	PM method recommended by UNEP (UNEP 2016)

*Based on total human land appropriation

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2.1.1. Life Cycle Assessment of legume crops

In this D5.3 report we show data for legume crops and legume-based products produced across three major European biogeographical regions encompassed within the TRUE Project, which are: Atlantic/Boreal, Continental and Mediterranean. The crops evaluated and their respective regions are listed below.

Chickpeas

- Organic, Spain (Mediterranean)
- Bulgaria (Continental)

Common bean

- Sud-Muntenia, Romania (Continental)

Faba bean

- Bayern, Germany (Continental)
- Calabria, Italy (Mediterranean)
- United Kingdom (Atlantic)

Lupin

- Bayern, Germany (Continental)

Peas

- Bayern, Germany (Continental)
- Baden-Württemberg, Germany (Continental)
- East of Scotland (Atlantic)
- United Kingdom (Atlantic)

Soybeans

- Bayern, Germany (Continental)
- Baden-Württemberg, Germany (Continental)
- Sud-Muntenia, Romania (Continental)

The LCA for each legume crop species was undertaken using a cradle-to-farm-gate boundary. This means that all processes until and including legume grain harvesting are included, from the extraction of raw materials, through e.g. manufacturing of fertilisers, to application of those fertilisers on the farm (Figure 1). Drying and storage of grains are excluded from the analysis since they are located outside of the established boundaries and depend on downstream uses. The functional unit is one kg of (air-dry) legume harvested during the agricultural year. This functional unit is compatible with results presented for legumes and other harvested commodities in international LCA databases such as Ecoinvent (Wernet *et al.*, 2016). LCA methodologies described here comply with recommendations made for *Product Environmental Footprints* in the European context (European Environmental Bureau, 2018). The LCA for all crops was modelled in the software Open LCA v1.9 (GreenDelta, 2006).

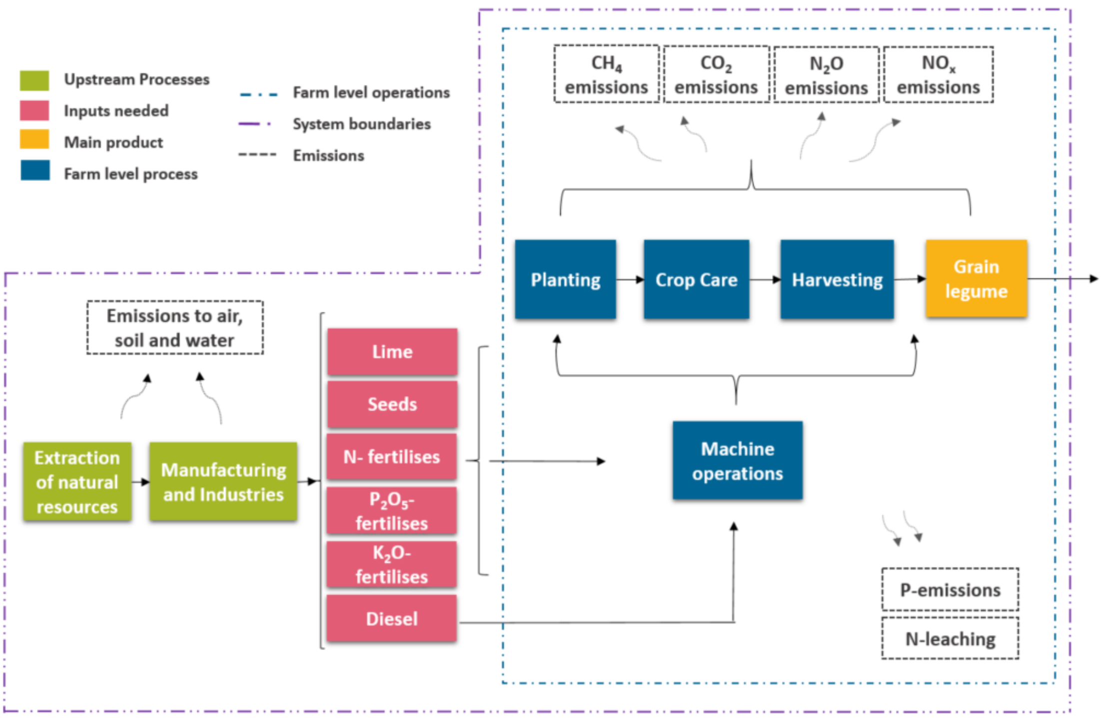

Figure 1: System boundaries considered in legume crop LCA.

2.1.1.1. Crop management data

Crop management comprises the specific agronomic techniques employed, and the main inputs and outputs, for crop cultivation. Key data include quantities of different fertilisers applied, crop care, crop harvesting, dry matter yields, etc. The main information collected for each crop was gathered as quantities of major inputs (primarily fertilisers) and yields, representing the factors that dominate the environmental footprint of crop production. Information collected for each crop type can be found in Table 2 through to Table 6. Data for beans, peas, soybean and lupin in Bayern, Germany, were provided by the Ministry of Agriculture in Bavaria (LfL, 2020). Inputs and dry yields for peas and soybeans for Baden-Württemberg in Germany were provided by the Ministry of Agriculture of the region (LEL, 2020). Information for soybean and common bean in Sud-Muntenia, Romania, faba beans in Calabria, Italy and peas from East Scotland were obtained from Reckling *et al.* (2016). Average data for pea and bean cropping in the United Kingdom were extracted from Redman (2018). Data for chickpea cultivation in Spain and Bulgaria were collected from primary sources. In Bulgaria, data were provided by a commercial farmer supplying chickpeas to a chickpea pasta manufacturer. In Spain, data were provided by Dr Eleonora Barilli, TRUE Project partner in Solintagro S.A.S (SOL).

Table 2: Main fertilizer application (kg/ha) and dry matter yields (Mg/ha) for beans in different regions in Europe.

	Beans (LfL)	Faba Beans (CB, Italy)	Common Bean (Romania)	Faba Beans (UK)
Yield average (Mg/ha)	2.67	1.38	2.23	3.82
P_20_5 (kg/ha)	37	19	40	43
K_2O (kg/ha)	44	0	0	47

Table 3: Main fertilizer application (kg/ha) and dry matter yields (Mg/ha) for peas in different regions in Europe.

	Peas (LfL, Germany)	Peas (LEL Germany)	Peas (Scotland)	Field Peas (UK)
Yield average (Mg/ha)	2.7	3.01	4.73	3.64
P_2O_5 (kg/ha)	35	38.5	49.05	35
K_2O (kg/ha)	44	49	49.8	40

Table 4: Main fertilizers application (kg/ha) and dry matter yields (Mg/ha) for soybeans in different regions in Europe.

