2025

Agri-footprint 7 Methodology Report

Part 2: Description of Data

Better Food. Better Health. Better World.

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Agri-footprint

About us

Agri-footprint is a high-quality, comprehensive life cycle inventory (LCI) database focused on the agriculture and food sector. It covers data on agricultural products: food, feed, and agricultural intermediate products. Since its conception in 2014, Agri-footprint has been critically reviewed and is now widely accepted by the food industry, LCA community, scientific community, and governmental institutions.

Mérieux NutriSciences | Blonk is a leading international expert in food system sustainability, inspiring and enabling the agri-food sector to give shape to sustainability. Our purpose is to create a sustainable and healthy planet for current and future generations. We support organizations in understanding their environmental impact in the agri-food value chain by offering advice and developing tailored software tools based on the latest scientific developments and data.

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Part 2: Description of Data

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1. Introduction

The main objective of Agri-footprint is to bring data and methodology together to make it easily available for the LCA community.

This document contains background information on the methodology, calculation rules and data that are used for the development of the data published in the 7th release of Agri-footprint and on the website (www.blonksustainability.nl/agri-footprint). This document will be updated whenever new or updated data is included in Agri-footprint.

Agri-footprint is available as a library within SimaPro and OpenLCA. Information, FAQ, logs of updates and reports are publicly available via the website (www.blonksustainability.nl/agri-footprint). Agri-footprint users can also ask questions via this website. The project team can also be contacted directly via tools@blonksustainability.nl , or the LinkedIn user group.

While part 1 of the report outlines the choices in methodology and general principles used in the development of the database, this document (part 2), outlines the sources of data and specific modelling choices for the development of the individual datasets. Part 3 describes the main differences in impact calculation between the current and previous Agri-footprint.

The document is structured to cover the main groups of life cycle inventories in Agri-footprint. It follows a standard agricultural supply chain (Figure 1): the cultivation of crops (Chapter 2.1), the post-harvesting of cultivated crops (Chapter 4), market mixes of crops including transportation (Chapter 5), the processing of crops and animal products into food and feed (Chapter 0), and the animal systems, including also the feed compound processing and slaughtering of animals (Chapter 7). The last chapter covers the various background processes (Chapter 8).

Of course, the supply chain is not always so straightforward; there are indeed many loops, such as the co-products of animal slaughtering being processed into feed ingredients. Also, some supply chains omit one or more of the steps described (e.g. various crops do not have post-harvest processing or processing).

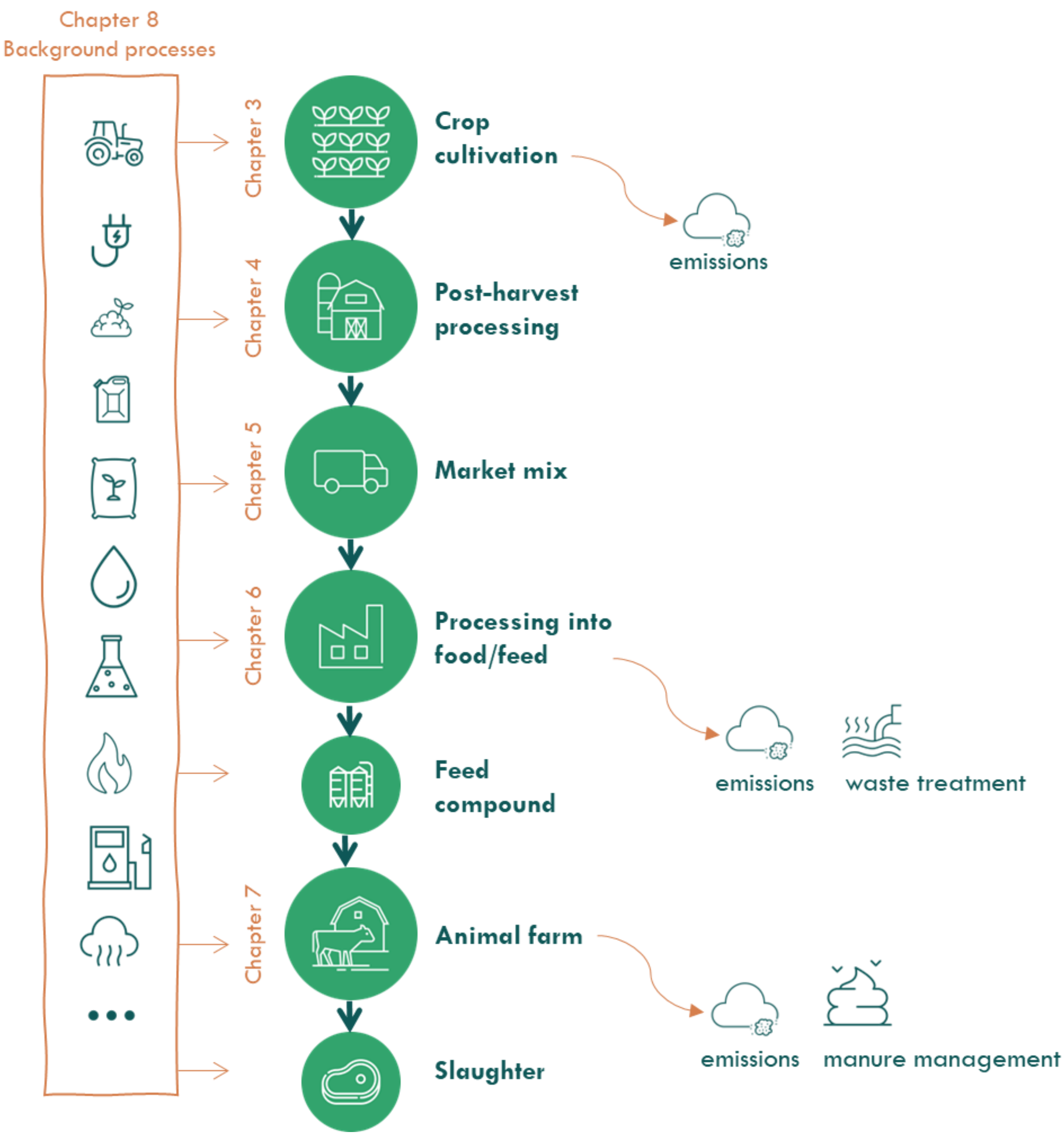


Figure 1: General agri-food supply chain representative of most Agri-footprint life-cycle stages. Indicated are also the chapters of reference for the data description.

2. What's new?

2.1 Agri-footprint 7

1. Update on activity data for cultivation: crop yields from FAOstat (section 3.2.1), LUC data from the LUC tool (section 3.2.4), manure data from FAOstat (section 3.2.5), synthetic fertilizer use from the NPK model (section 3.2.6), seed input from FAOstat (section 3.2.9) and pesticide data from FAOstat (section 3.2.11).
2. Update on data for market mixes: update of production and trade data from FAOstat (Chapter 5).
3. Update of Ecoinvent background data to version 3.10.
4. Update in methodology:
    a. Crop System Efficiency Index (CSEI) is applied to the cultivation modelling, replacing the double cropping methodology that was applied in earlier versions. More on this in section 3.2.3.
5. Extra products:
    a. Crude oil market mix for Indonesia, India and Philippines
    b. Groundnut shells and groundnut, shelled for China
    c. Market mixes for peanuts for 15 countries
    d. Post-harvest and market mix for seed cotton in the United States of America
6. Some products are renamed:
    a. Products from rice cultivation renamed from "at farm" to "at paddy"
    b. Crude peanut oil to Crude groundnut oil, to align with products name of the crop and other co-products
    c. Cream, from skimmed milk to Cream (skimmed)
    d. Maize germ meal expeller (pressing) to Maize germ expeller
    e. Maize germ meal extracted (solvent) to Maize germ meal (solvent)
    f. Sunflower seed expelled dehulled (pressing) to Sunflower seed expeller (pressing)
    g. Ethanol from sugarcane renamed to ethanol from molasses

7. Bug fixes:
    a. Pesticide data: correction in insecticide and fungicide emissions
    b. Peat emissions: correction in methane emissions for grass cultivations
    c. Energy content roughages: energy content of grass, fodder beet, lucerne at cultivation stage corrected
    d. Crop residues emissions for the following crops improved: sugar beet (based on IPCC: Potatoes and tubers), sugar cane (Perennial grasses), peas green (Beans and pulses) and beans, green (Beans and pulses)
    e. Price for linseed expeller corrected.
    f. Yield values corrected for Maize forage/US, from 8174 to 45477.8 kg/ha.
    g. The energy input for roughages updated:
        - Fodder Beet/NL
        - Grass (16% DM)/AU; BE; BR; DE; DK; ES; FR; GB; IE; IT; NL; NZ; PL; NZ; PL and US.
        - Lucerne/DK; IT; NL and US
        - Maize forage/BE; BR; DE; DK; FR; IT; NL; NZ; PL and US.
    h. Comments on “broiler fattening, at farm” and “one-day-chicken” are now correct.
    i. For “broiler fattening, at farm/JP” the inputs origin is corrected.
    j. Grass silage intake for beef system corrected, from 122137 to 260928 kg intake.
    k. Emissions and energy inputs for animal systems are now regionalized correctly.

2.2 Table of Changes

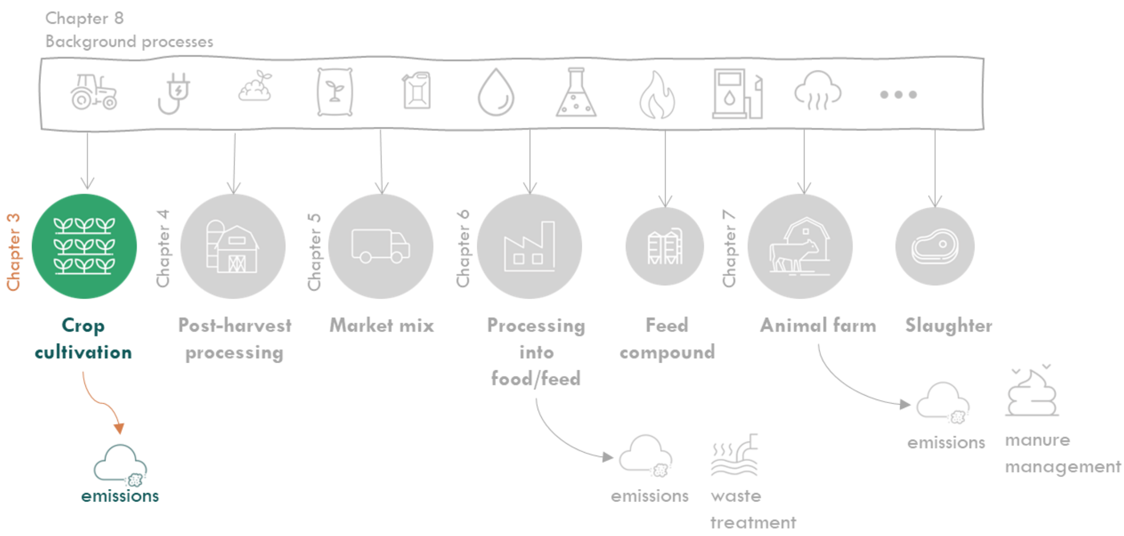
Table 2-1 Table of changes between Agri-footprint 6.3 and 7

Phase & chapter in methodology		Same data and modelling as Agri-footprint 6.3[1]	New in Agri-footprint 7		
			Updates in methodology	Updated data	Expansions
Cultivation	3	Water use (3.2.2) Land Use Change (3.2.4) Nitrogen from manure (3.2.5) Inorganic fertilizer application rates (3.2.6) Capital goods (3.2.7) Lime (3.2.8) Seed input (3.2.9) Transport requirements and emissions (3.2.10)	Water requirement ratio's removed for irrigation and rainwater (3.2.2) Fertilizer IFA data reports all the EU countries individually and no longer as a group (3.2.6). Crop System Efficiency Index (3.2.3). Negative emissions for heavy metal emissions converted to zero (3.4.8)	Yields (3.2.1). Yield for Maize forage/US. LUC data (3.2.4) Manure application (3.2.5) Inorganic fertilizer application rates & fertilizer consumption statistics (3.2.6) Seed input (3.2.9) Pesticide inputs (3.2.11) Energy input for roughages (3.2.12).	Bovine manure left and applied for Roughages (section 3.2.5) Inclusion of grassland management for roughages (section 3.2.4).
Post-harvest	4	Deshelling/dehusking activity data (4.1) Country specific drying process (4.2)			
Market mixes	5	Transport (5.3) Regionalized fertilizer market mixes (8.4)		Market mix data as derived from FAO trade data (5)	

[1] Please note that even while no changes are reported in this column, the impact for a product from these processes can still change from AFP6.3 to AFP7. For example, when activity data for processing soybeans into a feed ingredient such as soybean meal (chapter 6) have not changed, but the activity data for cultivation (chapter 3) of the ingoing material soybean have changed, there will still be a difference in the soybean meal LCI for AFP6.3 vs AFP7.

Processing	6	Slaughterhouse and meat processing (6.1.2) Processing of: • Cereal products (6.3) • Pulse products (6.5) • Roots and tuber products (6.6) Sugar products (6.7) Price data for economic allocation (6.4)			
Animal production systems	7	All animal systems Beef system (7.2) Slaughterhouse (7.5)		Corrections in broiler fattening comments. Some emissions and energy inputs for animal systems are now regionalized correctly. Wheat grain input added for Swine compound feed. Grass silage intake for beef system corrected.	
Background data	8	Transport (8.2) Fertilizer production (8.3)		Ecoinvent background data update to version 3.10.	

3. Cultivation of Crops



	AFP 1	AFP 2	AFP 3	AFP 4	AFP 5	AFP6	AFP 7
Crops	30	>300	>1000[2]	>1350[2]	>1700[2]	>1431[2]	**>1431[2]**
Market mixes				64	398	420	**457**
Food products	35	86	163	163	188	212	**212**
Animal production systems	4	4	4	4	4	37	**37**

Table 3-1 Number of processes included in Agri-footprint by version

3.1 Introduction and reader's guide

Data on crop cultivation is collected on a country basis and based on publicly available sources. Data has been updated to the period 2018 - 2022 data during the development of Agri-footprint 7 since most public data is available for these years. All modelled cultivations represent the national average within the respective country. Due to the lack of data, no distinction can be made between organic or conventional cultivation. For the crop cultivation model in Agri-footprint, the following outputs, inputs, and resources are considered:

- Crop yield (kg crop product / ha cultivated)
  - Including co-production and allocation properties (price, dry matter, gross energy content)
- Water use: for irrigation and rainwater (m3/ha/yr)

[2] Agri-footprint includes inventories for seed production starting from version 3.0

- Land occupation (ha/yr)
- Land transformations (ha/yr)
- Animal manure inputs (type and application rate kg N / ha cultivated)
- Fertilizer inputs (various types for NPK) (kg/ha)
- Capital good usage (ha/yr)
- Lime input (kg/ha)
- Start material input (kg/ha)
- Transport requirements for all of inputs (km)
- Pesticide inputs (kg/ha)
- Energy inputs (type and quantity / ha cultivated)

From these resources and inputs, the following emissions are quantified in the crop cultivation model:

- Nitrous oxide emissions
- Ammonia emissions
- Nitrate emissions
- Nitric oxide emissions
- Carbon dioxide emissions (LUC, lime, urea and urea solutions)
- Phosphorus emissions
- Pesticide emissions
- Heavy metal emissions
- Peat oxidation emissions
- Specific emissions:
    - Methane emissions for rice

All crop cultivation processes that have been modelled have a similar structure, an example of the crop cultivation process card in SimaPro® is shown in Figure 2.

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation %	Waste type	Category	Comment	
Wheat grain, at farm/DE Economic	Output_0 = 7.94E3	kg	Mass	83.87 %	Compost	Agricultural\Plant prod...\Cereals	Dry matter: 0.87 kg/kg, Gross Energy 15.86 MJ/kg	Crop yield & co-production
Wheat straw, at farm/DE Economic	Output_1 = 4.07E3	kg	Mass	16.13 %	Compost	Agricultural\Plant prod...\Cereals	Dry matter: 0.90 kg/kg, Gross Energy 16.17 MJ/kg	

Add

Outputs to technosphere: Avoided products	Amount	Unit	Distribution	SD2 or 2S	Min	Max	Comment

Add

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2	Min	Max	Comment	
Water, unspecified natural origin, DE	in water	0.000008017	m3	Undefined				Irrigation water based on yield and "blue water footprint" (Mekonnen & Hoekstra, 2010)	Water use
Occupation, annual crop	land	10000	m2a	Undefined				Land use based on estimated crop cycle described in Agri-Footprint 5.0 methodology report	Land use
Transformation, from forest, unspecified	land	0	m2	Undefined				Land use change impacts based on Direct Land Use Change Assessment Tool 2018, Blonk Consultants, Gouda	Land use change
Transformation, from grassland	land	0	m2	Undefined				Land use change impacts based on Direct Land Use Change Assessment Tool 2018, Blonk Consultants, Gouda	
Transformation, from permanent crop	land	3.414	m2	Undefined				Land use change impacts based on Direct Land Use Change Assessment Tool 2018, Blonk Consultants, Gouda	
Transformation, from annual crop	land	104.6	m2	Undefined				Land use change impacts based on Direct Land Use Change Assessment Tool 2018, Blonk Consultants, Gouda	
Transformation, to annual crop	land	108	m2	Undefined				Land use change impacts based on Direct Land Use Change Assessment Tool 2018, Blonk Consultants, Gouda	

Add

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	SD2	Min	Max	Comment	
Manure (pig), at farm/RER Economic	3522	kg	Undefined				Swine manure applied for soil maintenance. Based on FAO data on manure management (2012-2016) and methodology described in appendix 4 of Vellinga et al. (2013)	Manure input
Manure (poultry), at farm/RER Economic	308.9	kg	Undefined				Poultry manure applied for soil maintenance. Based on FAO data on manure management (2012-2016) and methodology described in appendix 4 of Vellinga et al. (2013)	
Di ammonium phosphate, as 100% (NH3)2HPO4 (NPK 22-57-0), at plant/RER E	24.79	kg	Undefined				Derived from Ammonium phosphate consumed in Germany (IFASTAT, 2016-2012) and total NPK use for Wheat cultivation (IFA 2011)	Fertilizer input
Ammonium sulfate, as 100% (NH4)2SO4 (NPK 21-0-0), at plant/RER Economic	35.13	kg	Undefined				Derived from Ammonium sulphate consumed in Germany (IFASTAT, 2016-2012) and total NPK use for Wheat cultivation (IFA 2011)	
Calcium ammonium nitrate (CAN), (NPK 26.5-0-0), at plant/RER Economic	261	kg	Undefined				Derived from Calc.amm. nitrate consumed in Germany (IFASTAT, 2016-2012) and total NPK use for Wheat cultivation (IFA 2011)	
NPK compound (NPK 15-15-15), at plant/RER Economic	21.02	kg	Undefined				Derived from N P K compound consumed in Germany (IFASTAT, 2016-2012) and total NPK use for Wheat cultivation (IFA 2011)	
Liquid urea-ammonium nitrate solution (NPK 30-0-0), at plant/RER Economic	64.71	kg	Undefined				Derived from Nitrogen solutions consumed in Germany (IFASTAT, 2016-2012) and total NPK use for Wheat cultivation (IFA 2011)	
Urea, as 100% CO(NH2)2 (NPK 46.6-0-0), at plant/RER Economic	97.51	kg	Undefined				Derived from Urea consumed in Germany (IFASTAT, 2016-2012) and total NPK use for Wheat cultivation (IFA 2011)	
PK compound (NPK 0-22-22), at plant/RER Economic	9.366	kg	Undefined				Derived from P K compound consumed in Germany (IFASTAT, 2016-2012) and total NPK use for Wheat cultivation (IFA 2011)	
Single superphosphate, as 35% Ca(H2PO4)2 (NPK 0-21-0), at plant/RER Econon	0.1822	kg	Undefined				Derived from Single superphos. consumed in Germany (IFASTAT, 2016-2012) and total NPK use for Wheat cultivation (IFA 2011)	
Triple superphosphate, as 80% Ca(H2PO4)2 (NPK 0-48-0), at plant/RER Econom	3.377	kg	Undefined				Derived from Triple superphos. consumed in Germany (IFASTAT, 2016-2012) and total NPK use for Wheat cultivation (IFA 2011)	
Potassium chloride (NPK 0-0-60), at plant/RER Economic	27.36	kg	Undefined				Derived from Potassium chloride consumed in Germany (IFASTAT, 2016-2012) and total NPK use for Wheat cultivation (IFA 2011)	
Potassium sulfate (NPK 0-0-50) (Mannheim), at plant/RER Economic	1.849	kg	Undefined				Derived from Potassium sulphate consumed in Germany (IFASTAT, 2016-2012) and total NPK use for Wheat cultivation (IFA 2011)	
Basic infrastructure, at farm/GLO Economic	1	ha	Undefined				Capital good used for cultivation	Capital good
Lime fertilizer, at plant/RER Economic	400	kg	Undefined				Lime use ph balancing, amount based on default values used in Feedprint (2012)	Lime input
Wheat grain, start material, at seed production/DE Economic	152.8	kg	Undefined				Amount of start material	Start material
Transport, truck 10-20t, EURO4, 80%LF, empty return/GLO Economic	114.9	tkm	Undefined				Transport of manure (30 km)	Transport
Transport, truck 10-20t, EURO4, 80%LF, empty return/GLO Economic	55.03	tkm	Undefined				Transport of other materials (50 km)	
Insecticide, at plant/RER Economic	0.2052	kg	Undefined				Insecticide use derived from Pesticide model	Pesticide input & emissions
Fungicide, at plant/RER Economic	0.3398	kg	Undefined				Fungicide use derived from Pesticide model	
Herbicide, at plant/RER Economic	0.9704	kg	Undefined				Herbicide use derived from Pesticide model	
Insecticide emissions, at farm/RER	0.2052	kg	Undefined				Emissions of insecticide active ingredients used within a specific region	
Fungicide emissions, at farm/RER	0.3398	kg	Undefined				Emissions of fungicide active ingredients used within a specific region	
Herbicide emissions, at farm/RER	0.9704	kg	Undefined				Emissions of herbicide active ingredients used within a specific region	

Add

Inputs from technosphere: electricity/heat	Amount	Unit	Distribution	SD2	Min	Max	Comment	
Energy, from diesel burned in machinery/RER Economic	4157	MJ	Undefined				Total fuel demand for on-field activities of arable crops (except irrigation). Derived from "Energy model for crop cultivation"	Energy inputs
Energy, from diesel burned in machinery/RER Economic	0.000005367	MJ	Undefined				Total fuel demand for irrigating arable crops. Derived from "Energy model for crop cultivation"	
Electricity mix, AC, consumption mix, at consumer, < 1kV DE S	0.000003853	MJ	Undefined				Total electricity use for irrigating arable crops. Derived from "Energy model for crop cultivation"	

Add

Outputs

Emissions to air	Amount	Unit	Distribution	SD2	Min	Max	Comment	
Carbon dioxide, fossil	176	kg	Undefined				Lime and dolomite emissions based on tier 1 calculations described in Guidelines for National Greenhouse Gas Inventories (IPCC, 2006)	Lime emissions
Carbon dioxide, fossil	88.87	kg	Undefined				Fertilizer emissions based on tier 1 calculations described in Guidelines for National Greenhouse Gas Inventories (IPCC, 2006)	Fertilizer emissions
Dinitrogen monoxide	2.357	kg	Undefined				Direct Fertilizer emissions based on tier 1 calculations described in Guidelines for National Greenhouse Gas Inventories (IPCC, 2006)	
Dinitrogen monoxide	0.7661	kg	Undefined				Indirect Fertilizer emissions based on tier 1 calculations described in Guidelines for National Greenhouse Gas Inventories (IPCC, 2006)	
Ammonia	10.59	kg	Undefined				Fertilizer emissions based on tier 2 ammonia emissions described in Air Pollutant Emission Guidebook (EMEP/EEA, 2016)	
Nitrogen monoxide	1.05	kg	Undefined				Fertilizer emissions based on NO emission based on global mean fertilizer-induced NO emission (EMEP/EEA, 2016)	
Carbon dioxide, land transformati	92.22	kg	Undefined				Land use change impacts based on Direct Land Use Change Assessment Tool 2018, Blonk Consultants, Gouda	Land use change emissions
Dinitrogen monoxide	0.5483	kg	Undefined				Direct Manure emissions based on tier 1 calculations described in Guidelines for National Greenhouse Gas Inventories (IPCC, 2006)	Manure emissions
Dinitrogen monoxide	0.1782	kg	Undefined				Indirect Manure emissions based on tier 1 calculations described in Guidelines for National Greenhouse Gas Inventories (IPCC, 2006)	
Ammonia	8.473	kg	Undefined				Manure emissions based on tier 1 calculations described in Guidelines for National Greenhouse Gas Inventories (IPCC, 2006)	
Dinitrogen monoxide	1.291	kg	Undefined				Direct Crop residues emissions based on tier 1 calculations described in Guidelines for National Greenhouse Gas Inventories (IPCC, 2006)	Crop residue emissions
Dinitrogen monoxide	0.2906	kg	Undefined				Indirect Crop residues emissions based on tier 1 calculations described in Guidelines for National Greenhouse Gas Inventories (IPCC, 2006)	

Add

Emissions to water	Sub-compartment	Amount	Unit	Distribution	SD2	Min	Max	Comment	
Nitrate		199.3	kg	Undefined				Fertilizer emissions based on tier 1 calculations described in Guidelines for National Greenhouse Gas Inventories (IPCC, 2006)	Fertilizer emissions
Phosphorus		0.4857	kg	Undefined				Fertilizer emissions based on total P and "applied (P component)" impact factor (ReCiPe, 2013)	
Cadmium		38.15	mg	Undefined				Heavy metals emissions based on heavy metals emissions described in Nemecek & Schnetzer (2012)	Heavy metal emissions
Chromium		20760	mg	Undefined				Heavy metals emissions based on heavy metals emissions described in Nemecek & Schnetzer (2012)	
Copper		3331	mg	Undefined				Heavy metals emissions based on heavy metals emissions described in Nemecek & Schnetzer (2012)	
Mercury		0.7381	mg	Undefined				Heavy metals emissions based on heavy metals emissions described in Nemecek & Schnetzer (2012)	
Nickel		0	mg	Undefined				Heavy metals emissions based on heavy metals emissions described in Nemecek & Schnetzer (2012)	
Lead		290.7	mg	Undefined				Heavy metals emissions based on heavy metals emissions described in Nemecek & Schnetzer (2012)	
Zinc		27720	mg	Undefined				Heavy metals emissions based on heavy metals emissions described in Nemecek & Schnetzer (2012)	
Nitrate		46.35	kg	Undefined				Manure emissions based on tier 1 calculations described in Guidelines for National Greenhouse Gas Inventories (IPCC, 2006)	Manure emissions
Phosphorus		0.4667	kg	Undefined				Manure emissions based on total P and "applied (P component)" impact factor (ReCiPe, 2013)	
Nitrate		109.2	kg	Undefined				Crop residues emissions based on tier 1 calculations described in Guidelines for National Greenhouse Gas Inventories (IPCC, 2006)	Crop residue emissions

Add

Emissions to soil	Sub-compartment	Amount	Unit	Distribution	SD2 or 2S	Min	Max	Comment	
Cadmium	agricultural	2136	mg	Undefined				Heavy metals emissions based on heavy metals emissions described in Nemecek & Schnetzer (2012)	Heavy metal emissions
Chromium	agricultural	135200	mg	Undefined				Heavy metals emissions based on heavy metals emissions described in Nemecek & Schnetzer (2012)	
Copper	agricultural	-3688	mg	Undefined				Heavy metals emissions based on heavy metals emissions described in Nemecek & Schnetzer (2012)	
Mercury	agricultural	26.09	mg	Undefined				Heavy metals emissions based on heavy metals emissions described in Nemecek & Schnetzer (2012)	
Nickel	agricultural	9827	mg	Undefined				Heavy metals emissions based on heavy metals emissions described in Nemecek & Schnetzer (2012)	
Lead	agricultural	16900	mg	Undefined				Heavy metals emissions based on heavy metals emissions described in Nemecek & Schnetzer (2012)	
Zinc	agricultural	441200	mg	Undefined				Heavy metals emissions based on heavy metals emissions described in Nemecek & Schnetzer (2012)	

Add

Figure 2: Cultivation LCI example of Wheat cultivation in Germany as shown in SimaPro

Data on crop cultivation is a combination of:

- Activity data that is directly derived from publicly available data
- Activity data that is obtained through modelling using publicly available data
- Emission modelling using international recognized standards based on the gathered activity data

3.2 Collected activity data

3.2.1 Yield

Yield of almost all crops in Agri-footprint are based on yields per harvested area provided in FAO Statistics (FAO, 2025a), using a five-year average from 2018 till 2022. One hectare of harvested area therefore becomes the functional unit of the LCI, unless something else is specified. From these five datapoints the standard deviation is obtained. Some crops are not reported in FAO Statistics, these include grass, maize forage and lucerne (based on literature). The LCIs of these specific crops are updated in Agri-footprint 7 based on information from more specific sources.

3.2.1.1 Co-production

In the new Agri-footprint version, the yield of the co-product is based on the fraction of “Above ground dry matter” (AGDM) or crop residues that can be harvested. The default harvesting factors for crop (groups) are based on “sustainable removal rates” or “practically removable fractions”. Since harvesting of the co-product varies considerably around the world, largely depending on demand for these roughages locally, it was chosen to use half of the maximum removal rates from literature. This resulted that following removal fractions are used in Agri-footprint:

- 33.5% for all cereals, except maize (15%), based on a “sustainable removal fraction” of two-thirds for cereals and 30% for maize (Searle and Bitnere, 2017).
- 10% for all pulses and soybeans, based on the “practically removable fraction” of pulses (Mcdonald, 2010)
- 30% for linseed and rapeseed, based on “typically recoverable fractions” (Copeland and Turley, 2008).

3.2.1.2 Properties of the products

Dry matter content and gross energy content of the products are based on (INRA et al., 2018; USDA, 2020). Economic value of the main and co-products are based on market trading prices for feed commodities in the United Kingdom[3,4].

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[3] https://www.fwi.co.uk/prices-trends
[4] https://farming.co.uk/prices/baled-hay-straw

Table 3-2: Prices used for economic allocation of specific crop groups in Agri-footprint (6.3)

Product(group)	Price (£/kg)	Co-product	Price (£/kg)	Comment
Cereal grain	0.16	Cereal straw/stover	0.06	Cereals based on wheat prices
Pulse	0.23	Pulse straw	0.03	Pulses based on pea prices
Linseed Rapeseed Soybeans	0.3	Straw	0.05	All three crops based on rapeseed prices

3.2.2 Water use

3.2.2.1 Irrigation water

The amount of irrigation water for all Agri-footprint cultivation processes is based on the 'blue water footprint' assessment of (Mekonnen and Hoekstra, 2010a). The estimation of irrigation water is based on the CROPWAT approach (Allen et al., 1998). The blue water footprint refers to the volume of surface and groundwater consumed as a result of the production of a good. The model used takes into account grid-based dynamic water balances, daily soil water balances, crop water requirements, actual water use and actual yields. The water footprint of crops have been published per country in m^3/tonne of product (Mekonnen and Hoekstra, 2010a). Combined with FAO yields (2014-2018) the total consumed blue water footprint is calculated in m^3/ha using the following equation:

$$Blue\ water\ consumption\ (\frac{m3}{ha}) = Blue\ water\ footprint\ \left(\frac{m3}{ton}\right) * Yield\ crop\ \left(\frac{ton}{ha}\right)$$

Blue water use is reported in Agri-footprint as "Water, unspecified natural origin" (sub-compartment 'in water'), with a specific country suffix, making the elementary flow region specific (e.g. "Water, unspecified natural origin, FR" – in water). Hereby the user is enabled to perform water stress related impact studies.

3.2.2.2 Rainwater

Agri-footprint 7 includes 'green water footprint' or rainwater to cultivation inventory. The same approach was used as described for irrigation water. The substance flow of rainwater is not characterized by the most commonly applied characterization methods. But since it is now included in the inventory, the user can adjust the method to include rainwater in their calculations in various LCA software.

3.2.3 Land Use Change

Fossil CO_2 emissions resulting from direct land use change were estimated using the "Direct Land Use Change Assessment Tool version 2021" that was developed alongside the PAS 2050-1 (BSI, 2012). This tool provides a predefined way of calculating greenhouse gas (GHG) emissions from land use change based on FAO statistics and IPCC calculation rules, following the PAS 2050-1 methodology. GHG emissions arise when land is transformed from one use to another. The most well-known example of this is conversion of forests to crop land. This tool can be used to calculate the emissions for a specific country-crop combination and attribute them to the cultivated crops.

The calculation has been under development continuously since the publication of the PAS2050-1 and has been reviewed by the World Resource Institute and has, as a result, earned the 'built on GHG Protocol' mark. This tool can be used to quantify land use change emissions in conformance with the GHG Protocol standards (http://www.ghgprotocol.org/standards). The tool provides three basic functionalities, based on data availability of the user. All these approaches are described in the PAS 2050-1 published by BSI, and are made operational in this tool using various IPCC data sources (IPCC, 2019a, 2006a).

For Agri-footprint, the option "calculation of an estimate of the GHG emissions from land use change for a crop grown in a given country if previous land use is not known" was used. This estimate is based on a number of reference scenarios for previous land use, combined with data from relative crop land expansions based on FAOSTAT data. These FAO statistics then provide an estimate of the share of the current cropland (for a given crop) which is the result of land use change from forest and/or grassland to cropland. This share is calculated based on an equal amortization period of 20 years, as described in the PAS 2050-1. This results in three scenarios of land transformation (m^2/ha*year): forest to (perennial or annual) cropland, grassland to (perennial or annual) cropland, and transformation between perennial and annual cropland, depending on the crop under study. The resulting GHG emissions are then the weighted average of the carbon stock changes for each of these scenarios. We use the weighted average because, in our opinion, this most accurately estimates the Land Use Change. In the development of Agri-footprint we have the principles that we want to provide consistent data across inventories, and the 'best estimate' rather than a worst-case approach, which the PAS 2050-1advises. Please see Annex B of the PAS2050-1 for an example calculation (BSI, 2012).

In case of grassland management and roughages, data gaps from FAO statistics had to be solved. Since no grassland expansion was reported in the past 20 years by FAO statistics, no LUC impact was accounted for grassland management. Due to data gap on maize silage cultivation, maize grain was used as an approximation for maize silage in estimating the land use change impacts. Due to data gap on lucerne cultivation, LUC was assumed to be 0 (country in scope in the database are ES, IT and US).

The carbon stock change calculations used for each are based on IPCC rules and default data for soil carbon stocks and carbon stock in grassland (IPCC 2006 and 2019); FAO statistics on land coverage of specific crops, total annual and perennial cropland and total grassland and forestland to calculate conversions (including data up to 2018) and the Forest Resource Assessment provides country-specific carbon stocks in natural forests (FAO, 2020). The basic approach is to first calculate the carbon stocks in the soil and vegetation of the old situation and then subtract these from those of the new situation, to arrive at the total carbon stock change. The assumptions for carbon stocks are dependent on country, climate & soil type. Emissions from nitrogen mineralization are related to oxidation of soil organic carbon and are included in the total emissions from land use change. A nice example of such a calculation is provided in the 'Annotated example of a land carbon stock calculation' document, which can be found at the European Commission's Biofuel site. The soil organic carbon changes and related biomass references are taken from various IPCC tables, which are documented in the direct land use change tool itself.