	Soybean (LfL)	Soybean (LEL Germany)	Soybean (Romania)
Yield average (Mg/ha)	2.51	2.32	2.15
P_2O_5 (kg/ha)	44	43.74	55
K_2O (kg/ha)	50	52.38	0

Table 5: Main fertilizers application (kg/ha) and dry matter yields (Mg/ha) for chickpeas in different regions in Europe.

	Chickpea Bulgaria	Chickpea Organic (Spain)
DMg/ha	**1.82**	**2.01**
N (kg/ha)	30	0
P_2O_5 (kg/ha)	98.3	0
K_2O (kg/ha)	144.6	0

Table 6: Main fertilizers application (kg/ha) and dry matter yields (Mg/ha) for lupin in Germany.

	Lupin (LfL)
Yield average (Mg/ha)	2.56
P_2O_5 (kg/ha)	30
K_2O (kg/ha)	30

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2.1.1.2. Assumptions on other inputs

In addition to the fertiliser inputs referred to above, an average application of 400 kg/ha of lime (acidity corrector) was allocated to every crop regardless the type of legume or location. Lime is commonly applied on the soil in order to regulate pH, depending on soil type (AHDB, 2017). Lime is applied periodically, e.g. every five years, and often prior to "lime-hungry" crops including some legumes. The reasons lime is applied is to counteract acidification driven in part by fertiliser inputs. Therefore, allocating an equal burden from lime application to all crops in rotation, including in this case legumes, is a conservative approach.

The application of crop protection agents can vary hugely in terms of both the specific compounds applied and their quantities. This depends on, *inter alia*, crop varieties and specific local agronomic and pedoclimatic conditions. Furthermore, crop protection agents contribute primarily towards toxicity impact categories (Table 1), for which characterisation factors are somewhat uncertain (European Environmental Bureau, 2018). Therefore, application of crop protection agents was not considered in the crop LCA.

Work is ongoing work in the TRUE Project to identify the most appropriate way to model nutrient cycling and break crops effects of legumes within whole-rotation LCAs, e.g. to consider the benefits of carrying over nitrogen biologically fixed by legumes to subsequent crops in rotations. However, data presented in the Open Access Database exclude these non-standard LCA results in the first instance. These results will be published later in the project.

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2.1.1.2.1. Fertiliser compounds

Nitrogen, phosphate and potash fertilisers can be applied to the soil as different commercial formulations. Each formulation contains a different amount of each element (N, P, and K), involves different production processes (and burdens) and can release different amounts of N in particular to air as ammonia (Sanz-Cobena *et al.*, 2014) and nitrous oxide (Buys *et al.*, 2018). One example of that is urea, a fertiliser comprising 46% nitrogen. Urea also has carbon in its formulation (CH_4N_2O) and once applied to the soil, this fertiliser not only drives soil N_2O emissions, but causes CO_2 emission via hydrolysis of the carbon, and causes significantly more ammonia volatilization than other nitrogen fertilisers. Other commercial fertilisers may contain more than one element in their formulation, such as the triple superphosphate ($Ca\ (H_2PO_4)_2.\ H_2O$), which contains on average 15% Ca and 45% P_2O_5; or monoammonium phosphate ($NH_4H_2PO_4$), providing both phosphate or/and nitrogen to the crop. Some commercial products are designed to have N, P and K on a single product, such as the NPK (15, 15, 15).

In order to define specific fertiliser compounds applied, we first looked for primary data. These were available for chickpea cultivation in Spain and Bulgaria. In other cases, where primary data were not available, we investigated specific secondary data, in particular studies that define market mixes in particular countries or links between types of fertiliser applied and e.g. soil and local climate condition. This was necessary for modelled legume crops in Italy, Romania and Scotland based on data from Reckling *et al*, (2016). If no local secondary information were available, the fertilizer compounds assumed to deliver the known quantities of N, P and K were based on the average consumption mix in the relevant country over the most recent three years reported (from 2015 to 2017). The consumption rates were obtained from IFASTAT (2020). In Italy, phosphate (P_2O_5) was mostly applied in the format of ammonium phosphate, representing 49% of the total phosphate followed by 28% as NPK formulated compounds. In Romania and Germany, the situation is similar, phosphate comes mostly also from ammonium phosphate with 44.5% and 54.7% consumption rates respectively, followed by NPK formulated compounds. Potassium in Germany and the United Kingdom is usually (>70%) applied as potassium chloride (KCl). In contrast, Romania uses potassium oxide only in formulated NPK-containing products. In Italy, 47% of applied potassium originates from NPK compounds, and 31% as KCl.

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2.1.1.2.2. Machine operations

Assumptions about machine operations were necessary when primary data or local simulated data were not available, such as the number of fertiliser applications on a field. Field operations comprise tillage and ploughing, sowing, fertiliser application by broadcast spreading and harvesting. Field machinery operations include preliminary work on the farm, such as attaching the adequate machine to the tractor; transfer to field (with an assumed distance of 1 km); field work (per ha surface); transfer to farm and concluding work such as uncoupling machinery. Broadcaster fertiliser spreading with a 500 L carrying capacity was considered twice per crop, once for lime and once for spreading the NPK compounds. The harvesting was assumed as harvesting of ground crop harvesting, by complete harvester. That process also includes the aforementioned activities.

2.1.1.2.3. Seeds

The following rates for seed applications were assumed.

- Beans: 250 kg/ha (Redman, 2018)
- Peas: 200 kg/ha (Redman, 2018)
- Soybean: 92kg/ha (BASF, 2020)
- Lupin: 100 kg/ha (Government of western Australia, 2018)
- Chickpeas: 77 kg/ha (Blonk Consultants, 2014)

Seed production process burdens were taken from the Ecoinvent v.3.5 database (Moreno-Ruiz *et al*, 2018). No specific data existed for lupin seeds, so faba bean seeds were used as a proxy.