The calculated CO_2 emissions from land use change (LUC) have been added in the database, the substance flow name is "Carbon dioxide, land transformation". Note that land transformations from forest, grassland, arable crops and perennial crops are also included for each cultivation (in m^2 per harvested hectare). For arable crops, the total “transformation to” and “transformation from” in the LCIs have been

3.2.4 Crop System Efficiency Index

3.2.4.1 Implementation of the Crop System Efficiency index (CSEI)

With increasing global food demand, land use efficiency gains are part of the solution to halt deforestation and other natural land conversions for agricultural land. Multiple cropping is a practice where a plot of land is subsequently planted with varying crops and harvested multiple times in a year. This practice is increasingly applied worldwide, contributing to increasing harvested areas without demanding additional agricultural land. An example is a crop rotation system of planting soybeans during the spring-summer seasons, harvesting the crops in late summer or early fall, and planting wheat in the same field after and harvesting this in spring-summer seasons (Figure 3).

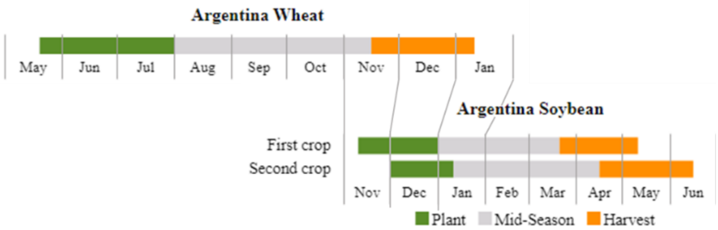

Figure 3: Multiple cropping in Argentina (2 crops/ha/yr) (Argentina Soybean Area, Yield and Production).

To represent multiple cropping practices more accurately in LUC and land occupation calculations, we propose the use of the ‘Crop System Efficiency Index’ (CSEI). What we are calculating with the Crop System Efficiency Index, is the (country average) length of the harvest cycle of temporary crops (in yr/harvest). The index considers both land efficiency gains from multiple cropping, and efficiency losses due to temporary fallow land.

To calculate the CSEI we are no longer referring to annual and perennial crops, this methodology required a specific classification of crops to be align with FAOSTAT on how the data is provided.

Temporary crops: This category belongs to all crops with a productive period < 5 years. In this category we can find all annual, and a few perennial crops. According to the FAOSTAT definition, the perennial crops included in this category are ***asparagus***, ***strawberries***, ***pineapples***, ***bananas*** and ***sugar cane***.

Permanent crops: This category belongs to all crops with a productive period < 5 years, all the other perennial crops are in this category.

The other components required are the *Temporary Crops*, *Fallow land* and *Temporary fallow* areas from FAOSTAT. With this information we can start to calculate the Crop System Efficiency Index (CSEI).

Within Life Cycle Assessment (LCA) studies it is often required to report the emissions emerging from LUC, such as the clearance of forests to cultivate crops, separately. However, multiple cropping activities have previously not been considered in the implemented methodology. The assumption that the occupation duration for a harvest of temporary crops is always 1 year, led to an overestimation of both the LUC emissions and the land occupation impact, especially in countries where multiple cropping practices are ubiquitous. Multiple cropping primarily occurs in tropical and subtropical regions where there is sufficiently long rainy season or suitable irrigation to cultivate two or three crops sequentially within a single agricultural year. The CSEI affects the Land Use Change emissions, Land occupation, Lime emissions, Peat emissions and the Capital goods. The CSEI is not crop specific, each country analyzed poses one CSEI value.

3.2.4.2 Calculating the Crop System Efficiency Index

The calculation starts with the *Harvested area of temporary crops* and *Temporary Cropland* to decide if multiple cropping is the case.

$$Multiple\ Crop\ Index\ (MCI)[yr/harvest] = \frac{Temporary\ Cropland\ [ha*yr]}{Harvested\ area\ of\ temporary\ crops\ [ha*harvest]}$$

In case the result is smaller than 1, this is related to multiple cropping: the sum of harvested area for temporary crops is larger than the total temporary cropland.

The reason for an MCI of greater than 1, is not always clear or straightforward. Comparing national statistics with FAO data for the Netherlands showed that the harvested area of some fodder crops was not included in the harvested cropland in FAO data but was included in the total temporary cropland area. This example shows that a MCI > 1 can be associated with incomplete FAO data and does not always point to land use inefficiencies. Therefore, the following rule is implemented:

If MCI > 1, the value should be adjusted to 1, leading to a MCI corrected value (MCIc)

As fallow land is associated with crop rotation and multiple cropping, it is allocated to all Temporary Cropland. This is expressed in the Fallow Land Index (FI).

$$\text{Fallow land } Index\ (FI)[-] = \frac{Temporary\ Fallow\ Land\ [ha*yr]}{Temporary\ Cropland\ [ha*yr]}$$

In the last step the adjusted Crop System Efficiency Index can be obtained:

$$System\ Efficiency\ Index\ (CSEI)\ [yrharvest] = MCIc\ [yrharvest] * (1+FI\ [-])$$

For AFP 7, the values used to calculate the CSEI were derived from land use data from 2002, as reported by the FAO. In the next release of AFP, this issue will be corrected by updating the dataset to the corresponding reference year. Currently only 1 value for CSEI is calculated per country, meaning that this value represents the average value of CSEI for all temporary crops in that country. For countries where the CSEI could not be calculated, data gaps were filled using the country-specific crop cycle values from AFP 6.3 as a reference for temporary crops.

3.2.4.3 Possible CSEI results:

CSEI < 1: Multiple cropping is the case, more than one crop is produced and harvested per year, per hectare. The land occupation value calculated is multiplied by this value.

CSEI = 1: There is no multiple cropping, or the efficiency gains from multiple cropping are counteracted by efficiency losses from fallow land. The land occupation value should not be modified.

CSEI > 1: Per hectare harvested, more than 1 hectare should be destinated to this process. The land occupation value should be multiplied by this value.

3.2.5 Nitrogen from manure

The calculation for manure application rates are based on the methodology used in the Feedprint study (Vellinga et al., 2013a). The manure application rates are estimated using statistics on the total number of animals, the manure produced and the total area on which manure can be applied. This estimation results in a country average amount of manure applied per hectare (independent of the crop being cultivated). In reality, the amount of manure applied will depend on the specific crop that is being grown and on the geographic and temporal availability of manure. However, such detailed information is not available and since application of manure will be of benefit to arable soil for a number of years and cropping cycles (as it releases nutrients relatively slowly), this average manure application rate is maintained/justified.

Amount of nitrogen applied to soils from poultry and swine manure is derived from FAO Statistics on manure management (FAO, 2025b, using 5 year average (2018-2022). Based on the methodology described in the Feedprint study, only manure from swine and poultry are assumed to be applied to arable agricultural soils. For roughages the bovine manure is included, for applied bovine manure, we calculate the total manure applied and we divide it by the Sum of Temporary and Permanent Meadows and Pastures (ha) reported. And for the manure left, the total bovine manure left is divided by the difference between Permanent Meadows and Pastures, and the Permanent Meadows and Pastures Cultivated (2018-2022).

Using the nitrogen content of swine and poultry manure (Wageningen UR, 2012), the total amount of manure from poultry and manure ‘as is’ are quantified which is added to the LCI.

3.2.6 Inorganic fertilizer application rates

The fertilizer information in Agri-footprint is derived using statistics and aggregate data to estimate application rates for crops in specific regions. The majority of these fertilizer application rates, in terms of NPK per crop country combination were derived from the “NPK model”. The model is based on national statistics available on NPK land application per country (IFA, 2025), production and harvested area of country-crop combinations (FAO, 2025a) and estimates of fertilizer use by crop category per country (IFA, 2022). More information about the NPK model can be found in Appendix A. For AFP 7 the NPK model can determine the NPK use for member countries of the European Union, other sources were used as well. These include: (Pallière, 2011) for crops in Europe, and data from (Rosas, 2011) and Fertistat (FAO, 2011) for crops outside of Europe. Data from Pallière were preferred because they are more recent. The source of NPK for fertilizer use is mentioned in the overall process description for each specific crop.

To match these total N, P and K application rates, to specific fertilizer types (e.g. Urea, NPK compounds, super triple phosphate etc.), 5 year average (2018-2022) data on regional fertilizer consumption rates from IFA statistics were used (IFA, 2025).

3.2.7 Capital goods

The capital goods in cultivation processes are called “Basic infrastructure”, which is the same process as modelled in the PEFCR for feed (European Commission, 2018a). The assumption is that 30 m^2 of roads and pavements are applied per hectare and affected by the CSEI. Using concrete slabs, 15 cm thick, lifetime of 33.3 years (Wageningen UR, 2015a) and density of 2400 kg/m^3, the total concrete input for basic infrastructure can be determined, which is 327.27 kg concrete per hectare with a 33 years as amortization period.

3.2.8 Lime

Lime input for adapting the soil acidity for Agri-footprint cultivation processes is assumed to be 400 kg by default, independent of country or crop. This is based on lime application rates described in Feedprint, which uses an uniform distribution between 0 and 800 kg lime for every crop country combination (van Zeist et al., 2012a).

3.2.9 Seed input

Seed input or start material for cultivation is based on FAO crop cultivation statistics (FAO, 2025). Seed input in Agri-footprint is based on 5-year average data from 2018 till 2022. In Agri-footprint versions 3 and 4, seed input was based on crop country specific data, in which the seed input varied considerably among countries, due to data quality issues. In order to tackle this, it was chosen to use global average seed input for each crop as start material, based on the same data from Agri-footprint 5 onward[5].

3.2.9.1 Yield correction for cultivation of start material

In Agri-footprint 3 and 4 the background process of seed material was a copy of the cultivation process of the same crop country combination, with the exception that the yield of the seed background process is 80% of the cultivation process. Hereby the seed production process is less productive and in terms of environmental performance the seed has higher environmental burdens.

In Agri-footprint 7, the yield correction factor is different per crop(type) based on data of Feedprint.

Table 3-3: Overview of assumptions in Feedprint cultivation seed production that is applied in Agri-footprint

Group:	Yield Ratio:	Includes:
Cereals	1	Barley, oat, rice, rye, sorghum, triticale, wheat

[5] https://blonksustainability.nl/news/behind-the-scenes-seed-application-and-seed-production-in-agri-footprint

Potatoes	0.66	Potatoes,
Maize	0.33	Maize, maize silage
Oilseed	0.57	Linseed, rapeseed, sunflower seed,
Grasses	0.15	Grasses
Forage legumes	0.06	Lucerne
Grain legumes	1	Lupine, soybean, green peas, green beans, dry beans, dry peas, broad bean, chickpeas, cow peas, lentil, pigeon peas
Sugar beet	0.04	Fodder beet, sugar beet, onions, curly kale

3.2.10 Transport requirements

Transport requirements are based on:

- A transportation distance of 30 km for manure
- A transportation distance of 50 km for all other inputs

3.2.11 Pesticide input and emissions

There is a complex relation between the total amount of pesticides used and ecotoxicity impact caused, due to large differences between the toxicities (i.e. characterization factors) of individual substances. In order to accurately predict impacts from ecotoxicity, specific pesticides applications are needed (in kg active ingredient (a.i.) per pesticide/ha). In practice, however, this level of detail in pesticide application data is often difficult to achieve. There are only a few countries who monitor and report reliable data on the application of pesticide active ingredients per crop.
Until Agri-footprint 4, pesticide application inventory based on a thorough literature study were included. This approach proved difficult to continue as the database grew and limited the possibility of updating the data on a yearly basis.

Since AFP 5, a more simplified approach is used. In Agri-footprint 7, pesticide applications per crop and country of cultivation (kg a.i./ha) were modelled for insecticides, herbicides and fungicides (based on 5-year average data from 2018 till 2022) recent FAO statistics for total pesticide use (FAO, 2025c) and the modelling rationale explained in 11.2Appendix II. Use of statistical data allows for continuous update of this inventory and permits to easily include new crop/country cultivation processes to the growing Agri-footprint portfolio. Moreover, following a modelling logic rather than trying to compile the scarcely available specific pesticide application rates per country and crop, gives, in our opinion, the 'best estimate' of pesticide inputs per crop.
The pesticide inventory in Agri-footprint 7 is a default inventory which can be used to gain insights in the toxicity impact of biomass taking into account the limitations as reported in this chapter. Primary data for pesticide data (when available) are always preferred over this inventory.

3.2.12 Energy input

Up until Agri-footprint version 4 energy use was calculated based on data obtained from the farm simulation tool MEBOT (Schreuder et al., 2008). Since Agri-footprint version 5, the "Energy model for crop cultivation" was used to determine the energy demand (van Paassen et al., 2018). The tool was developed in co-operation between representatives from Wageningen University and Blonk Consultants. The model has a bigger scope and uses the most recent specific indicators, such as yield, mechanization factors and irrigation, to determine the energy use at cultivation stage more accurately. Also, the energy demand for irrigation is reported separately (diesel as well as electricity demand for irrigation), hereby it would be possible to make more detailed contribution analysis of irrigation. Roughages energy input updated for AFP 7.

3.3 Collected activity data for roughages

Key activity data for roughages are not available in publicly available statistics like FAOstat. Therefore, for roughages like fodder beet, grass, maize forage and lucerne that are part of the Agri-footprint database, specific datapoints are collected differently. The table below is an overview of the key activity data collected for roughages: Yield and synthetic fertilizer use. For manure a similar approach is used for roughages as described in section 3.2.6, with the exception that manure requirements for roughages are fulfilled by manure from bovine. Due to a lack of information for pesticide applications, we assume 0 kg/ha used.

Table 3-4 Key activity data for roughages

Country	Roughage	Yield (kg./ha)	Source	Irrigation (m3/ha)	N (kg N/ha)	P (kg P2O5/ha)	K (kg K2O/ha)	Source Fertilizer
DE	Grass	37500	(Smit, Metzger, & Ewert, 2008)	0	66	5	4	Pallière, C. (2011) Grass based on "Total Grassland"
FR	Grass	31250	(Smit, Metzger, & Ewert, 2008)	9	36	9	17	Pallière, C. (2011) Grass based on "Total Grassland"
IE	Grass	62500	(Smit, Metzger, & Ewert, 2008)	0	67	11	16	Pallière, C. (2011) Grass based on "Total Grassland"
IT	Grass	40000	ISTAT, 2018	64	4	22	1	Pallière, C. (2011) Grass based on "Total Grassland"
NL	Grass	60606	(Smit, Metzger, & Ewert, 2008)	0	150	17	5	Pallière, C. (2011) Grass based on "Total Grassland"
PL	Grass	25000	(Smit, Metzger, & Ewert, 2008)	0	87	28	28	Pallière, C. (2011) Grass based on "Total Grassland"
GB	Grass	56250	(Smit, Metzger, & Ewert, 2008)	0	54	8	11	British Survey of Fertiliser Practice Fertiliser use on farm for the 2019 crop year
US	Grass	38087	USDA, National Agricultural Statistics Service, 2017. Data for hay.	0	58	7	13	IFA (2017) Assessment of Fertilizer Use by Crop at the Global Level; USDA 2017 for total managed grassland area.
NZ	Grass	75000	Aden, N., Change, C., Farm, F., Barron, N., & Shannon, M. (2015). Grassland Production & Utilisation	0	140	57	24	Reviewer NZ
AU	Grass	62500	Aden, N., Change, C., Farm, F., Barron, N., & Shannon, M. (2015). Grassland Production & Utilisation (Value for NZ)	0	3	9	2	IFA (2017) Assessment of Fertilizer Use by Crop at the Global Level, Australian bureau of statistics, 2017 for total managed grassland area.
BE	Grass	37500	(Smit, Metzger, & Ewert, 2008)	0	124	29	50	Pallière, C. (2011) Grass based on "Total Grassland"
BR	Grass	75000	Maciel, A.M. Life Cycle Assessment of Milk Production. 2019. 82p. (Ecology Master Dissertation) - Federal University of Juiz de Fora, Institute of Biological Sciences. Juiz de Fora, 2019.	0	0.6	0.3	0.2	IFA (2017) Assessment of Fertilizer Use by Crop at the Global Level, FAOstat, 2021 for total managed grassland area.
ES	Grass	15710	Eurostat 2018-2022 data	0	2	1	1	Pallière, C. (2011) Grass based on "Total Grassland"
DK	Grass	65000	(Smit, Metzger, & Ewert, 2008)	0	27	3	12	Pallière, C. (2011) Grass based on "Total Grassland"
DE	Maize forage	43196	FAO 2014-2018, based on Maize	20	75	15	14	Pallière, C. (2011) Maize silage based on "Silage maize"
FR	Maize forage	41255	FAO 2014-2018, based on Maize	841	40	15	30	Pallière, C. (2011) Maize silage based on "Silage maize"
IT	Maize forage	52000	ISTAT, 2018	1091	80	5	5	Pallière, C. (2011) Maize silage based on "Silage maize"
NL	Maize forage	46478	FAO 2014-2018, based on Maize	178	29	20	6	Pallière, C. (2011) Maize silage based on "Silage maize"
PL	Maize forage	28642	FAO 2014-2018, based on Maize	24	126	66	73	Pallière, C. (2011) Maize silage based on "Silage maize"
BE	Maize forage	44671	FAO 2014-2018, based on Maize	10	55	30	55	Pallière, C. (2011) Maize silage based on "Silage maize"
BR	Maize forage	85000	Maciel, A.M. Life Cycle Assessment of Milk Production. 2019. 82p. (Ecology Master Dissertation) - Federal University of Juiz de Fora, Institute of Biological Sciences. Juiz de Fora, 2019.	46	10	55	62	Based on EC reviewer data

DK	Maize forage	46478	FAO 2014-2018, based on Maize	178	47	7.1	0	Pallière, C. (2011) Maize silage based on "Silage maize"
IT	Lucerne	27300	Eurostat 2014-2018 data	0	3	0	0	Pallière, C. (2011) Lucerne based on "Fodder (legumes)"
ES	Lucerne	37567	Eurostat 2014-2018 data	0	12	40	40	Pallière, C. (2011) Lucerne based on "Fodder (legumes)"
DK	Lucerne	49716	Eurostat 2014-2018 data	0	96	8	41	Pallière, C. (2011) Lucerne based on "Fodder (legumes)"
US	Lucerne	19768	https://www.extension.purdue.edu/extmedia/ay/ay-331-w.pdf	0	0	45	55	https://www.extension.purdue.edu/extmedia/ay/ay-331-w.pdf
NL	Fodder beet	17500	Fodder beet, growers guidelines 2019. in UK	0	200	80	400	"https://verantwoordeveehouderij.nl/upload_mm/1/3/c/891019e0-89e6-4ab4-83da-c317bac6c542_PDFadviesbemesting.pdf#page=169"
NL	Lucerne	27500	Phosphorus and Potassium Fertilization of Alfalfa. Sofia Lissbrant, W. Kess Berg, Jeffrey Volenec, Sylvie Brouder, Brad Joern, Suzanne Cunningham, and Keith Johnson	0	40	75	0	Feedprint
NZ	Maize forage	20470	Corn for Silage Area Harvested, Yield, and Production – States and United States: 2018-2020. Crop Production 2020 Summary (January 2021). USDA, National Agricultural Statistics Service	0	135	62.5	50	"Best Fertilizer for Maize: Organic, NPK, Compost Manure, and Schedule (agrifarming.in)"
US	Maize forage	8174	New Zealand survey of maize areas and volumes.	0	200	40	75	"https://www.dairynz.co.nz/feed/crops/maize/ - https://mro.massey.ac.nz/server/api/core/bitstreams/deb5e911-db16-4e16-809e-3a61e2017c2b/content"

3.4 Modelled emissions

Table 3-4 gives an overview of what emissions are considered and which methods are used to quantify the emission flow. Besides this, not all emissions are considered for the most important aspects. For instance, laughing gas emissions are quantified for fertilizer inputs, manure inputs and crop residues, but is “not applicable” for lime inputs. Please note that ammonia emissions from manure is based on the tier 1 IPCC methods, whereas for fertilizer use ammonia emissions are based on the more detailed method described in EMEP/EEA.

Table 3-5: Overview of modelled emissions, literature source and which aspects are included for the calculations

Emission	Level	Method	Fertilizer	Manure	Crop residues	Lime
(In)direct laughing gas emissions	Tier 1	IPCC (IPCC, 2019b)	Yes	Yes	Yes	-
Ammonia emissions	Tier 1		No	Yes	No	-
Nitrate emissions	Tier 1		Yes	Yes	Yes	-
Carbon dioxide emissions	Tier 1		Yes	-	-	Yes
Nitrogen monoxide emissions	Tier 1	EMEP/EEA (European Environment Agency, 2016)	Yes	Yes	No	-
Ammonia emissions	Tier 2		Yes	No	No	-
Phosphor emissions		ReCiPe (M. A. J. Huijbregts et al., 2016)	Yes	Yes	No	-
Heavy metal emissions		Nemecek & Schnetzer (Nemecek and Schnetzer, 2011)	Yes	Yes	Yes	Yes

Some emissions are specifically for a certain crop or item, these include:

- Methane emissions for rice cultivation

3.4.1 Nitrous oxide (N_20) emissions

There are a number of pathways that result in nitrous oxide emissions, which can be divided into direct emissions (release of N_2O directly from N inputs) and indirect emissions (N_2O emissions through a more intricate mechanism). Beside nitrous emissions due to N additions, there are other activities that can result in direct nitrous oxide emissions, such as the drainage of organic soils, changes in mineral soil management, and emissions from urine and dung inputs to grazed soils. These latter two categories are not taken into account in the crop cultivation models, as it is assumed that crops are cultivated on cropland remaining cropland and the organic matter contents of the soils does not substantially change, and that cropland is not grazed. The emissions from grazing of pastureland are however included in the animal system models. The following equations and definitions are derived from IPCC methodologies on N_2O emissions from managed soils;

$$N_2O - N_{direct} = N_2O - N_{Ninputs} + N_2O - N_{OS} + N_2O - N_{PRP}$$

Equation 3-1 (IPCC, 2019b)

Where,

$N_2O–N_{Direct}$ = annual direct N_2O–N emissions produced from managed soils, [kg N_2O–N]
$N_2O–N_{N\ inputs}$ = annual direct N_2O–N emissions from N inputs to managed soils, [kg N_2O–N]
$N_2O–N_{OS}$ = annual direct N_2O–N emissions from managed organic soils, [kg N_2O–N]
$N_2O–N_{PRP}$ = annual direct N_2O–N emissions from urine and dung inputs to grazed soils, [kg N_2O–N]

Note that the unit kg N_2O-N should be interpreted as kg nitrous oxide measured as kg nitrogen. In essence, Equation 3-1 to Equation 3-7 describe nitrogen balances. To obtain [kg N_2O], [kg N_2O-N] needs to be multiplied by $\left(\frac{44}{28}\right)$, to account for the mass of nitrogen (2*N, atomic mass 14) within the mass of a nitrous oxide molecule (2*N+1*O, atomic mass 16). See Table 3-6 for a list of emissions factors and constants.

The N_2O emissions from inputs are driven by four different parameters; the application rate of synthetic fertilizer, application of organic fertilizer (e.g. manure), amount of crop residue left after harvest, and annual release of N in soil organic matter due to land use change. The latter was incorporated in the aggregated emissions from land use change as described in 3.2.3.

Beside the direct emissions, there are also indirect emission pathways, in which nitrogen in fertilizer is first converted to an intermediate compound before it is converted to N_2O (e.g. volatilization of NH_3 and NO_x which is later partly converted to N_2O). The different mechanisms are shown schematically in Figure 4.

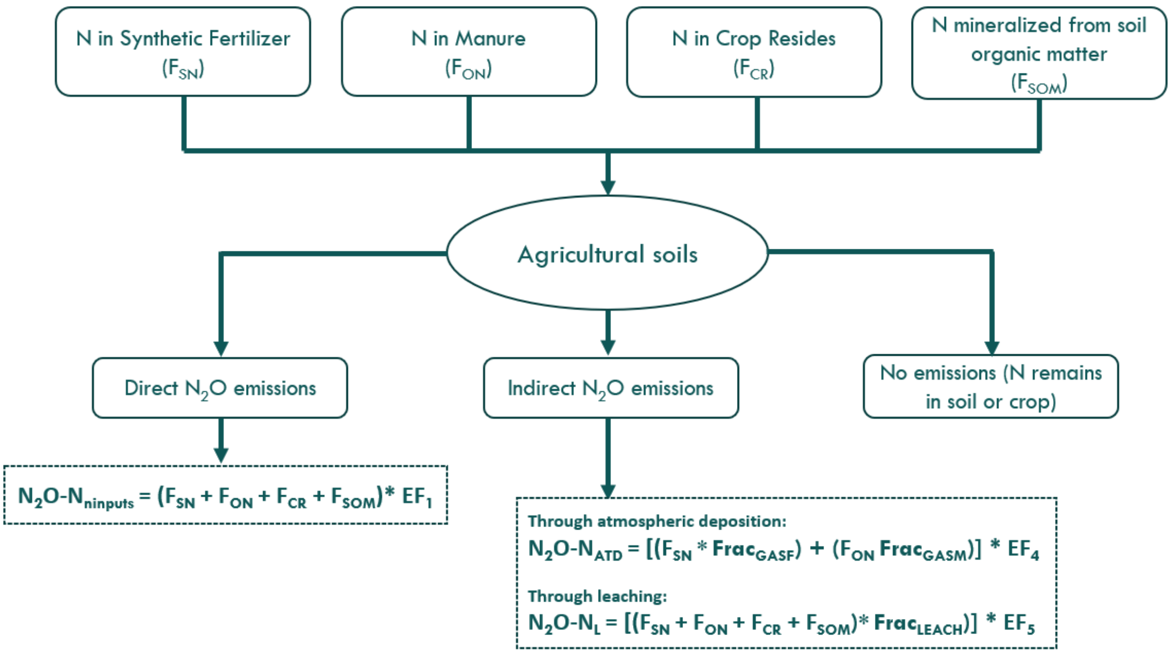

Figure 4: Nitrous oxide emission (direct and indirect) from due to different N inputs (IPCC, 2019b).

The equations listed in Figure 4, will be discussed in more detail below. First, the major contribution from direct emissions of N_2O is from N inputs:

$$N_2O - N_{Ninputs} = (F_{SN} + F_{ON} + F_{CR} + F_{SOM}) * EF_1$$

Equation 3-2 (IPCC, 2019b)

Where,

F_{SN} = the amount of synthetic fertilizer N applied to soils, [kg N]

F_{ON} = the amount of animal manure, compost, sewage sludge and other organic N additions applied to soils, [kg N]
F_{CR} = the amount of N in crop residues (above-ground and below-ground), including N-fixing crops (leguminous), and from forage/pasture renewal, returned to soils, [kg N]
F_{SOM} = the amount of N in mineral soils that is mineralized, in association with loss of soil C from soil organic matter as a result of changes to land use or management, [kg N]
EF_1 = emission factor for N_2O emissions from N inputs, $[\frac{kg\ N_2O-N}{kg\ N\ input}]$

As mentioned before, the contribution of F_{SOM} is incorporated in the emissions from land use change, which are calculated elsewhere (see 3.2.3). F_{CR} is dependent on the type of crop and yield and is determined separately. The IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019b) provides guidance on how to do this using an empirical formula and data for a limited number of crops and crop types. The emission factor EF_1 in Equation 3-2 has a default value of 0.01 (i.e. 1% of mass of N from fertilizer and crop residue will be converted to N_2O); as listed in Table 3-6.

In Agri-footprint the direct N_2O emissions are modelled according to the IPCC Tier 1 approach. The uncertainty range of the EF_1 emission factor is very high (0.003 – 0.03) because climatic conditions, soil conditions and agricultural soil management activities (e.g. irrigation, drainage, tillage practices) affect direct emissions.

F_{SN} has been determined using mainly data from (Pallière, 2011), as described in Sections 3.2 and 3.2.6 of this report. The contribution of F_{ON} has been determined on a country basis, as described in the methodology report of the Feedprint study (Vellinga et al., 2013a), which formed the basis of the crop cultivation models in this study, see Section 3.2.

There are two other, indirect, mechanisms that also contribute to the total N_2O emissions:

$$N_2O - N_{indirect} = N_2O_{(ATD)} - N + N_2O_{(L)} - N$$

Equation 3-3 (IPCC, 2019b)

Where,

$N_2O_{(ATD)}$–N = amount of N_2O–N produced from atmospheric deposition of N volatilized from managed soils, [kg N_2O–N]
$N_2O_{(L)}$–N = annual amount of N_2O–N produced from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs, [kg N_2O–N]

The amount of N_2O that is emitted through atmospheric deposition depends on the fraction of applied N that volatizes as NH_3 and NO_x, and the amount of volatized N that is converted to N_2O:

$$N_2O - N_{ATD} = [(F_{SN} * Frac_{GASF}) + ((Fon + Fprp) * FracGASM)] * EF_4$$

Equation 3-4 (IPCC, 2019b)

Where,

F_{SN} = annual amount of synthetic fertilizer N applied to soils, [kg N]
F_{ON} = annual amount of animal manure, compost, sewage sludge and other organic N additions applied to soils, [kg N]
$Frac_{GASF}$ = fraction of synthetic fertilizer N that volatilizes as NH_3 and NO_x, $\left[\frac{kg\ N\ volatilized}{kg\ N\ applied}\right]$
$Frac_{GASM}$ = fraction of applied organic N fertilizer materials (F_{ON}) and of urine and dung N deposited by grazing animals (F_{PRP}) that volatilizes as NH_3 and NO_x, $\left[\frac{kg\ N\ volatilized}{kg\ N\ applied\ or\ deposited}\right]$

EF_4 = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces, $\left[\frac{kg\ N_2O-N}{kg\ NH_3-N + NO_x-N\ volatilized}\right]$
F_{PRP} = annual amount of urine and dung N deposited by grazing animals on pasture, range and paddock, [kg N]

In Agri-footprint no mixed enterprise farming systems are considered. Therefore, in the crop cultivation models, F_{PRP} was set to 0 (no urine and dung from grazing animals). However, emissions from grazing were taken into account in the animal systems, where appropriate. The default emission factor EF_4 and the default fractions are listed in Table 3-6. Equation 3-5 shows the calculation procedure for determining N_2O emission from leaching of applied N from fertilizer (SN and ON), crop residue (CR), grazing animals (PRP) and soil organic matter (SOM).

$$N_2O - N_L = \left[(F_{SN} + F_{ON} + F_{PRP} + F_{CR} + F_{SOM}) * Frac_{LEACH-(H)}\right] * EF_5$$

Equation 3-5 (IPCC, 2019b)

$Frac_{LEACH-(H)}$ = fraction of all N added to/mineralized in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, $\left[\frac{kg\ N}{kg\ of\ N\ additions}\right]$
EF_5= emission factor for N_2O emissions from N leaching and runoff, $\left[\frac{kg\ N_2O-N}{kg\ N\ leached\ and\ runoff}\right]$

3.4.2 Ammonia (NH_3) and nitrate (NO_3^-) emissions – tier 1

Again, the IPCC calculation rules (IPCC, 2019b) were applied to determine the ammonia and nitrate emissions. This approach of modelling ammonia volatilization was used only for emissions from manure; the ammonia volatilization from inorganic fertilizer was indeed modelled following EMEP/EEA guidelines (see chapter 3.2.6). It was assumed that all nitrogen that volatizes converts to ammonia, and that all nitrogen that leaches is emitted as nitrate. In essence, Equation 3-6 & Equation 3-7 are the same as the aforementioned equations for nitrous emissions from atmospheric deposition and leaching (Equation 3-4 & Equation 3-5) but without the secondary conversion to nitrous oxide.

Ammonia (NH_3) emissions:

$$NH_3 - N = (F_{SN} * Frac_{GASF}) + ((F_{ON} + F_{PRP}) * Frac_{GASM})$$

Equation 3-6 (IPCC, 2019b)

Where,

NH_3-N = ammonia produced from atmospheric deposition of N volatilized from managed soils, [kg NH_3–N]

Nitrate (NO_3^-) emissions to water:

$$NO_3^- - N = (F_{SN} + F_{ON} + F_{PRP} + F_{CR} + F_{SOM}) * Frac_{LEACH-(H)} * Frac_{wet}$$

Equation 3-7 (IPCC, 2019b)

Where,

NO_3^--N = nitrate produced from leaching of N from managed soils, [kg NO_3^--N]
The IPCC includes a note “that in the Tier 1 method, for wet climates or dry climate regions where irrigation (other than drip irrigation) is used, the default $Frac_{leach}$ is 0.24. For dry climated, the default $Frac_{leach}$ is zero.” In Agri-footprint 6 we have included now a $Frac_{wet}$ to better quantify the nitrate

emissions that are taken place in agricultural systems. The $Frac_{wet}$ represents the share of wet climate within a country, data is taken from the land use change tool (Blonk Consultants, 2021).

3.4.3 Carbon dioxide (CO_2) emissions

Carbon dioxide emissions from lime, dolomite and urea containing compounds are included in the inventory. Both lime and dolomite are resources of fossil origin. Carbon dioxide emissions from urea containing compounds are included as well since: "CO_2 removal from the atmosphere during urea manufacturing is estimated in the Industrial Processes and Product Use Sector (IPPU Sector)" (IPCC, 2019b). In Agri-footprint, two urea containing compounds are present: urea (which is 100% urea) and liquid urea ammonium nitrate solution (which contains 36.6% urea).

CO_2 emissions from limestone, dolomite and urea containing compounds:

$$\mathrm{CO_2 - C_{em}} = (\mathrm{M_{Limestone}} * \mathrm{EF_{Limestone}}) + (\mathrm{M_{Dolomite}} * \mathrm{EF_{Dolomite}}) + (\mathrm{M_{Urea}} * \mathrm{EF_{Urea}})$$

Equation 3-8 (IPCC, 2019b)

Where,

CO_2–C_{em} = C emissions from lime, dolomite and urea application, [kg C]
$M_{limestone}$, $M_{dolomite}$, M_{urea} = amount of calcic limestone ($CaCO_3$), dolomite ($CaMg(CO_3)_2$) or urea respectively, in [kg]
$EF_{limestone}$, $EF_{dolomite}$, EF_{urea} = emission factor, $\left[\frac{kg\ C}{kg\ of\ limestone, dolomite\ or\ urea}\right]$

Default emission factors are reported in Table 3-6.

3.4.4 IPCC tier 1 emissions factors and constants

Table 3-6: IPCC Tier 1 emission factors and constants.

IPCC Tier 1 Emission factors and constants [and units]	Value [IPCC 2006]	Value [IPCC 2019]
$EF_1 \left[\frac{kg\ N_2O - N}{kg\ N_{applied}}\right]$	0.01	0.01
$EF_4 \left[\frac{kg\ N_2O - N}{kg\ N_{volatized}}\right]$	0.01	0.01
$EF_5 \left[\frac{kg\ N_2O - N}{kg\ N_{leached}}\right]$	0.0075	0.011
$EF_{Dolomite} \left[\frac{kg\ CO_2 - C}{kg\ Dolomite}\right]$	0.13	0.13
$EF_{Lime} \left[\frac{kg\ CO_2 - C}{kg\ lime}\right]$	0.12	0.12
$EF_{Urea} \left[\frac{kg\ CO_2 - C}{kg\ Urea}\right]$	0.2	0.2
$Frac_{GASM} \left[\frac{kg\ NH_3 - N}{kg\ N_{in\ manure\ applied}}\right]$	0.2	0.21
$Frac_{GASF} \left[\frac{kg\ NH_3 - N}{kg\ N_{in\ fertilizer\ applied}}\right]$	0.1	0.11
$Frac_{LEACH} \left[\frac{kg\ NO_3^- - N}{kg\ N_{applied}}\right]$	0.3	0.24
Conversion from kg CO2-C to kg CO2	$\left(\frac{44}{12}\right)$	$\left(\frac{44}{12}\right)$
Conversion from kg N2O-N to kg N2O	$\left(\frac{44}{28}\right)$	$\left(\frac{44}{28}\right)$
Conversion from kg NH3-N to kg NH3	$\left(\frac{17}{14}\right)$	$\left(\frac{17}{14}\right)$
Conversion from kg NO3--N to kg NO3-	$\left(\frac{62}{14}\right)$	$\left(\frac{62}{14}\right)$

3.4.5 Nitric Oxide (NO) emissions

Since Agri-Footprint 5 onwards, nitric oxide emissions from fertilizer and manure application are considered. Although nitric oxide is produced as an intermediate product of the nitrification and denitrification processes, no methodology has been developed in the IPCC guidelines of 2006 to quantify its emission. A default value of 0.04 kg NO2 per kg of N fertilizer and kg N from manure applied is used for Agri-footprint 6 (European Environment Agency, 2016).