2.1.1.2.4. Field emissions

The following field emissions were calculated.

i) Direct emissions of nitrous oxide (N_2O) from crop residues that remain in the field and from synthetic N fertiliser applied based on IPCC guidelines, equation11.2 (IPCC, 2019).

ii) Indirect emission of N_2O due to volatilised synthetic nitrogen fertiliser applied - calculated based on IPCC, equation 11.9 (IPCC, 2019).

iii) Indirect emissions of N_2O due to leaching from synthetic nitrogen fertiliser applied and from crop residues that remain in the field – calculated based on IPCC, equation 11.10 (IPCC, 2019).

iv) Nitrogen oxides (NOx) produced during the denitrification process. NOx emissions occurs from direct N_2O emitted from soil and synthetic fertilisers only – calculated according to (Nemecek and Kägi, 2007).

v) Ammonia (NH_3) emission calculated based on the synthetic fertiliser fraction that volatilises. The fraction of volatilization changes according to the synthetic fertiliser formulation (Table 7) (IPCC, 2019).

vi) Carbon dioxide (CO_2) emissions due to Lime or Urea application according to (IPCC, 2006).

vii) Nitrate to water emissions from the leaching fraction of added synthetic fertilisers and from the crop residues that remain on the soil (IPCC, 2019).

viii) Phosphorus emissions (P) to water due to phosphate synthetic fertilisers added to the soil. Calculated based on LCAD Tool (Styles, Gibbons, Arwel P. Williams, *et al.*, 2015; Styles, Gibbons, Arwel Prysor Williams, *et al.*, 2015).

The emission factors necessary for these calculations can be found below in Table 7.

Table 7: Fraction of volatilization of synthetic nitrogen fertiliser added to soils according to the fertiliser type (IPCC, 2019).

Emission Factor	Reference /Source	Comment	Value
EF1= emission factor **for N added from synthetic fertiliser**	(IPCC, 2019)	Synthetic N in wet climates	0.016
FracGASF = **fraction of synthetic fertiliser N that volatilises as NH_3 and NOx, kg N volatilised (kg of N applied)-1**	(IPCC, 2019)	Value for Urea	0.15
		Value for Ammonium based	0.08
		Value for Nitrate based	0.01
		Value for ammonium-Nitrate based	0.05
		Default	0.11
EF4 = emission factor **for N_2O emissions from atmospheric deposition of N on soils and water surfaces, [kg N–N_2O (kg NH_3–N + NO_x–N volatilised)-1]**	(IPCC, 2019)	Wet climate	0.014
FracLEACH-(H) = fraction of all N added to/mineralised in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, kg N **(kg of N additions)-1**	(IPCC, 2019)	IPCC default values for wet climates	0.24
EF5 = emission factor **for N_2O emissions from N leaching and runoff, kg N_2O–N (kg N leached and runoff)-1**	(IPCC, 2019)	IPCC default values	0.011
NO_x**= Values of NOx emitted from N_2O**	(Nemecek and Kägi, 2007)	default values	0.21
Carbon emission factor **urea**	(IPCC, 2006)	default values	0.2
Carbon **emission factor limestone**	(IPCC, 2006)	default values	0.12
Carbon **emission factor dolomite**	(IPCC, 2006)	default values	0.13
P emissions factor **to water**	LCAD Tool (Styles, Gibbons, Arwel P. Williams, *et al.*, 2015; Styles, Gibbons, Arwel Prysor Williams, *et al.*, 2015)	default values	0.01

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2.1.2. Life Cycle Assessment of legume products

2.1.2.1. Chickpea pasta

Chickpea pasta footprints were modelled based on a mass functional unit of one serving of 80 g (dry weight) of cooked pasta. Activity data for chickpea pasta production were collected from Variva Ltd. The company also provided the primary data for the farm cultivation of wheat and chickpeas (see above). Packaging production, but not the disposal of packaging, was accounted for in this study. Figure 2 shows the system boundaries of the attributional LCA of chickpea pasta and durum wheat pasta production, from cradle to fork. The full life cycle inventory of all inputs and outputs, along with footprint data, are presented in the Open Access database. A full methodological description will shortly be undergoing peer-review.

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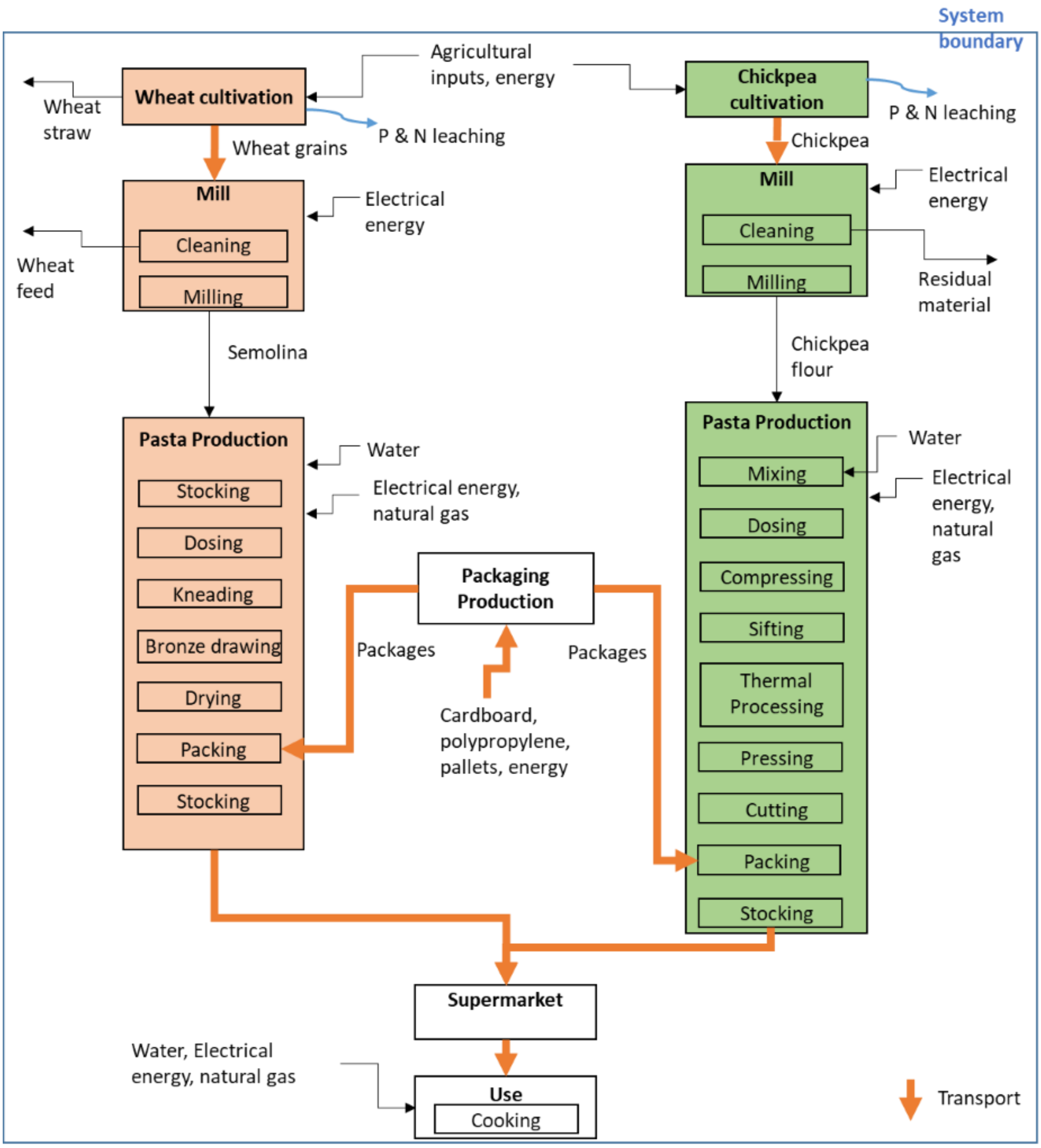

Figure 2: System boundaries of chickpea and durum wheat pasta production and cooking.

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2.1.2.2. Pea-protein balls

The environmental footprints of pea-protein balls made were calculated based on a mass functional unit of a single serving of 100 g cooked. Data on the pea protein balls were collected from IGV GmBH. The production, but not disposal, of packaging was considered in the study. Figure 3 shows the system boundaries of pea protein balls versus Swedish beef meatballs from cradle to fork.

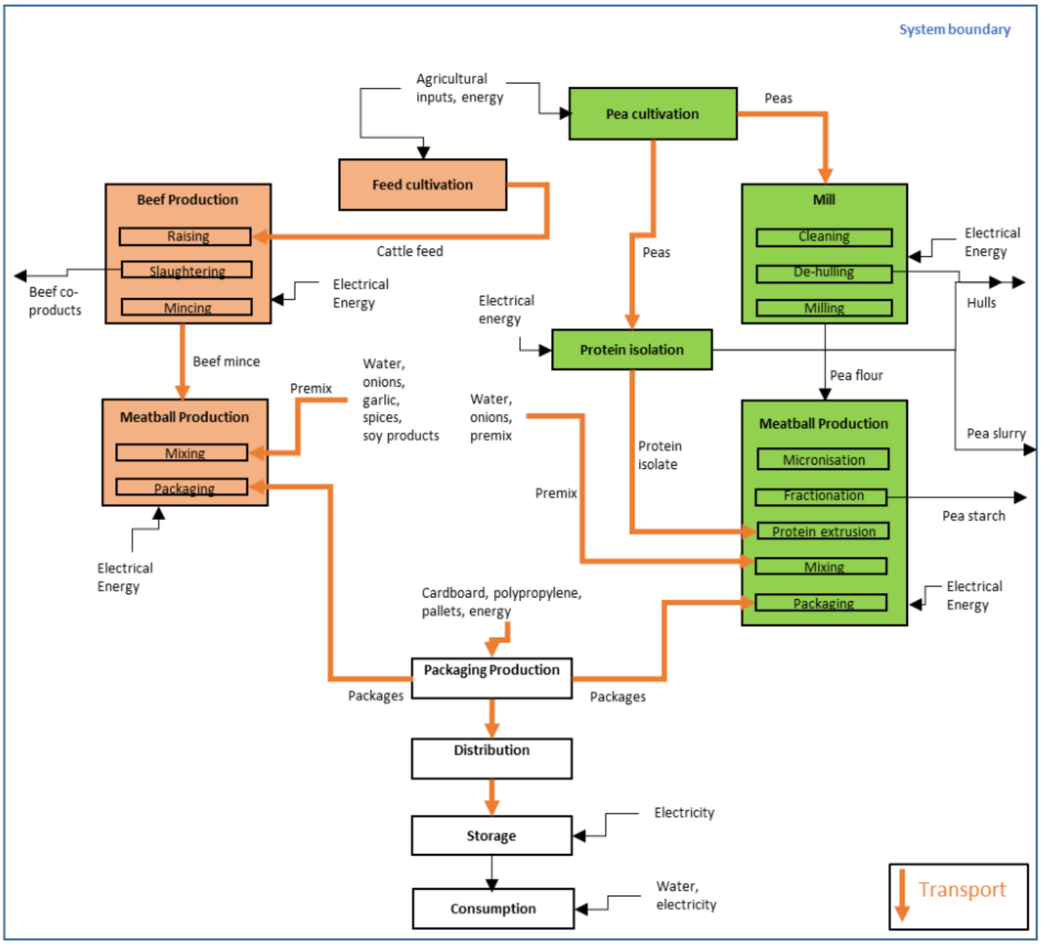

Figure 3: System boundaries of pea protein balls and Swedish beef meatballs.

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2.1.2.3. Gin produced using neutral spirit derived from distilled peas

Pilot trial data from Arbikie Distillery were used to model the environmental footprint of gin produced from pea kernels, with hulls and pot-ale co-products going to animal (cattle) feed. System burdens were allocated to gin and animal-feed co-products based on gross energy contents, but an alternative "system expansion" approach was also applied in which "credits" were attributed to the high-protein animal feed co-product assuming substitution of imported Brazilian soybean meal (Figure 4). For a full description of LCA methodology and results, see the peer-reviewed articles (Lienhardt, Black, Saget, Costa, Chadwick, R. M. Rees, *et al.*, 2019; Lienhardt, Black, Saget, Costa, Chadwick, R. Rees, *et al.*, 2019).