3.4.6 Ammonia (NH_3) emissions – tier 2

For ammonia emissions from inorganic fertilizers a more detailed tier 2 approach is used based on emission factors for specific type of fertilizers described by EMEP/EEA (European Environment Agency, 2016). All eight inventoried nitrogen containing fertilizers in chapter 3.2.6 each have their own specific emission factor described in Figure 5.

	Climate					
	Cool		Temperate		Warm	
	normal pH (a)	high pH (b)	normal pH (a)	high pH (b)	normal pH (a)	high pH (b)
Anhydrous ammonia (AH)	19	35	20	36	25	46
AN	15	32	16	33	20	41
Ammonium phosphate (AP) (c)	50	91	51	94	64	117
AS	90	165	92	170	115	212
CAN	8	17	8	17	10	21
NK mixtures (d)	15	32	22	33	20	41
NPK mixtures (d)	50	91	67	94	64	117
NP mixtures (d)	50	91	67	94	64	117
N solutions (e)	98	95	100	97	126	122
Other straight N compounds (f)	10	19	14	20	13	25
Urea (g)	155	164	159	168	198	210

(a) A 'normal' pH is a pH of 7.0 or below.
(b) A 'high' pH is a pH of more than 7.0 (usually calcareous soils).
(c) AP is the sum of ammonium monophosphate (MAP) and diammonium phosphate (DAP).
(d) NK mixtures are equivalent to AN, NPK and NP mixtures, which are 50 % MAP plus 50 % DAP.
(e) N solutions are equivalent to urea AN.
(f) Other straight N compounds and equivalent to calcium nitrate.
(g) Urea is an organic compound with the chemical formula $CO(NH_2)_2$.

Figure 5: Emission factors for ammonia emissions from fertilizers (g NH_3/kg N applied) (European Environment Agency, 2016)

Due to the lack of data on the pH of soils, it is assumed that all soils around the world are "normal". Using the climate zone criteria described in the reference and average temperatures of countries around the world, each country is either classified as "cool", "temperate" or "warm".

3.4.7 Phosphor emissions

The phosphorous content of synthetic fertilizers and manure is emitted to the water. An emission factor of 0.1 per kg of phosphor for manure and synthetic fertilizer based on default modelling of ReCiPe (M. Huijbregts et al., 2016) is applied.

3.4.8 Heavy metal emissions

The emissions of heavy metals are based on a methodology described in (Nemecek and Schnetzer, 2012). The emissions are the result of inputs of heavy metals due to fertilizer and manure application and of deposition and outputs of heavy metals due to leaching and removal of biomass.

Heavy metals are added to the soil due to application of fertilizers and manure and due to deposition. The heavy metal content of fertilizers and manure was based on literature as stated in Table 3-7 and Table 3-8, respectively. The deposition of heavy metals is stated in Table 3-9.

Table 3-7: Heavy metal content of fertilizers

Mineral fertilizers	Unit	Cd	Cr	Cu	Hg	Ni	Pb	Zn
Urea	mg/kg	2.796	36.301	12.116	0.047	9.739	25.583	94.598
Nitrogen solutions	mg/kg	1.800	23.370	7.800	0.030	6.270	16.470	60.900
NPK compound	mg/kg	6.840	94.005	18.195	0.060	16.755	18.405	157.230
Anhydrous ammonia	mg/kg	4.920	63.878	21.320	0.082	17.138	45.018	166.460
Ammonium nitrate	mg/kg	2.100	27.265	9.100	0.035	7.315	19.215	71.050
Calcium ammonium nitrate	mg/kg	1.658	22.656	8.883	0.036	6.975	15.877	62.940
Ammonium phosphate	mg/kg	23.835	326.648	57.305	0.193	54.929	50.268	522.890
Ammonium sulfate	mg/kg	1.260	16.359	5.460	0.021	4.389	11.529	42.630
Triple superphosphate	mg/kg	18.960	260.640	43.440	0.144	42.384	32.160	402.720
Single superphosphate	mg/kg	8.295	114.030	19.005	0.063	18.543	14.070	176.190
PK compound	mg/kg	8.712	120.736	20.966	0.066	19.976	14.916	185.944
Ground rock	mg/kg	12.640	173.760	28.960	0.096	28.256	21.440	268.480
Potassium chloride	mg/kg	0.060	3.480	2.880	0.000	1.500	0.480	3.720
Potassium sulphate	mg/kg	0.050	2.900	2.400	0.000	1.250	0.400	3.100
Lime	mg/kg	0.280	8.249	8.169	0.040	5.886	5.446	37.481

Table 3-8: Heavy metal content of manure

Manure	Unit	Cd mg/kg Fertilizer	Cr mg/kg Fertilizer	Cu mg/kg Fertilizer	Hg mg/kg Fertilizer	Ni mg/kg Fertilizer	Pb mg/kg Fertilizer	Zn mg/kg Fertilizer
Cattle	mg/kg	0.038	1.755	4.378	0.017	1.594	1.211	18.254
Pigs	mg/kg	0.060	1.230	42.059	0.007	1.621	1.260	94.674
Poultry	mg/kg	0.952	5.446	61.974	0.053	11.925	10.141	293.594

Above European values are also used for other continents because data is not available, incomplete or it is not stated if the values are 'per kg dry matter' or 'per kg manure as is'. Please note that ranges in heavy metal contents of animal manure are large as shown in Table 3-8. And note that the amount of copper (Cu) and zinc (Zn) in pig slurry and manure are high because additional copper and zinc is added to the feed by pig farmers for animal health reasons.

It is assumed that only pig and poultry manure are applied in cultivation of arable crops[6] because cattle systems are often closed-loop systems. The ratio pig / poultry manure is based on FAO data on the amount of available nitrogen per type of animal manure.

Table 3-9: Deposition of heavy metals (Nemecek and Schnetzer, 2012)

		Cd	Cu	Zn	Pb	Ni	Cr	Hg
Deposition	mg/ha/yr	700	2,400	90,400	18,700	5,475	3,650	50

Heavy metals are removed from the soil via removal of biomass and via leaching. The heavy metal content of biomass of crops is shown in Table 3-10. Leaching heavy metals to ground water is mentioned in TAble 3-11.

Table 3-10: Heavy metals in biomass (Delahaye et al., 2003)

Crop	Cd (mg/kg "as is")	Cr (mg/kg "as is")	Cu (mg/kg "as is")	Hg (mg/kg "as is")	Ni (mg/kg "as is")	Pb (mg/kg "as is")	Zn (mg/kg "as is")
Fodder beets, rapes, carrots	0.04	0.22	1.08	0.0011	0.094	0.154	6.2
Chicory roots	0.04	0.22	1.66	0.0011	0.094	0.154	2.6
Wheat	0.013	2.28	4.1	0.00862	0.86	0.1	24.8
Rye	0.013	0.93	3.11	0.00862	0.86	0.3	28.8
Barley	0.013	2.28	3.9	0.00862	0.19	1	24
Oat	0.013	2.28	3.6	0.00862	0.86	0.05	24.7
Maize	0.52	0.24	1.58	0.01	0.86	1.3	21.6
Triticale	0.013	2.28	4.7	0.00862	0.86	0.14	34
Other cereals	0.013	2.28	4.1	0.00862	0.86	0.1	24.8

[6] Please note that cattle manure is applied on those crops which are cultivated on dairy farms for feed (e.g. maize silage) due to the closed system.

Pulses/Lupine	0.02	1.4	8.03	0.013	0.86	0.4	33.7
Oilseeds	0.1	0.5	12.62	0.00862	0.86	1	49.6
Cassava	0.009	2.28	2.92	0.01	0.86	0.9	13
Sweet potato	0.009	2.28	5.7	0.0088	0.86	0.31	5.6
Rapeseed	0.02	1.4	4.4	0.013	1	0.4	46.5
Potatoes	0.03	0.4	1.1	0.003	0.25	0.03	2.9
Sugar beet	0.04	0.22	1.1	0.0011	0.094	0.154	6.2
Chicory	0.03	0.4	2.1	0.003	0.25	0.03	12.5
Onions	0.012	0.4	0.4	0.002	0.04	0.021	1.6
Maize silage	0.1	0.24	3.6	0.01	0.861	0.1	36
Fodder beet	0.2	1.32	8.3	0.0188	3.9	2.25	43
Grass fresh	0.2	0.6	8.3	0.0188	3.9	2.25	44
Vegetables & fruit	0.03	0.5	0.5	0.002	0.14	0.54	4

*Not referred to in (Delahaye et al., 2003) but average of other crops.

Table 3-11 : Heavy metal leaching to groundwater (Nemecek and Schnetzer, 2012)

		Cd	Cu	Zn	Pb	Ni	Cr	Hg
Leaching	mg/ha/yr	50	3,600	33,000	600	n.a.	21,200	1,3

An allocation factor is required because not all heavy metal accumulation is caused by agricultural production. Heavy metals are also caused by deposition from other activities in the surrounding area. The allocation factor is calculated as follows:

$$A_i = M_{agro\,i} / (M_{agro\,i} + M_{deposition\,i})$$

Equation 3-9

A_i = allocation factor for the share of agricultural inputs in the total inputs for heavy metal i
$M_{agro\,i}$ = input due to agricultural activities (fertilizer and manure application) for heavy metal i
$M_{deposition\,i}$ = input due to deposition for heavy metal i

Heavy metal emissions into the ground and surface water are calculated with constant leaching rates as:

$$M_{leach\,i} = m_{leach\,i} * A_i$$

Equation 3-10

Where,

$M_{leach\,i}$ = leaching of heavy metal i to the ground and surface water

$m_{leach\,i}$ = average amount of heavy metal emission (

Table 3-11)
A_i = allocation factor for the share of agricultural inputs in the total inputs for heavy metal i

Heavy metals emissions to the soil are calculated as follows:

$$M_{soil\,i} = (\Sigma inputs_i - \Sigma outputs_i) * A_i$$

Equation 3-11

Where,

$\boldsymbol{M_{soil\ i}}$ = accumulation in the soil of heavy metal i
$\mathbf{A_i}$ = *allocation factor for the share of agricultural inputs in the total inputs for heavy metal i*

$$\Sigma \text{inputs}_i = A * A_{\text{content i}} + B * B_{\text{content i}} + C$$

Equation 3-12

Where,

$\boldsymbol{A}$ = fertilizer application (kg/ha/yr)
$\boldsymbol{A_{content\ i}}$ = heavy metal content i for fertilizer applied (Table 3-7)
$\boldsymbol{B}$ = manure application (kg DM/ha/yr)
$\boldsymbol{B_{content\ i}}$ = heavy metal content i for manure applied (Table 3-8)
$\boldsymbol{C}$ = deposition (Table 3-9)

$$\Sigma \text{outputs}_i = M_{\text{leach i}} + D * D_{\text{content i}}$$

Equation 3-13

Where,

$\boldsymbol{D}$ = yield (kg DM/ha/yr)
$\boldsymbol{D_{content\ i}}$ = heavy metal content i for crop (Table 3-10)

When more heavy metals are removed from the soil via leaching and biomass than is added to the soil via fertilizers, manure and deposition, the balance can result in a negative emission. In Agri-footprint 7, negative emissions are converted to zero.

3.4.9 Emissions from drained peat soils

In previous versions of Agri-footprint peat emissions from drained soils were only considered for a limited amount of crops. Now this is included for all crops. For all GHG emissions estimations of drained peat soils, the calculation is based on the factor $A_{crop,\ country}$, which for each crop-country combination is defined by

$$A_{crop,\ country} = \frac{harvested\ area\ of\ crop\ in\ country\ on\ drained\ peat\ soils}{total\ harvested\ area\ of\ crop\ in\ country}$$

Once $A_{crop,\ country}$ is determined, CO2 emission factors are extrapolated from the specific country National Inventory Report (NIR) 2019 submission (average of 2012-2017 data). In case the country does not submit a NIR, and for N2O emissions factors, IPCC (2013) supplement is used (IPCC Guidelines on Wetlands from 2006[7]). To calculate the GHG emissions from peat oxidation per ha crop in each country, the emission factors are multiplied by the $A_{crop,\ country}$. CO_2 emissions from the extraction of peat and peat burning due to fires are not considered, and only the on-site peat emissions from drained organic soil are considered. The emission factors are dependent on type of land occupation (orchard, palm, cropland, paddy rice and grassland) and climate (tropical, temperate and boreal). We assumed that each country has one dominant climate.

$A_{crop,\ country}$ is determined in two steps

[7] https://www.ipcc-nggip.iges.or.jp/public/wetlands/index.html

1. **Calculation of country-level average values:** Estimation of a country-specific value $A_{country}$, i.e. not on a crop-specific level. Data on the parameter $A_{country}$ was collected from National Inventory Reports (2012-2017 average)[8]. When not available, $A_{country}$ is extrapolated with data from FAOSTAT.
2. **Correction of A to crop-specific data:** To obtain a crop-country specific value for A, we used geospatial data for cultivated peat soils[9] and crop cultivation[10], the latter representing yields in the year 2000. For each crop-country combination, we calculated the value for $A_{crop,\ country}$ based on these geospatial datasets, which we call $A^{geo}_{crop,\ country}$ to obtain a more crop-specific model of peat-related GHG emissions. As the data is relatively old and also has data gaps, we used $A^{geo}_{crop,\ country}$ only to correct the country-level averages $A_{country}$ calculated in step 1. If $A^{geo}_{country}$ is the country-level weighted (by harvested area) average of the $A^{geo}_{crop,\ country}$, we therefore set

$$A_{crop,\ country} = A_{country} \cdot \frac{A^{geo}_{crop,\ country}}{A^{geo}_{country}}.$$

On this way, we take into account crop-specific variations of drained organic peat soils. Although some crops, in particular tubers, seem to be cultivated more frequently on peat-rich soils, it should be noted that the variability of $A^{geo}_{crop,\ country}$ is typically less than 20%, i.e. the crop type has a much smaller influence on the GHG emissions from peat oxidation than the country.

For Indonesia and Malaysia, the area of drained organic soil cultivated with palm oil is well documented in literature (Schrier-Uijl et al., 2013). Therefore, specific values of A for palm are used, and the country average is adjusted based on the crop specific harvested areas derived from FAOSTAT.
It should be noted that our approach to model greenhouse gas emissions from peat soils is a rough approach, and should be considered a first order approximation. The real situation for a specific field of a certain crop in a country can of course deviate substantially.

Since the impact of drained peat oxidation can be large on climate change, and its intrinsic uncertainty, it was

decided to give the possibility to show the impact of peat separately (similar as LUC). For this, one existing and two additional substances are used:

- Carbon dioxide, peat oxidation
- Methane, peat oxidation
- Dinitrogen monoxide, peat oxidation

For LCA software users, please check if these substances are included in carbon footprint related impact categories. Else, the user needs to adapt the method to include peat

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[8]https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/national-inventory-submissions-2019
[9] http://www.fao.org/geonetwork/srv/en/metadata.show?id=56901&currTab=distribution
[10] http://www.earthstat.org/harvested-area-yield-175-crops/

emissions in their carbon footprint numbers. It is advised to show peat emission impacts separately, similar as greenhouse gas emissions related to land use change.

3.4.10 Regionalized emissions and resources

In previous versions of Agri-footprint only water use was regionalized. With that we mean that within the LCI itself, the region is specified. For example, water use in the Netherlands would have the have the substance name of “Water, unspecified natural origin, NL”, as stated in chapter 3.2.2.2. In recent SimaPro updates more regionalized substances have been added some of them are also relevant for Agri-footprint. The names of certain emissions or resources have been changes to enable regionalization of certain. The following substances are now also regionalized in Agri-footprint LCIs.

Table 3-12: Update and regionalized substances in Agri-footprint, with Netherlands as an example

Substance name Agri-footprint 5	Substance name Agri-footprint 6 & 7
Occupation, annual crop	Occupation, annual crop, NL
Occupation, permanent crop	Occupation, permanent crop, NL
Occupation, grassland/pasture/meadow	Occupation, grassland/pasture/meadow, NL
Transformation, from annual crop	Transformation, from annual crop, NL
Transformation, from forest, unspecified	Transformation, from forest, extensive, NL
Transformation, from grassland	Transformation, from grassland/pasture/meadow, NL
Transformation, from permanent crop	Transformation, from permanent crop, NL
Transformation, to annual crop	Transformation, to annual crop, NL
Transformation, to grassland	Transformation, to grassland/pasture/meadow, NL
Transformation, to permanent crop	Transformation, to permanent crop, NL
Ammonia	Ammonia, NL
Nitrogen monoxide	Nitrogen monoxide, NL
Nitrate	Nitrate, NL
Phosphorus	Phosphorus, NL
Water, unspecified natural origin, NL	Water, unspecified natural origin, NL

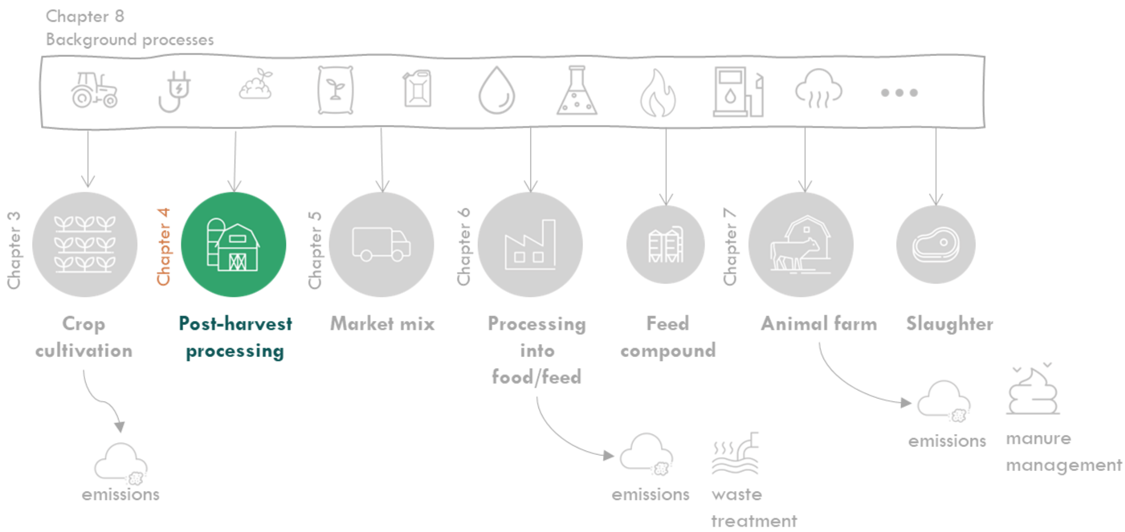
Depending on the environmental impact used within LCA software, the regionalization can lead to different but more specific environmental impact results.