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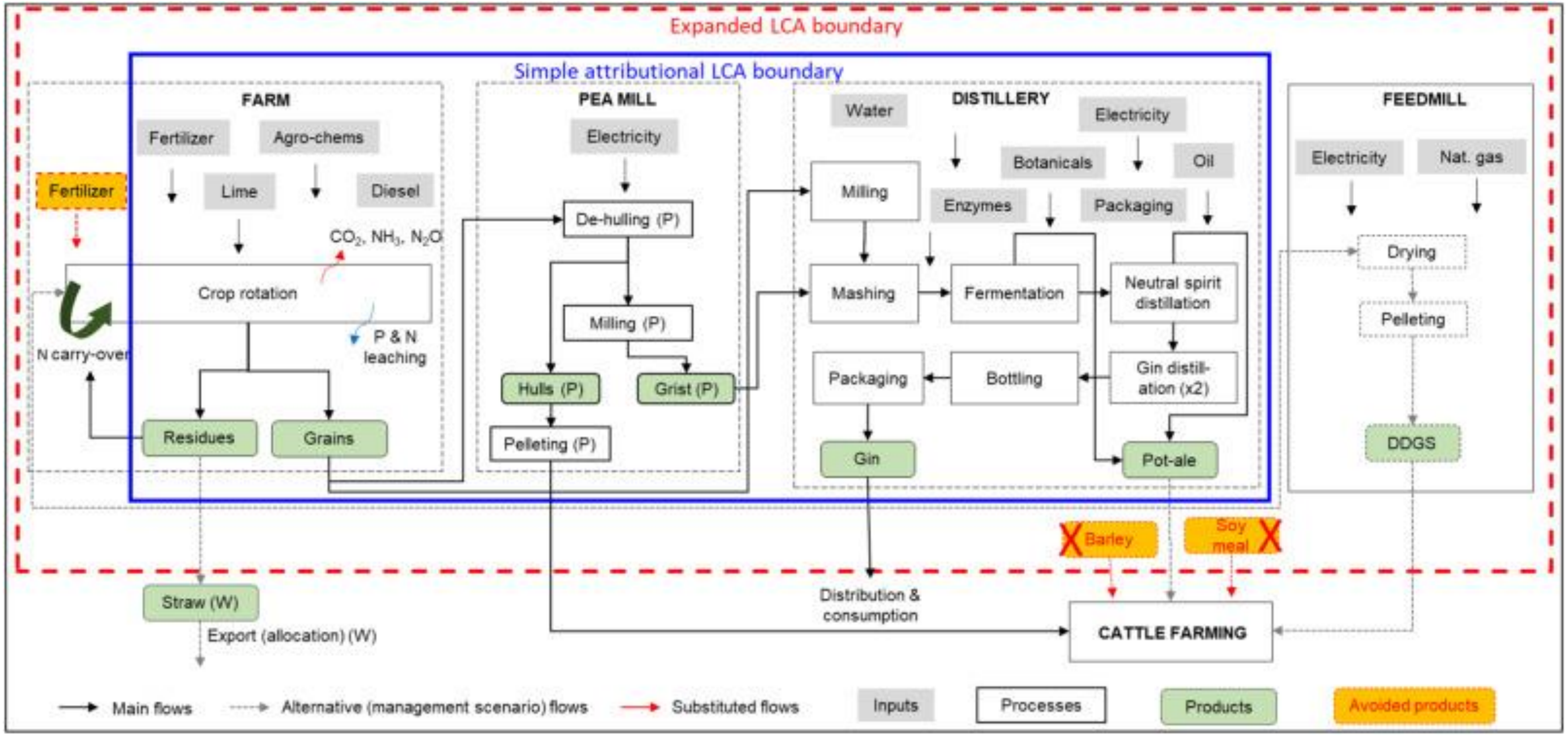

Figure 4. Processes considered within system boundaries for gin production from peas and wheat, based on simple attributional LCA (energy allocation) and system expansion

3. Results

3.1. Legumes crop

The LCA results for each legume crop can be observed on in Table 8 and Table 9. All the results are represented per kg of dry grain of each crop. These results are displayed, along with key inputs, in the Open Access Database.

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Table 8: Environmental burdens of producing one kg (dry weight) of peas and beans across major European agro-climatic regions

	Atlantic Region	**Atlantic Region**	**Continental region**	**Continental region**		**Continental region**	**Continental region**	**Atlantic Region**	**Mediterranean region**	
Indicator	**Pea, Scotland**	**Field Peas, United Kingdom**	**LFL Pea, Germany**	**BW LEL Pea, Germany**		**Common Bean, Romania**	**LFL Bean, Germany**	**Spring Beans, United Kingdom**	**Faba Bean, Italy**	**Unit**
Acidification terrestrial and freshwater	1.49×10^{-3}	2.54×10^{-3}	2.39×10^{-3}	2.26×10^{-3}		2.93×10^{-3}	2.46×10^{-3}	3.09×10^{-3}	4.33×10^{-3}	mol H+ eq
Cancer human health effects	3.75×10^{-9}	5.68×10^{-9}	6.31×10^{-9}	5.76×10^{-9}		1.14×10^{-8}	9.66×10^{-9}	7.38×10^{-9}	1.81×10^{-8}	CTUh
Climate change	3.81×10^{-1}	4.74×10^{-1}	5.16×10^{-1}	4.88×10^{-1}		6.08×10^{-1}	5.43×10^{-1}	5.08×10^{-1}	8.46×10^{-1}	kg CO_2 eq
Climate change - biogenic	1.62×10^{-3}	3.40×10^{-4}	2.78×10^{-3}	2.50×10^{-3}		3.37×10^{-3}	2.82×10^{-3}	3.80×10^{-4}	5.40×10^{-3}	kg CO_2 eq
Climate change - fossil	3.79×10^{-1}	4.74×10^{-1}	5.13×10^{-1}	4.85×10^{-1}		6.04×10^{-1}	5.40×10^{-1}	5.07×10^{-1}	8.40×10^{-1}	kg CO_2 eq
Climate change - land use and transform.	2.31×10^{-4}	3.70×10^{-4}	3.45×10^{-4}	3.37×10^{-4}		4.32×10^{-4}	3.57×10^{-4}	4.30×10^{-4}	6.10×10^{-4}	kg CO_2 eq
Ecotoxicity freshwater	7.31×10^{-1}	8.04×10^{-1}	1.25×10+00	1.14×10+00		4.44×10^{-1}	3.72×10^{-1}	9.31×10^{-1}	6.59×10^{-1}	CTUe
Eutrophication freshwater	1.18×10^{-4}	3.90×10^{-4}	1.47×10^{-4}	1.55×10^{-4}		1.93×10^{-4}	1.58×10^{-4}	4.90×10^{-4}	2.34×10^{-4}	kg P eq
Eutrophication marine	2.21×10^{-3}	6.00×10^{-3}	3.82×10^{-3}	3.44×10^{-3}		3.60×10^{-3}	6.79×10^{-3}	6.39×10^{-3}	2.37×10^{-2}	kg N eq
Eutrophication terrestrial	4.92×10^{-3}	7.49×10^{-3}	8.06×10^{-3}	7.38×10^{-3}		9.83×10^{-3}	8.32×10^{-3}	9.09×10^{-3}	1.53×10^{-2}	mol N eq
Ionising radiation, HH	1.34×10^{-2}	1.78×10^{-2}	1.93×10^{-2}	1.81×10^{-2}		2.34×10^{-2}	1.98×10^{-2}	1.97×10^{-2}	3.51×10^{-2}	kBq U-235 eq
Land use	$2.98\times10^{+2}$	$3.77\times10^{+2}$	$5.21\times10^{+2}$	$4.68\times10^{+2}$		$6.37\times10^{+2}$	$5.31\times10^{+2}$	$4.04\times10^{+2}$	$1.03\times10^{+3}$	Pt
Non-cancer human health effects	1.51×10^{-7}	2.99×10^{-7}	2.59×10^{-7}	2.36×10^{-7}		3.72×10^{-7}	3.10×10^{-7}	4.37×10^{-7}	5.91×10^{-7}	CTUh
Ozone depletion	2.27×10^{-8}	3.09×10^{-8}	3.90×10^{-8}	3.60×10^{-8}		4.71×10^{-8}	4.00×10^{-8}	3.40×10^{-8}	7.24×10^{-8}	kg CFC11 eq
Photochemical ozone formation, HH	1.45×10^{-3}	1.96×10^{-3}	2.40×10^{-3}	2.20×10^{-3}		2.92×10^{-3}	2.46×10^{-3}	2.07×10^{-3}	4.55×10^{-3}	kg NMVOC eq
Resource use, energy carriers	2.08	3.62	3.44	3.21		4.16	3.55	4.08	6.28	MJ
Resource use, mineral and metals	1.48×10^{-6}	2.64×10^{-6}	2.33×10^{-6}	2.25×10^{-6}		2.79×10^{-6}	2.41×10^{-6}	3.05×10^{-6}	3.95×10^{-6}	kg Sb eq
Respiratory inorganics	8.65×10^{-9}	1.74×10^{-8}	1.40×10^{-8}	1.36×10^{-8}		1.76×10^{-8}	1.48×10^{-8}	2.16×10^{-8}	2.50×10^{-8}	disease inc.
Water scarcity	1.86×10^{-1}	2.06×10^{-1}	3.03×10^{-1}	2.94×10^{-1}		1.49×10^{-1}	1.25×10^{-1}	2.52×10^{-1}	1.68×10^{-1}	m3 depriv.