3.4.11 Specific Emissions

3.4.11.1 Methane emissions in rice cultivations

Methane emissions that are a result of rice cultivation have been inventoried for rice cultivations in Agri-footprint. In version 6 the emission factors for rice cultivation are based on information from a single public source. FAOstat reports on the “implied emissions factor for CH4” for rice cultivation for 120+ countries (FAOSTAT, 2019). This factor is converted from gram methane/harvested square meter to kg biogenic methane per harvested hectare in the LCI’s for rice cultivation.

4. Processing of crops at post-harvest



The post-harvest processing is a new step added to the modelled Agri-footprint supply chain. It is meant for those crop products that are usually processed directly at farm/orchard, before being commercialized. This is of relevance since FAO data on yield are sometimes expressed as harvested products (e.g. groundnuts, with shell) while FAO data on trade statistics are based on post-harvest processed crops (e.g. groundnuts, shelled). The change of weight should be then included in the transportation; therefore, this intermediate step becomes important.

Depending on the type of agricultural product, the following post-harvesting steps are considered in Agri-footprint:

Table 4-1 Overview of post-harvest activities applied

Product group	Crops	Post-harvest activity
Cereal grains	Barley, maize, oats, rice, rye, sorghum, triticale, wheat	Drying
Roots and tubers	Cassava, potatoes, onions	Cooling
Sugar crops		No activity considered
Pulses	Beans, field peas, broad beans, chick peas, lupins, pigeon peas	Drying
Oil bearing crops	Groundnuts, linseed, mustard seed, rapeseed, sesame, soybeans, sunflower seed	Drying
Vegetables		No activity considered

4.1 Deshelling/dehusking

This post-harvest process is relevant for groundnuts and coconuts. The share of shell/husk over the total weight (30% for groundnuts and 39% for coconuts) was based on FAOstat for groundnuts. The mass balance for coconuts is based on confidential information from a coconut processor in Sri Lanka. The energy use was based on an average default calculated from different nuts deshelling (cashew, almond and groundnut) literature sources (Table 4-2).

Table 4-2 Electricity and diesel use of nuts used for deriving a nut deshelling default.

		Electricity	Diesel	Source
Cashew	MJ/ton input	11	360	(Jekayinfa and Bamgboye, 2006)
Almond	MJ/ton input	248	18	(Kendall et al., 2015)
Groundnut	MJ/ton input	246	97	(Center for Agricultural and Rural Sustainability, 2012)
Average	MJ/ton input	168	158	

4.2 Drying of crops

In previous versions of Agri-footprint the drying of crops was based on default values for heat and electricity use for certain crops only. In Agri-footprint 6, more country specific data was used to determine the energy use for drying crops. Data on humidity of harvested crops from Eurostat was used in order to determine the humidity of crops before drying. (Eurostat, 2021a). A 5-year average value (2014-2018) was used to incorporate yearly differences in humidity of crops when harvested. For crops which are not reported in Eurostat, the crop group average values were used. Hereby drying is consistently applied for all crops within the same crop group. An overview of Agri-footprint crops, crop group, Eurostat crop and safe humidity values for storage are shown in Table 4-3.

Table 4-3 Humidity values for crop storage

AFP crop	Crop group	Eurostat crop	Humidity storage
Wheat grain	Cereals	Wheat and spelt	12%
Rye grain	Cereals	Rye	12%
Barley grain	Cereals	Barley	12%
Oat grain	Cereals	Oats	12%
Triticale grain	Cereals	Triticale	12%
Sorghum grain	Cereals	Sorghum	12%
Rice grain	Cereals	Rice	12%
Other cereals	Cereals	Cereals and cereal products	12%
Peas, dry	Pulses	Field peas	10%
Broad beans	Pulses	Broad and field beans	10%
Lupins	Pulses	Sweet lupins	10%
Other pulses	Pulses	Other dry pulses and protein crops n.e.c.	10%
Rapeseed	Oil bearing crops	Rape and turnip rape seeds	8%
Sunflower seed	Oil bearing crops	Sunflower seed	8%
Soybeans	Oil bearing crops	Soya	8%
Linseed	Oil bearing crops	Linseed (oilflax)	8%
Other oil-bearing crops	Oil bearing crops	Other oilseed crops n.e.c.	8%

Based on the humidity of the crop from Eurostat and the safe humidity of storage from various FAO documents, it can be calculated how much water needs to be evaporated from crop to reach the desired humidity. This is calculated using the following equation:

$$Amount\ water\ (kg\ water\ per\ ton\ stored\ product) = \left(\frac{1-\ DM\ crop\ safe\ storage}{1-DM\ crop\ harvest} * 1000\ kg\right) - 1000$$

Equation 14

Where,

DM crop safe storage is taken from Table 4-3.

DM crop harvest is taken from Eurostat, 5 year average (2014-2018)

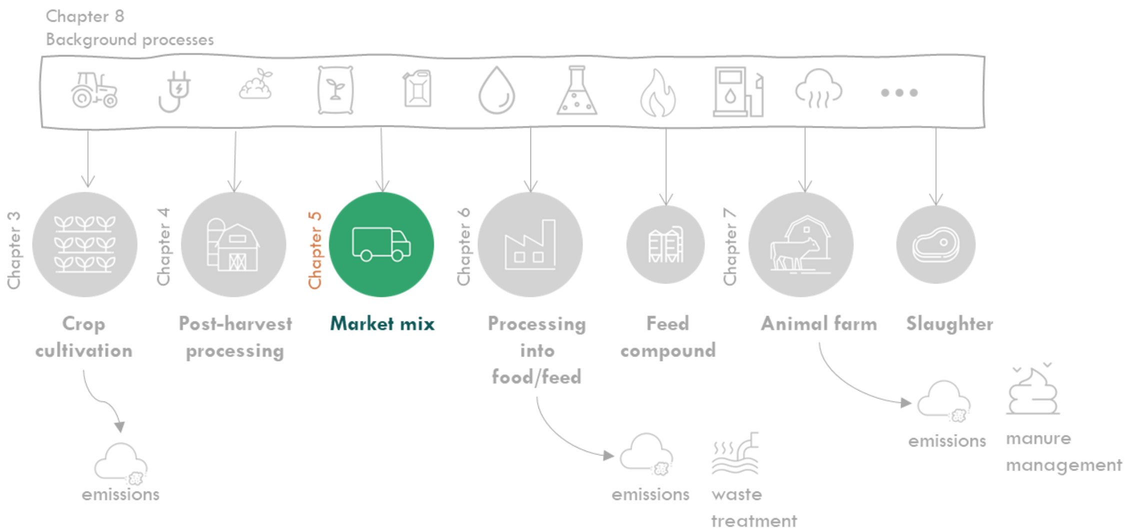
For all European countries, country specific data from Eurostat is used. For all other countries the EU average is taken as default. For future Agri-footprint versions, we intend to use more specific data for all non-European countries.

For all grains, pulses and oilseeds, it was considered that FAOstat reports the yield as traded, therefore already dried; no moisture loss was then accounted for. The rest of the drying was assumed to be performed by a fluid bed dryer (150 MJ electricity/ton of water evaporated and 4500 MJ steam/ton of water evaporated) based on (Fox et al., 2010).

4.3 Cooling of crops

For onions, sweet potatoes and potatoes it is assumed that crops are cooled during storage. A default value of 30 kWh/ton is assumed for all countries. The default value of 30 kWh/ton is derived from a commercial party specialized in cooling.

5. Market mix of commodities



In Agri-footprint version 7, the market mixes of raw materials and processes commodities have been updated. The market mixes of commodities also contain the transportation requirements for transporting the materials from the various sources to the specific country market, based on transportation distances from the PEFCR Feed (European Commission, 2018a).

5.1 Market mix of raw materials

The market mix of specific raw materials is determined by adding the total import of the raw materials from various countries (FAO, 2024a) to specific country with the national production of the same product (FAO, 2024b). To overcome huge trade and production fluctuations from year to year, 5-year averages are used (2018-2012). For the underlying trading countries, a market mix is constructed to determine the source country of the raw material. This can be best explained using an example, as shown in Figure 6.

For example, country A is 10% self-sufficient and imports 20% from country B, 30% from country C and 40% from country D. Building a market mix based on the “first layer approach” is quite problematic, since it is quite possible that a specific county only acts as transit country or imports a lot from other countries. Therefore, for each country that trades with country A directly (country B, C and D), their market mixes are inventoried as well. By default, Agri-footprint inventories at least 4 levels deep in order to determine the cultivation countries of the commodity in country A. Since country D does not produce the commodity itself, but only acts as a transit country, it is not part of the overall market mix of the commodity in country A, whereas country F is indirectly the largest cultivator of the commodity in country A

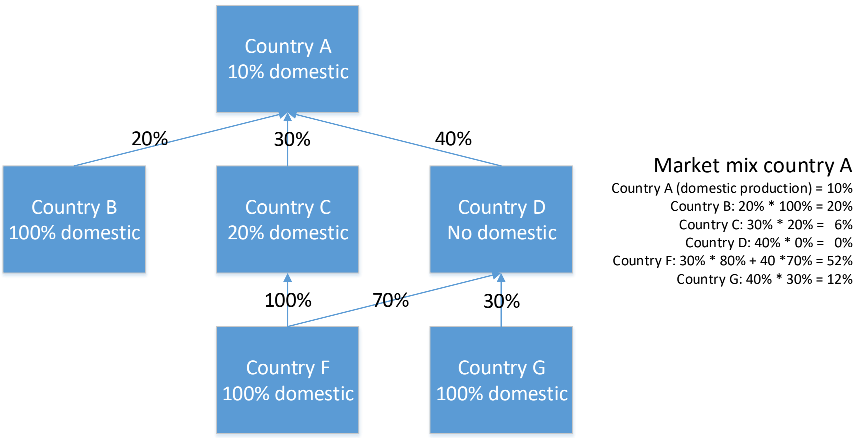


Figure 6: Graphic illustration of how market mixes are calculated in Agri-Footprint

Not for all countries there is cultivation data available in Agri-footprint. How the final market mix is eventually determined can be best illustrated using an example as shown Table 5-1.

Table 5-1: How the market mix and coverage is estimated, example of Dutch maize (fictive) market mix

Source country	Crop	Quantity (%)	Reporter country	Cultivation data?		Market mix
France	Maize	39.95	Netherlands	TRUE	39.95	45%
Hungary	Maize	11.70	Netherlands	TRUE	11.70	13%
Ukraine	Maize	10.30	Netherlands	TRUE	10.30	12%
Germany	Maize	8.65	Netherlands	TRUE	8.65	10%
Brazil	Maize	8.10	Netherlands	TRUE	8.10	9%
Netherlands (domestic)	Maize	6.16	Netherlands	FALSE		
Romania	Maize	2.85	Netherlands	TRUE	2.85	3%
Argentina	Maize	2.35	Netherlands	TRUE	2.35	3%

Belgium	Maize	2.27	Netherlands	TRUE	2.27	3%
Serbia	Maize	2.21	Netherlands	FALSE		
Russia	Maize	0.86	Netherlands	FALSE		
Slovakia	Maize	0.86	Netherlands	TRUE	0.86	1%
Poland	Maize	0.78	Netherlands	TRUE	0.78	1%
Bulgaria	Maize	0.76	Netherlands	TRUE	0.76	1%
United States	Maize	0.60	Netherlands	TRUE	0.60	1%
	Included	**98.40**		**Coverage:**	**89.18**	**100%**

Based on the trade and production statistics that are available for maize can be seen that 98.4% of all available maize on the Dutch market is from 15 different countries. 1.6% of the market mix comes from countries providing less than 0.5% of the market mix and are therefore cut out. Also, not for all countries there is maize cultivation data available in Agri-Footprint. In the fictive example above, this means that maize cultivation in the Netherlands, Serbia and Russia are excluded from the Dutch market mix. For the datasets for which cultivation data is available, the coverage determines the quality of the market mix. In the case of maize on the Dutch market, 89.2% of maize cultivation data is available. The final market mix is rescaled based on the relative shares of the different countries totaling 100%. For each market mix, the coverage information is given in the comment field of the market mix LCI.

5.2 Market mix of processed materials

The same principle that is used for raw materials is also used for processed materials. Combining trade data with national production of processed crops (FAO, 2018b). Production data for processed crops is quite limited. But with some additional information production data of co-products were inventoried as well. For example: in FAOstat only the quantity of soybean oil is given. By using a fixed soybean oil to soybean meal yield ratio, the amount of soybean meal production can be quantified as well. An overview of additional inventoried processed commodities is given in Table 5-2.

Table 5-2: How inventoried products are quantified, production data and ratios used

Production data	Production inventoried	Ratio (Data/inventoried)	Comment / source:
Groundnuts, with shell	Groundnuts, shelled	0.7	For trade data, groundnuts in shell are converted at 70% and reported on a shelled basis. (FAO definition)
Rice, paddy	Rice - total (Rice milled equivalent)	0.625	Industry average[11]
Oil, coconut (copra)	Cake, copra	0.604	Coconut copra meal (AFP process)
Oil, cottonseed	Cake, cottonseed	2.658	Feedprint: Cottonseed
Oil, groundnut	Cake, groundnuts	1.053	Feedprint: Peanut solvent crushing solvent extraction
Oil, linseed	Cake, linseed	1.829	Feedprint: linseed solvent extraction

[11] https://www.uaex.edu/publications/pdf/mp192/chapter-14.pdf

Oil, maize	Cake, maize	1.871	Maize germ meal expeller, wet milling (AFP process)
Oil, palm kernel	Cake, palm kernel	1.128	Palm kernel expeller (AFP process)
Oil, rapeseed	Cake, rapeseed	1.390	Rapeseed meal, solvent (AFP process)
Oil, sesame	Cake, sesame seed	1.373	Feedprint: Sesame solvent extraction
Oil, soybean	Cake, soybeans	3.693	Soybean meal, solvent (AFP process)
Oil, sunflower	Cake, sunflower	1.250	Sunflower seed meal (AFP process)
Sugar beet	Sugar Raw Centrifugal	0.128	Sugar, from sugar beet (AFP process)
Sugar cane	Sugar Raw Centrifugal	0.132	Sugar, from sugar cane (AFP process)

5.3 Transportation requirements for market mixes

Transportation requirements are largely based on the methodology applied in Feedprint (Vellinga et al., 2013b). In short, the transport model consists of two parts. First the distance within the country of origin (where the crop is cultivated) is estimated, it is assumed that the crops are transported from cultivation areas to central collection hubs. From there, the crops are subsequently transported to the country of the market mix.

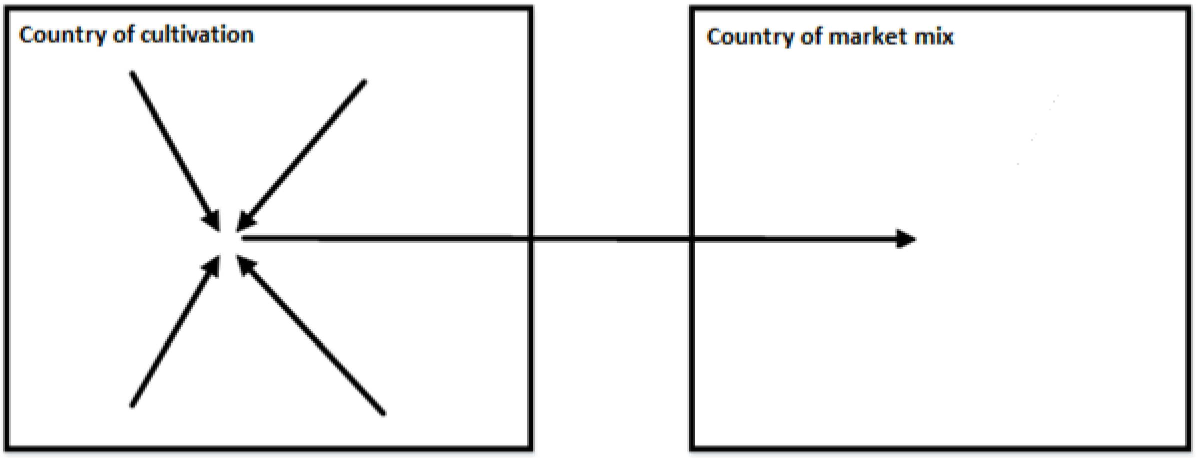
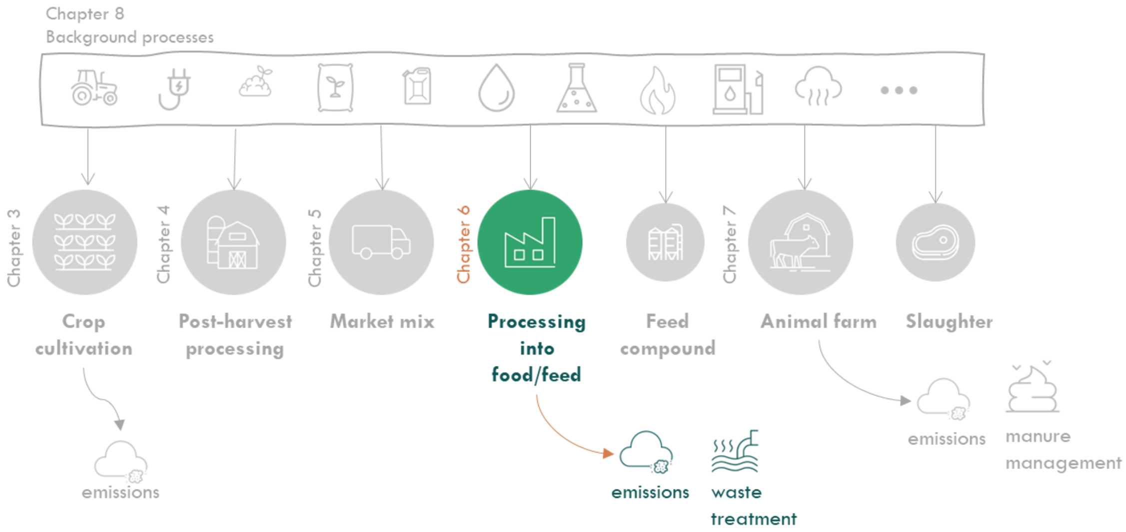


Figure 7: Generic transport model from a central hub in land of cultivation to the market location within a specific country

5.3.1 Data collection

The transport model of Feedprint (Vellinga et al., 2013b) has been used as a basis but has been updated and extended to cover all relevant transport flows for new cultivation countries. The transport distances used in Agri-footprint 7 has been based on the transport distances described in Annex 6 of the PEFCR Feed (European Commission, 2018b).

6. Processing of crops and animal products into feed and food ingredients UPDATE!



6.1 Introduction and reader's guide

Table 6-1is a simplified list of processed feed and food products, and the related data source that formed the basis of the inventory. Average process specific data were derived for these processes, often the regional average of the EU or USA. Differences between countries are caused by the connection to different background data for electricity and heat.

Table 6-1 Simplified list of processed feed and food products, and the related data source that formed the basis of the inventory.

Crop/animal products	Feed products	Food products	Source and original region of data
Animal products	Fat from animals Greaves meal Animal meal Blood meal	Food grade fat Cream (full fat)	(van Zeist et al., 2012a) (European Commission, 2005) (Safriet, 1995)
	Fish meals Fish oils		(Cashion et al., 2017a, 2016a; van Zeist et al., 2012a)
	Milk powder (skimmed) Milk powder (full fat) Whey powders	Cream (skimmed) Milk powder (skimmed) Milk powder (full fat) Milk standardized (full fat) Milk standardized (skimmed) Cheese	(van Zeist et al., 2012a) (Sheane et al., 2011)
Cereal products	Brewer's grains		(van Zeist et al., 2012b)

Crop/animal products	Feed products	Food products	Source and original region of data
	Maize germ meal expeller Maize germ meal extracted Maize gluten meal dried Maize gluten meal wet Maize gluten feed dried Maize gluten feed wet Maize solubles Maize starch dried	Maize flour Maize starch Maize germ oil	(van Zeist et al., 2012b, 2012c) (Eijk and Koot, 2005) (Bolade, 2009) (Bechtel et al., 1999)
	Oat grain peeled Oat husk meal Oat mill feed high grade	Oat grain peeled	(van Zeist et al., 2012b)
	Rye middlings	Rye flour	(van Zeist et al., 2012b)
	Wheat bran Wheat germ Wheat gluten feed Wheat gluten meal Wheat middlings & feed Wheat starch slurry	Wheat starch Wheat flour	(van Zeist et al., 2012b, 2012c)
	Rice bran meal Rice feed meal Rice husk meal	White rice Brown rice Rice brokens Refined rice bran oil	(Goyal, S. et al. 2012) (Blengini and Busto, 2009) (Roy, P. et al 2007)
Oilseed products	Coconut copra meal	Refined coconut oil	(van Zeist et al., 2012d)
	Palm kernel expeller Palm kernels Crude palm oil Fatty acid distillates	Refined palm oil Refined palm kernel oil	(van Zeist et al., 2012d)
	Rapeseed expeller Rapeseed meal	Refined rapeseed oil	(van Zeist et al., 2012d) ((S&T)2 Consultants, 2010) (Schneider and Finkbeiner, 2013)
	Crude soybean oil Soybean protein-concentrate Soybean expeller Soybean hull Soybean lecithin Soybean meal Soybean okara Soybean, heat treated	Refined soybean oil Soybean protein-concentrate Soybean protein-isolate	(van Zeist et al., 2012d) (Sheehan et al., 1998) (OTI, 2010) (Schneider and Finkbeiner, 2013) (van Veghel, 2017)
	Sunflower seed dehulled Sunflower seed expelled dehulled Sunflower seed meal	Refined sunflower oil	(van Zeist et al., 2012d)
	Groundnut meal Crude peanut oil		(van Zeist et al., 2012d)
	Linseed expeller Linseed meal Crude linseed oil	Refined linseed oil	(van Zeist et al., 2012d)
Legume products	Broad bean hulls	Broad bean meal	(Broekema and Smale, 2011)
	Lupins fibre Lupins hull Lupins okara Lupins protein slurry	Lupins oil Lupins protein-concentrate Lupins protein-isolate	(van Veghel, 2017)

Crop/animal products	Feed products	Food products	Source and original region of data
	Pea wet animal feed Pea starch-concentrate Pea slurry	Pea protein-isolate Pea protein-concentrate Pea starch slurry	(van Veghel, 2017)
Roots & tubers products	Cassava root dried Cassava peel Cassava pomace (fibrous residue)	Tapioca starch	(Chavalparit and Ongwandee, 2009) (van Zeist et al., 2012e)
	Potato juice concentrated Potato pulp pressed fresh + silage Potato pulp dried	Potato protein Potato starch dried	(van Zeist et al., 2012c)
Fruit and vegetable products	Citrus pulp dried		(van Zeist et al., 2012e)
Sugar products	Sugar beet molasses Sugar beet pulp wet Sugar beet pulp dried	Sugar from sugar beet	(van Zeist et al., 2012f) (Klenk et al., 2012)
	Sugar cane molasses	Sugar from sugar cane	(van Zeist et al., 2012f)

6.1.1 Waste in processing

Not all waste flows are included in the processing LCIs. There are several reasons why some minor waste flows have been omitted in the following case:

- Not a lot of information is available from literature on the quantity and type
- The fate of these flows is not known (to wastewater, mixed into feed streams, recycled, as soil improver or other waste), and
- The flows are usually small and fall well below the cut-off of 5%.

In Agri-footprint 7 the bio-waste flows that were not recirculated in the process have been modelled as wastewater treated if liquid waste and landfilled if solid waste. Even if the fates are not always known, these assumptions help the user in visualizing the complete mass balance of the process.

6.1.2 Water use in processing

Some of the original processing LCI's were taken from Feedprint in which water use was not accounted for as an input. The original data sources used in the Feedprint study often contain water use data. These were used as the primary data source for water use in processing. If data could not be found in these sources, other data from literature were used. Sometimes, no water use data for a specific crop/processing combination could be found. In that case, water use data from an analogous process for a different crop were used as a proxy. The water use sources for a specific process are indicated in the next chapters.

Water use is reported in Agri-footprint as "Water, unspecified natural origin" (sub-compartment 'in water'), with a specific country suffix, making the elementary flow region specific (e.g. "Water, unspecified natural origin, FR" – in water). Hereby the user can perform water stress related impact studies.

6.1.3 Energy use in processing

For energy use, system processes based on the Ecoinvent database are used. Electricity use is country specific, while use of heat from natural gas and light/heavy fuel oil are more regionalized (Table 6-2).

Table 6-2. List of energy sources used based on Ecoinvent

List of energy sources used
Electricity, low voltage {…}| market for | Cut-off, S
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW | Cut-off, S
Heat, district or industrial, natural gas {RoW}| heat production, natural gas, at industrial furnace >100kW | Cut-off, S
Heat, district or industrial, other than natural gas {RoW}| heat production, heavy fuel oil, at industrial furnace 1MW | Cut-off, S - Copied from ecoinvent
Heat, district or industrial, other than natural gas {RoW}| heat production, light fuel oil, at industrial furnace 1MW | Cut-off, S

6.1.4 Auxiliary material/other ingredients in processing

Several other inputs are used in the processing LCI's. For some of the auxiliary material the production process is modelled in Agri-footprint database. The description of these can be found in chapter 8. Other auxiliary materials and input used are based on the Ecoinvent database (system processes) as listed in Table 6-3.

Table 6-3 Auxiliary material used in various processes, based on background system processes.

Auxiliary material/Other ingredients	Process
Sodium chloride, powder {GLO}| market for sodium chloride, powder | Cut-off, S	Cheese production
Sulfur {GLO}| market for sulfur | Cut-off, S	Cassava, sugar beet and sugar cane processing
Limestone, unprocessed {RoW}| market for limestone, unprocessed | Cut-off, S	Sugar beet processing
Base oil {GLO}| market for base oil | Cut-off, S	Soybean crushing
Nitrogen, liquid {RoW}| market for nitrogen, liquid | Cut-off, S	Various oil refining

6.2 Animal products

6.2.1 Meat co-products

Processing of meat co-products into blood meal, greaves meal, food grade fat, fat from animals and animal meal is based on Feedprint (van Zeist et al., 2012a) and other literature sources (European Commission, 2005; Safriet, 1995).

6.2.2 Fish co-products

General processing of landed fish and offal, from fishery into fish oil and meal is based on Feedprint (van Zeist et al., 2012a) and other literature sources (Jespersen et al., 2000; Olesen and Nielsen, 2000; Pelletier et al., 2009; Pelletier, 2006).

In addition, marine ingredients yielding from reduction of a variety of specific fish sources are modelled, as listed in Table 6-4. The yield data and energy needed for processing are from (Cashion et al., 2017b, 2016b). By lack of specific price data, prices for general fish meal and fish oil are used to calculate allocation shares (1454 USD/ton fish meal and 1703 USD/ton fish oil, OECD stats 5-year average). (Cashion et al., 2016) also reports energetic contents for the fish meals separately and a general energy content for fish oil, which are used for allocation on energy basis.

Table 6-4. Fish meals and oils from fish reduction

Source	Output	Yield from 1t input (kg)	Economic allocation share
Alaska pollock by-products	Fish meal, from Alaska pollock	170	89.5%
	Fish oil, from Alaska pollock	17	10.5%
Anchoveta	Fish meal, from Anchoveta	240	80.4%
	Fish oil, from Anchoveta	50	19.6%
Atlantic menhaden	Fish meal, from Atlantic menhaden	240	80.4%
	Fish oil, from Atlantic menhaden	50	19.6%
Blue whiting	Fish meal, from Blue whiting	197	89.8%
	Fish oil, from Blue whiting	19	10.2%
Capelin	Fish meal, from Capelin	165	64.7%
	Fish oil, from Capelin	77	35.3%
Cod by-products	Fish meal, from Cod by-products	170	89.5%
	Fish oil, from Cod by-products	17	10.5%
European pilchard (sardine)	Fish meal, from European pilchard (sardine)	230	52.2%
	Fish oil, from European pilchard (sardine)	180	47.8%
Gulf menhaden	Fish meal, from Gulf menhaden	210	52.8%
	Fish oil, from Gulf menhaden	160	47.2%
Haddock	Fish meal, from Haddock	170	89.5%
	Fish oil, from Haddock	17	10.5%
Atlantic Herring	Fish meal, from Atlantic Herring	204	60.8%
	Fish oil, from Atlantic Herring	115	39.2%
Krill	Fish meal, from Krill	160	99.4%
	Fish oil, from Krill	0.80	0.6%
Sand Eel	Fish meal, from Sand Eel	197	79.9%
	Fish oil, from Sand Eel	42.4	20.1%
South American pilchard (sardine)	Fish meal, from South American pilchard (sardine)	230	52.2%
	Fish oil, from South American pilchard (sardine)	180	47.8%
Sprat	Fish meal, from Sprat	188	67.0%
	Fish oil, from Sprat	79	33.0%
Atlantic Herring by-products	Fish meal, from Atlantic Herring by-products	200	81.0%
	Fish oil, from Atlantic Herring by-products	40	19.0%
Mackerel by-products	Fish meal, from Mackerel by-products	194	47.5%
	Fish oil, from Mackerel by-products	186	52.5%

6.3 Cereal Products

6.3.1 Wet milling (maize, wheat)

Wet milling of maize is characterized by many intermediate steps and different type of food/feed co-products. The overall process is based on Feedprint (van Zeist et al., 2012c).

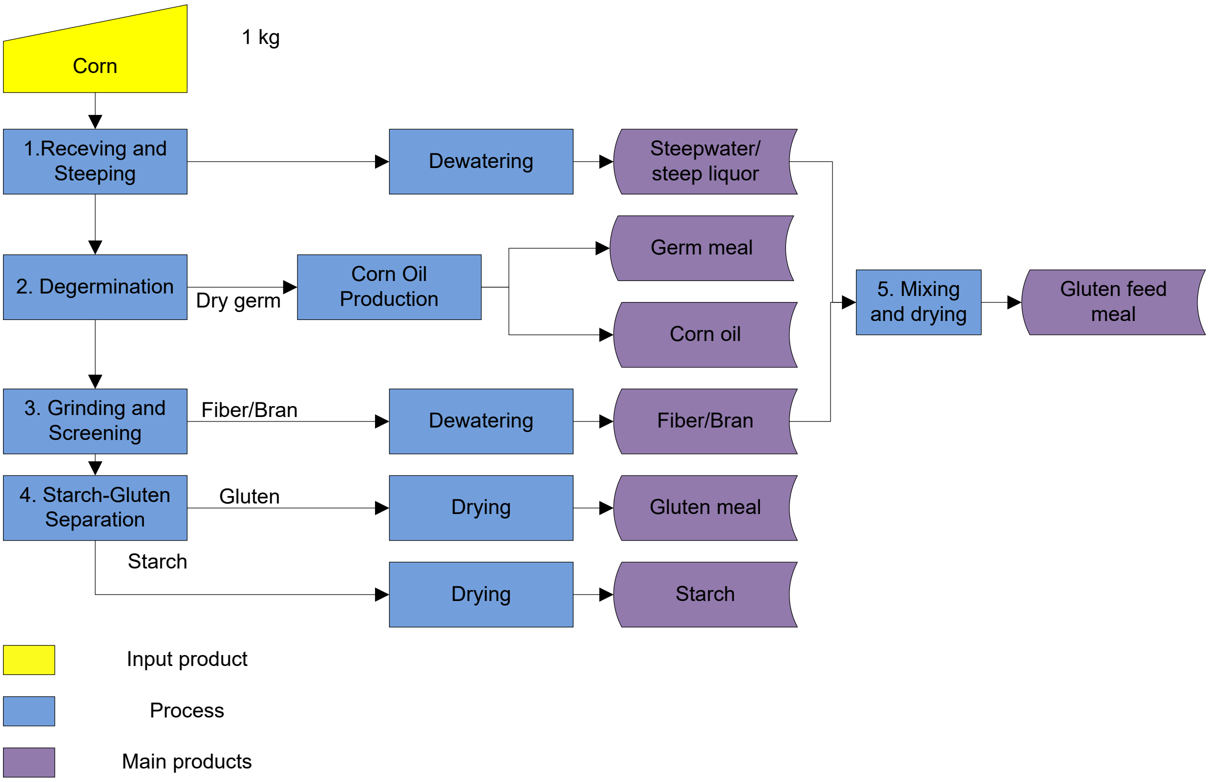


Figure 8: Wet milling of maize (van Zeist et al., 2012c).

While in maize all the sub steps are modelled, the wet milling of wheat is aggregated in one single LCI. The overall process is also based on Feedprint (van Zeist et al., 2012c). Water use for wet milling was not included in Feedprint, therefore the value was based on a report from (European Commission, 2006). For the water use in the corn oil production subs step (maize germ oil), rapeseed crushing (solvent) water use was used as proxy.

6.3.2 Dry milling (maize, wheat, rye, oat)

The mass balance for the dry milling of maize was based on (Bolade, 2009), which describes maize dry milling options in Africa. This publication is not detailed enough to include all co-products from dry milling of maize, thus the simplified mass balance gives flour and a generic by-products amount stemming from maize dry milling. Energy requirements for the dry milling of maize could have been based on (Li et al., n.d.) and (Mei et al., 2006). This is a publication of ethanol production from maize in a North American region, so the energy consumption is most likely underestimated, since dry milling to meal/flour takes several milling rounds, which is not required for producing ethanol. Besides, energy requirements vary greater than mass balances between regions. So, for dry milling of maize in EU countries, the decision was made to apply the energy requirements for wheat dry milling in

Europe by (Eijk and Koot, 2005) for the dry milling of maize in Europe, as this inventory is more representative of the technology in scope (dry milling of maize for food purposes).

Dry milling of rye grain, wheat grain and oat grain are based on Feedprint (van Zeist et al., 2012b). Water use in dry milling is based on (Nielsen and Nielsen, 2001).

6.3.3 Dry milling (rice)

This process describes the production of brown rice (rice without husks) and rice husks from a rice dry milling process in China Figure 9. Rice husk meal is typically used as animal feed. Traditionally, the process of de-husking was done manually, but nowadays the de-husking machine consists of a pair of rubber-lined rollers which are mounted in an enclosed chamber. As the rice passes through these rollers the husks are removed by friction leaving the paddy intact.