TRUE has received funding from the European Union's Horizon 2020 Research & Innovation Action under Grant Agreement Number 727973.

Table 9: Environmental burdens of producing one kg (dry weight) of soybean, lupin or chickpea across major European biogeographical regions.

	Continental region				**Mediterranean region**		**Unit**
Indicator	**Soybean, Romania**	**BW LEL Soybean, Germany**	**LFL Soybean, Germany**	**LFL Lupine, Germany**	**Chickpea, Spain**	**Chickpea, Bulgaria**	
Acidification terrestrial and freshwater	3.04×10^{-3}	2.76×10^{-3}	2.55×10^{-3}	2.31×10^{-3}	2.68×10^{-3}	9.97×10^{-3}	mol H+ eq
Cancer human health effects	7.35×10^{-9}	6.93×10^{-9}	6.40×10^{-9}	7.48×10^{-9}	1.00×10^{-8}	1.39×10^{-8}	CTUh
Climate change	7.26×10^{-1}	6.89×10^{-1}	6.51×10^{-1}	5.15×10^{-1}	4.12×10^{-1}	9.73×10^{-1}	kg CO_2 eq
Climate change - biogenic	3.48×10^{-3}	3.23×10^{-3}	2.99×10^{-3}	2.89×10^{-3}	3.70×10^{-4}	7.00×10^{-4}	kg CO_2 eq
Climate change - fossil	5.75×10^{-1}	5.50×10^{-1}	5.22×10^{-1}	5.12×10^{-1}	4.09×10^{-1}	9.69×10^{-1}	kg CO2 eq
Climate change - land use and transform.	1.47×10^{-1}	1.36×10^{-1}	1.26×10^{-1}	3.33×10^{-4}	2.40×10^{-3}	2.95×10^{-3}	kg CO2 eq
Ecotoxicity freshwater	1.01×10+00	9.26×10^{-1}	8.56×10^{-1}	3.22×10^{-1}	1.47×10+00	1.91×10+00	CTUe
Eutrophication freshwater	2.18×10^{-4}	1.82×10^{-4}	1.68×10^{-4}	1.35×10^{-4}	1.00×10^{-4}	4.20×10^{-4}	kg P eq
Eutrophication marine	8.25×10^{-3}	7.64×10^{-3}	7.07×10^{-3}	3.42×10^{-3}	1.30×10^{-3}	1.10×10^{-2}	kg N eq
Eutrophication terrestrial	9.90×10^{-3}	9.19×10^{-3}	8.53×10^{-3}	7.99×10^{-3}	1.06×10^{-2}	3.77×10^{-2}	mol N eq
Ionising radiation, HH	2.31×10^{-2}	2.12×10^{-2}	1.96×10^{-2}	1.83×10^{-2}	1.78×10^{-2}	3.50×10^{-2}	kBq U-235 eq
Land use	$6.31\times10^{+2}$	$5.84\times10^{+2}$	$5.40\times10^{+2}$	$5.31\times10^{+2}$	$6.91\times10^{+2}$	$7.71\times10^{+2}$	Pt
Non-cancer human health effects	3.08×10^{-7}	2.83×10^{-7}	2.62×10^{-7}	3.02×10^{-7}	5.29×10^{-7}	6.54×10^{-7}	CTUh
Ozone depletion	4.50×10^{-8}	4.19×10^{-8}	3.87×10^{-8}	3.64×10^{-8}	3.44×10^{-8}	6.61×10^{-8}	kg CFC11 eq
Photochemical ozone formation, HH	2.98×10^{-3}	2.76×10^{-3}	2.56×10^{-3}	2.39×10^{-3}	2.55×10^{-3}	3.79×10^{-3}	kg NMVOC eq
Resource use, energy carriers	4.14×10+00	3.85×10+00	3.55×10+00	3.31×10+00	3.25×10+00	6.78×10+00	MJ
Resource use, mineral and metals	2.93×10^{-6}	2.72×10^{-6}	2.51×10^{-6}	2.23×10^{-6}	1.95×10^{-6}	5.02×10^{-6}	kg Sb eq
Respiratory inorganics	1.90×10^{-8}	1.70×10^{-8}	1.57×10^{-8}	1.35×10^{-8}	1.48×10^{-8}	6.92×10^{-8}	disease inc.
Water scarcity	1.82×10^{-1}	1.55×10^{-1}	1.43×10^{-1}	1.09×10^{-1}	5.41×10^{-2}	3.80×10^{-1}	m3 depriv.

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3.2. Legume products

Results shown in Table 12 are per 80 g DW cooked pasta. The factory to fork stages were modelled using data from Variva Ltd., a Bulgarian pasta company.

Table 12: Environmental footprint results for chickpea pasta, per 80 g dry weight serving (cooked).

Indicator	Chickpea pasta, Spain	Chickpea pasta, Bulgaria	Unit
Acidification terrestrial and freshwater	6.40×10^{-4}	1.25×10^{-3}	mol H+ eq
Cancer human health effects	1.22×10^{-9}	1.49×10^{-9}	CTUh
Climate change	1.18×10^{-1}	1.65×10^{-1}	kg CO_2 eq
Ecotoxicity freshwater	1.92×10^{-1}	2.27×10^{-1}	CTUe
Eutrophication freshwater	8.61×10^{-5}	1.10×10^{-4}	kg P eq
Eutrophication marine	1.80×10^{-4}	1.03×10^{-3}	kg N eq
Eutrophication terrestrial	1.53×10^{-3}	3.81×10^{-3}	mol N eq
Ionising radiation, HH	2.08×10^{-2}	2.21×10^{-2}	kBq U-235 eq
Land use	$6.52\times10^{+1}$	$7.21\times10^{+1}$	Pt
Non-cancer human health effects	4.14×10^{-8}	4.81×10^{-8}	CTUh
Ozone depletion	8.98×10^{-9}	1.14×10^{-8}	kg CFC11 eq
Photochemical ozone formation, HH	3.60×10^{-4}	4.40×10^{-4}	kg NMVOC eq
Resource use, energy carriers	1.47×10+00	1.74	MJ
Resource use, mineral and metals	1.45×10^{-7}	3.91×10^{-7}	kg Sb eq
Respiratory inorganics	4.23×10^{-9}	8.88×10^{-9}	disease inc.
Water scarcity	4.21×10^{-2}	7.02×10^{-2}	m^3 depriv.

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Results shown in Table 13 are per 100 g cooked protein balls. The factory to fork stages were modelled using data from IGV GmbH, a German company.

Table 103: Environmental footprint results for pea protein meatballs, per 100 g dry weight serving (cooked).

Continental region		
Indicator	**Pea protein ball, Germany**	**Unit**
Acidification terrestrial and freshwater	3.9×10^{-3}	mol H+ eq
Cancer human health effects	6.2×10^{-9}	CTUh
Climate change	5.3×10^{-1}	kg CO_2 eq
Ecotoxicity freshwater	5.9×10^{-1}	CTUe
Eutrophication freshwater	3.7×10^{-4}	kg P eq
Eutrophication marine	1.3×10^{-3}	kg N eq
Eutrophication terrestrial	1.1×10^{-2}	mol N eq
Ionising radiation, HH	1.6×10^{-1}	kBq U-235 eq
Land use	$3.1\times10^{+1}$	Pt
Non-cancer human health effects	1.3×10^{-7}	CTUh
Ozone depletion	6.0×10^{-8}	kg CFC11 eq
Photochemical ozone formation, HH	1.8×10^{-3}	kg NMVOC eq
Resource use, energy carriers	8.5	MJ
Resource use, mineral and metals	1.3×10^{-6}	kg Sb eq
Respiratory inorganics	2.4×10^{-8}	disease inc.
Water scarcity	3.5×10^{-1}	m^3 depriv.

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Results for pea gin are presented in Table 14, based on two methodological approaches to account for animal-feed co-products: allocation and system expansion.

Table 14: Environmental footprint results for pea gin/L, based on simple attributional LCA (left) and system expansion (right).

Indicator	**Allocated gin footprint**	**Expanded boundary gin footprint**	**Unit**
Acidification terrestrial and freshwater	1.30×10^{-2}	7.50×10^{-3}	mol H+ eq
Cancer human health effects	7.50×10^{-8}	5.30×10^{-8}	CTUh
Climate change	2.20×10+00	-2.20	kg CO_2 eq
Ecotoxicity freshwater	8.90×10+00	-5.90	CTUe
Eutrophication freshwater	4.30×10^{-4}	2.10×10^{-4}	kg P eq
Eutrophication marine	2.60×10^{-3}	-7.60×10^{-3}	kg N eq
Eutrophication terrestrial	2.40×10^{-2}	-8.30×10^{-3}	mol N eq
Ionising radiation, HH	2.70×10^{-1}	3.80×10^{-1}	kBq U-235 eq
Land use	2.60×10+00	1.80	m^2.yr
Non-cancer human health effects	5.30×10^{-7}	-1.00×10^{-6}	CTUh
Ozone depletion	3.10×10^{-7}	5.10×10^{-7}	kg CFC11 eq
Photochemical ozone formation, HH	6.30×10^{-3}	5.00×10^{-3}	kg NMVOC eq
Resource use, energy carriers	$2.90\times10^{+1}$	$3.90\times10^{+1}$	MJ
Resource use, mineral and metals	5.10×10^{-6}	7.40×10^{-6}	kg Sb eq
Respiratory inorganics	NA	NA	disease inc.
Water scarcity	NA	NA	m^3 depriv.

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4. Conclusions

The Open Access Database described in this deliverable report contains interim attributional LCA results for a range of important legume crops along with three novel legume products. Ongoing research will develop rotation-level footprints for legume-modified rotations, and consequential LCA of large-scale diet shifts and commodity substitutions with legumes across Europe. In the meantime, these provide freely available 'building blocks' for researchers and wider legume stakeholders to build up environmental profiles for legume value chains.

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Annex I - Background to the 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 sustainability*' – '*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 supplies 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.

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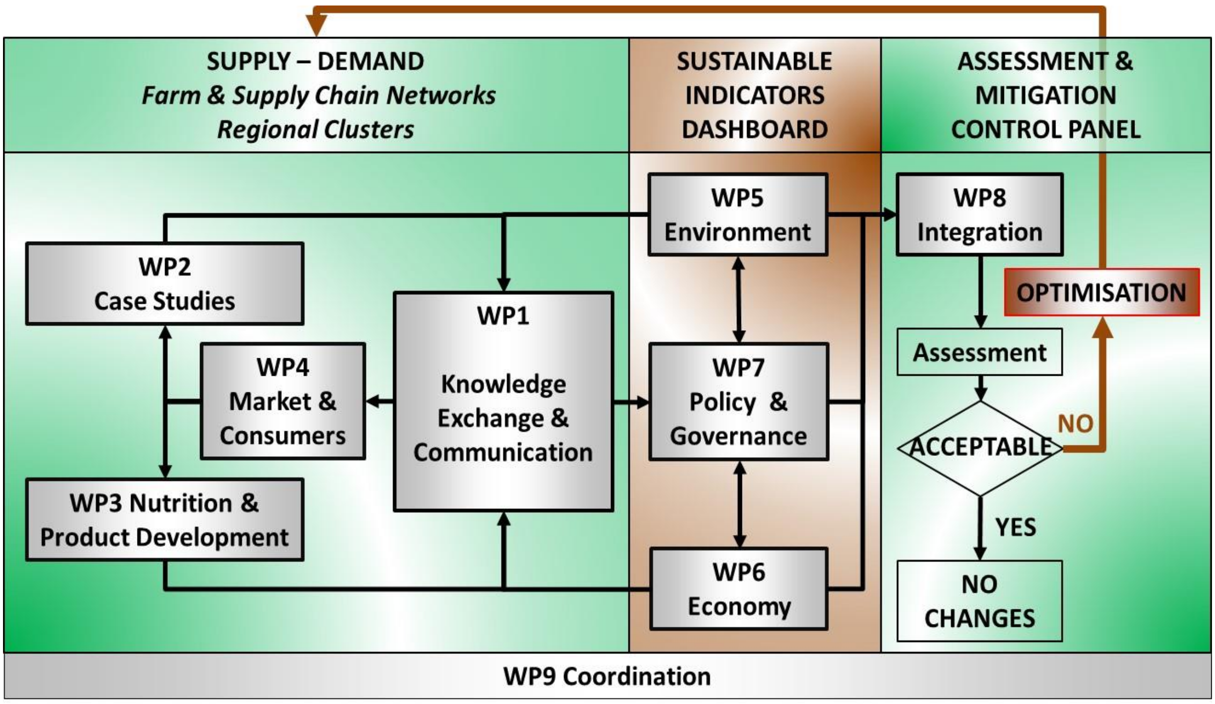
Work-package structure

The flow of information and knowledge in TRUE, from the 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	Universitaet 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 Fur 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 Inst. for Development of Međimurje County (PIRED)	Croatia	Development Agency

*Coordinating institution

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Objectives

Objective 1: Facilitate knowledge exchange (UHOH, WP1)

- *Develop a blueprint for co-production of knowledge*

Objective 2: Identify factors that contribute to successful transitions (AUA, WP2)

- *Relevant and meaningful Sustainable Development Indicators (SDIs)*

Objective 3: Develop novel food and non-food uses (UCP, WP3)

- *Develop appropriate food and feed products for regions/cropping systems*

Objective 4: Investigate international markets and trade (IFAU, WP4)

- *Publish guidelines of legume consumption for employment and economic growth*
- *EU infrastructure-map for processing and trading*

Objective 5: Inventory data on the environmental intensity of production (TCD, WP5)

- Life Cycle Analyses (LCA) -novel legumes rotations and diet change

Objective 6: Economic performance - different cropping systems (SRUC & UHOH, WP6)

- *Accounting yield and price risks of legume-based cropping systems*

Objective 7: Enable policies, legislation and regulatory systems (ESSRG, WP7)

- *EU-policy linkages (on nutrition) to inform product development/uptake*

Objective 8: Develop decision support tools: growers to policymakers (JSI, WP8)

- *User-friendly decision support tools to harmonise sustainability pillars*

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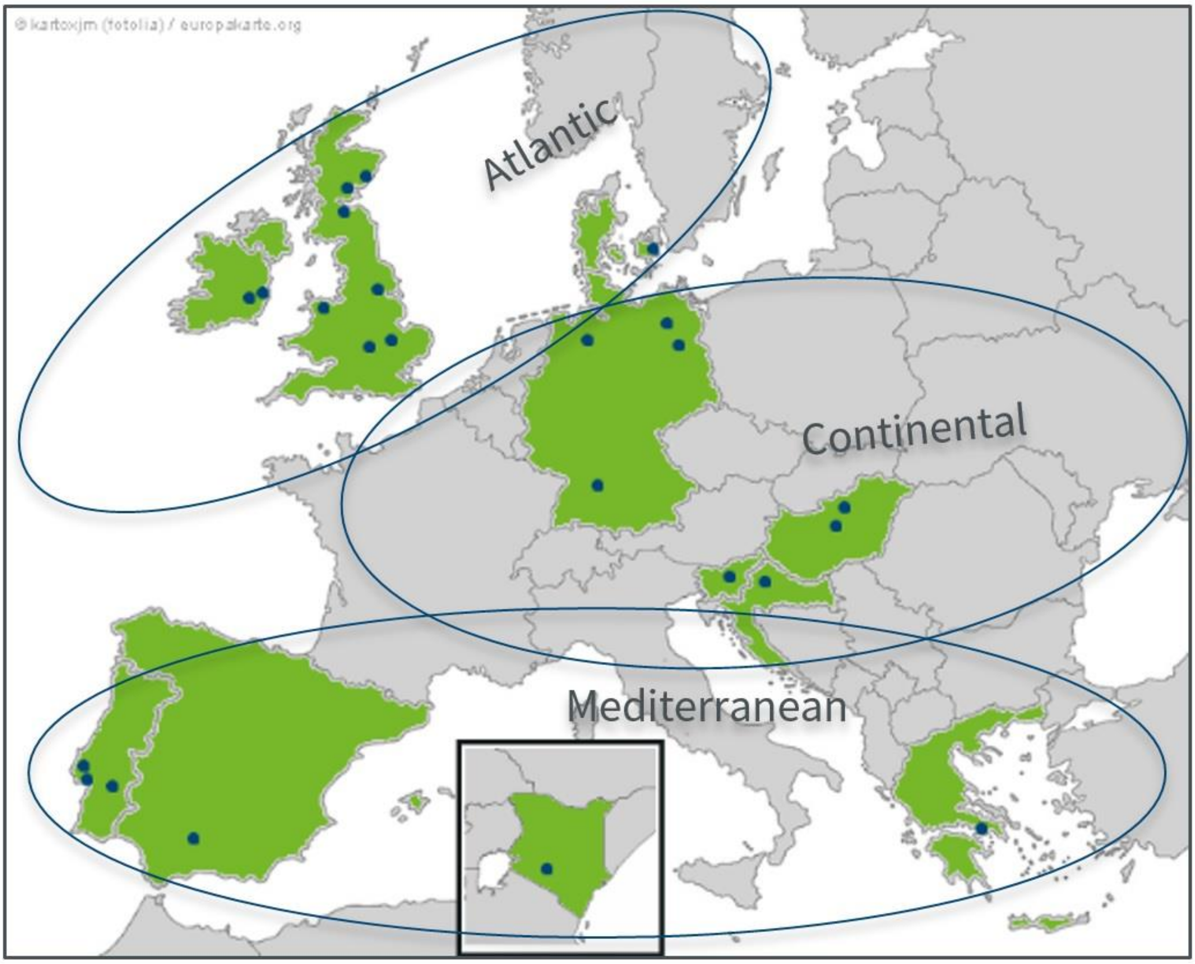
Legume Innovation Networks



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

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Available online at: www.true-project.eu.