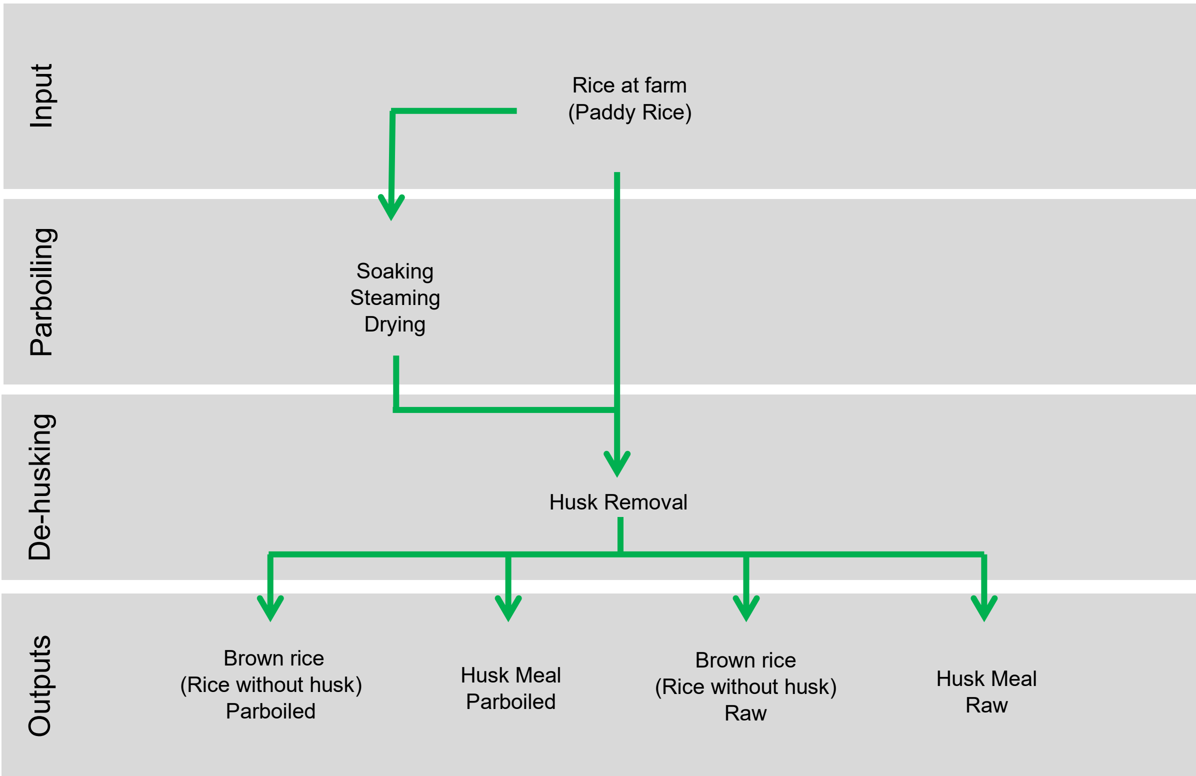


Figure 9: Diagram describing the process of production of rice without husks and rice husks from a rice dry milling process.

The parboiling process consists on soaking, partially boiling and drying the rice in the husk. Parboiling before de-hulling is optional, although it is estimated that half of the paddy rice is parboiled before processing. The advantages of parboiling are a reduction on grain breaking and improved nutritional content due to the fixation of thiamine to the rice endosperm. Weight changes or losses during the parboiling process were not taken into account.

These process steps are aggregated into a single process in the inventory and include the use of electricity and steam. The mass balance of the process is based on data from (IRRI, 2015a) (but mass of hulls and white rice is combined into a single output). Data on inventory inputs were taken from regional data (Goyal et al., 2012). To ensure the data consistency the data was compared to other publicly reported data for milling (Blengini and Busto, 2009; Roy et al., 2007). The data showed good agreement with the referenced studies as it showed similar input/output ratios. Water use in dry milling are based on (Nielsen and Nielsen, 2001).

Another process describes the production of white rice, rice husks, rice bran and rice brokens from a rice dry milling process in China Figure 10). The process starts with paddy rice, followed by de-husking and the milling process. Parboiling before de-hulling is optional, although it is estimated that half of the paddy rice is parboiled before processing. The advantages of parboiling are a reduction on grain breaking (less brokens) and improved nutritional content due to the fixation of thiamine to the rice endosperm.

The de-husking machines consists of a pair of rubber-lined rollers which are mounted in an enclosed chamber, as the rice passes through these rollers the husks are removed by friction leaving the paddy intact. The milling encompasses polishing to remove the bran and grading white rice and broken. These process steps are aggregated into a single process in the inventory, and it includes the use of electricity and steam. The mass balance of the process is based on data from (IRRI, 2015b) (but mass of hulls and white rice is combined into a single output). Data on inventory inputs are taken from regional data (Goyal et al., 2012), and compared to other publicly reported data for milling (Blengini and Busto, 2009; Roy et al., 2007). Water use in dry milling are based on (Nielsen and Nielsen, 2001).

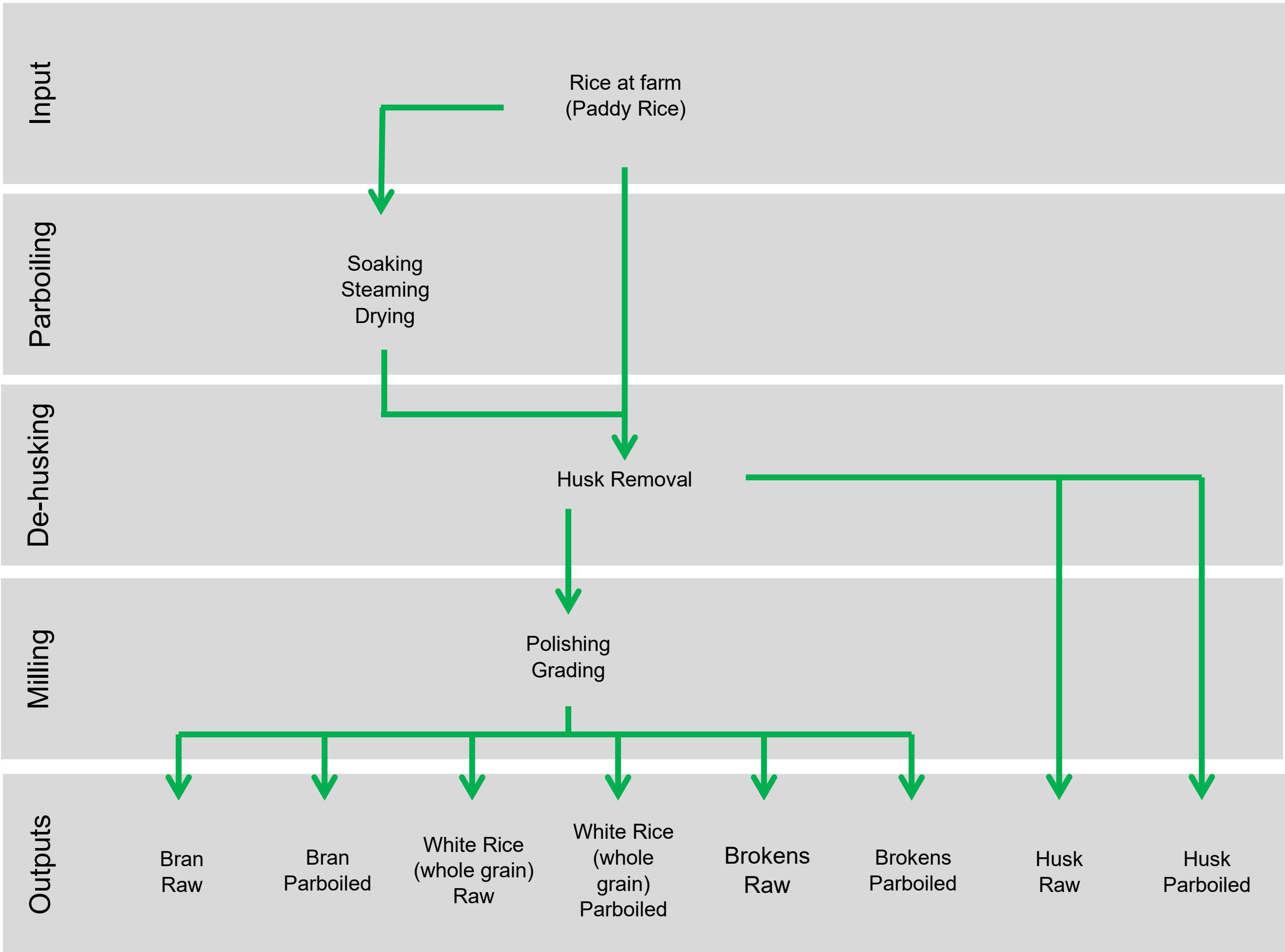


Figure 10: Diagram describing the process of production of white rice, rice husks, rice bran and rice brokens from a rice dry milling process in China

6.4 Oilseed products

The partial and full dehulling (pre-processing) of sunflower seed is based on the Feedprint report (van Zeist et al., 2012d). The soybean heat treatment is based on (Sheehan et al., 1998).

6.4.1 Crushing

The crushing of oil palm fruit (pressing), oil palm kernel (pressing), sunflower (solvent and pressing), groundnuts (solvent), coconut (pressing) and linseed (pressing and solvent) are based on Feedprint (van Zeist et al., 2012d).

The crushing of sunflower was updated compared to previous versions. Previously the hulls were considered as a waste flow landfilled that resulted in a certain amount of impact. In reality, the fate of sunflower hulls is very case-specific therefore they were considered as co-product assuming no value in case of economic allocation. When data will be available on the fate and price of sunflower hulls, it will be possible to update the process.

For the inventory of non-European crushing of soybean (pressing and solvent) and rapeseed (pressing and solvent) the Feedprint documentation was used (van Zeist et al., 2012d), for Europe a FEDIOL report was used as the main data source (Schneider and Finkbeiner, 2013).

FEDIOL represents the European Vegetable Oil and Protein meal Industry. Its federation members (1) purchase, store and transport oilseeds and vegetable oils; (2) process oilseeds into meals and crude oils, (3) refine and transform crude vegetable oils and (4) sell oils in bulk and in bottles to the food, feed and energy markets and meals to the feed market.

FEDIOL commissioned TU Berlin to conduct an LCA of oilseed crushing and vegetable oil refining. The objectives of this study were the establishment of a valid database, relating to primary data from the industry, and the assessment of potential environmental impacts of oilseed crushing focusing on rape seed oil, soybean oil and palm oil. These objectives make this study (Schneider and Finkbeiner, 2013) a good reference for an LCI of the crushing of soybeans and rapeseed in countries in the EU. Primary data from FEDIOL member companies (with best possible accuracy) are collected regarding all relevant processes. The data relate to crushing of oilseeds (soybeans, rape seed) at production facilities located in Europe. In total, 85% of the oilseed crushing and oil refining capacity in Europe is covered by FEDIOL members. The data obtained from FEDIOL members are aggregated based on information from more than twenty sites and six different countries, covering between 85 and 90% of all FEDIOL activities. Hence, the sample can be seen as representative for Europe since the participating companies constitute a high share of overall European activity.

For the crushing of soybeans and rapeseed in the US, other data sources have been used. The main sources of data for crushing of soybean and rapeseed are (OTI, 2010), (Sheehan et al., 1998) and ((S&T)2 Consultants, 2010). An important feature of the soybean crushing in the FEDIOL report is that no hulls are produced, since they are recirculated and incorporated in the meal. Furthermore, a small modification was applied: the soybean lecithin co-product was moved from crushing to soybean oil refining, since produced during degumming of the oil (typical step of oil refining).

For sunflower crushing (solvent) was assumed same water use as for rapeseed crushing (Schneider and Finkbeiner, 2013). For crushing through pressing no water use is assumed. Coconut crushing is also assumed dry, as this is currently the most economic process. For palm kernel processing, no data is found but is assumed to be insignificant by (Schmidt, 2007).

6.4.1.1 Price data for meals and oils

Table 6-5 shows an overview of product values and allocation percentages. Please note that output value per kg has no consistent unit between processes. It might be for example price in USD/ton, price in EUR/ton but also relative values as communicated by industry experts when actual prices are confidential. Units are always consistent within a process, so the allocation shares are calculated accurately. To update prices of oils and meals/expellers, a 5-year average was taken from FAOSTAT data. Since FAOSTAT does not distinguish between meals (output from a solvent process) or expellers (output from a pressing process) but publishes aggregated prices for “cakes” we assign meals/expellers similar values.

Table 6-5. Important allocation updates in AFP 7. *) Output value per mass has no consistent unit between processes. It might be for example price in USD/ton, price in EUR/ton but also relative values as communicated by industry experts when actual prices are confidential. Units are always consistent within a process to assure correct allocation. [1])USD/ton based on FAOSTAT 5-year average

Process		Outputs	Amount	AFP 7	
			kg	Value/ton *	Economic allocation %
Palm fruit bunch crushing		Palm oil	200	960[1]	81.5%
		Palm kernel	55	790[1]	18.5%
Groundnut crushing	solvent	Crude peanut oil	360	1351[1]	79.4%
		Groundnut meal	379	333[1]	20.6%
Linseed crushing	solvent	Crude linseed oil	350	1210[1]	51.8%
		Linseed meal	640	616[1]	48.2%
Linseed crushing	pressing	Crude linseed oil	270	1210[1]	42.6%
		Linseed expeller	715	616[1]	57.4%
Maize wet milling, germ oil production	pressing	Crude maize germ oil	330	1091[1]	66.4%
		Maize germ meal expeller	655	278[1]	33.6%

Maize wet milling, germ oil production	solvent	Crude maize germ oil	430	1091[1]	75.3%
		Maize germ meal extracted	555	278[1]	24.7%
Palm kernel crushing		Crude palm kernel oil	470	1090[1]	89.3%
		Palm kernel expeller	530	116[1]	10.7%
Rapeseed crushing	pressing	Crude rapeseed oil	310	897[1]	59.8%
		Rapeseed expeller	680	275[1]	40.2%
Rapeseed crushing (EU)	solvent	Crude rapeseed oil	413.2	897[1]	70.1%
		Rapeseed meal	574.4	275[1]	29.9%
Rapeseed crushing (nonEU)	Solvent	Crude rapeseed oil	428	897[1]	73.0%
		Rapeseed meal	518	275[1]	27.0%
Rice bran oil production		Crude rice bran oil	140	1564[1]	34.6%
		Rice bran meal	860	480[1]	65.4%
Soybean crushing	pressing	Crude soybean oil	140	776[1]	24.7%
		Soybean expeller	830	400[1]	75.3%
Soybean crushing	solvent, with protein-concentrate	Crude soybean oil	180	776[1]	11.3%
		Soybean hull	74	125	0.7%
		Soybean molasses	290	35	0.8%
		Soybean protein-concentrate	540	2000	87.2%
Soybean crushing (EU)	solvent	Crude soybean oil	192.31	776[1]	32.2%

		Soybean meal	784.62	400[1]	67.8%
Soybean crushing (nonEU)	solvent	Crude soybean oil	190	776[1]	33.6%
		Soybean meal	706	400[1]	64.3%
		Soybean hull	74	125	2.1%
Sunflower seed crushing	pressing	Crude sunflower oil	220	866[1]	68.8%
		Sunflower seed expelled dehulled	415	209[1]	31.2%
		Sunflower hull	350	0	0.0%
Sunflower seed crushing	solvent	Crude sunflower oil	285	866[1]	77.2%
		Sunflower seed meal	350	209[1]	22.8%
		Sunflower hull	350	0	0.0%
Maize dry milling		Maize flour	595	412[1]	75.1%
		Maize middlings	405	200	24.9%

6.4.2 Oil refining

Two literature sources have been used to model the refining of crude oil (Nilsson et al., 2010; Schneider and Finkbeiner, 2013). The refining efforts, auxiliary products required, and by-products depend on the type of vegetable oil.

Table 6-6: Process in- and outputs of oil refining

		Sunflower oil	Rapeseed oil	Soybean oil	Palm oil	Palm kernel oil
Literature source		(Nilsson et al., 2010)	(Schneider and Finkbeiner, 2013)			(Nilsson et al., 2010)
Inputs						
Crude oil	kg	1,046.46	1,032	1,038	1,080	1,068.8
Water	Kg	0	500	540	130	0
Bleaching earth	Kg	3.03	4.0	5.4	12	4.3
Phosphoric acid (85%)	Kg	0	0.7	1.0	0.85	0
Sulfuric acid (96%)	Kg	0	2.0	2.0	0	0
Nitrogen	Kg	0	0.5	0	1.5	0

Activated carbon	Kg	5.05	0.2	0.2	0	0
Sodium hydroxide	kg	0	3.0	2.8	0	0
Steam	Kg	266	170	225	115	214.67
Electricity	kWh	54.8	27	40	29	48.07
Diesel fuel	Kg	8.02	0	0	0	8.53
Outputs						
Refined oil	Kg	1,000	1,000	1,000	1,000	1,000
By-products	kg	37.95	20	23	70	67.2

For some less commonly used oils, no data were available. Therefore, the average of sunflower, rapeseed and soybean oil processing was used. Palm oil processing was not considered applicable as proxy, due to its high free fatty acid content and high levels of other substances (carotenes and other impurities) not commonly found in other vegetable oil types.

Table 6-7: Average process in and outputs of oil refining of maize germ oil, rice bran oil, coconut oil, linseed oil.

Inputs		
Crude oil	kg	1,039
Water	Kg	347
Bleaching earth	Kg	4.14
Phosphoric acid (85%)	Kg	0.57
Sulfuric acid (96%)	Kg	1.33
Nitrogen	Kg	0.17
Activated carbon	Kg	1.81
Sodium hydroxide	Kg	1.93
Steam	Kg	220
Electricity	kWh	40.6
Diesel fuel	Kg	2.67
Outputs		
Refined oil	Kg	1,000
By-products	kg	27.0

Table 6-5 presents the key parameters that were used to determine the allocation fractions for the co-products of rapeseed, soybean and palm oil refining. For the other refined oils, it is assumed that the by-products have the same properties as rapeseed and soybean oil (i.e. same LHV and average of the economic values for co-products) see Table 6-6.

Table 6-8: Key parameters required for mass, energy and economic allocation.

		Rapeseed oil	Soybean oil	Palm oil	Data source
Mass allocation:					
Dry matter refined oil	g/kg	1,000	1,000	1,000	(Schneider and Finkbeiner, 2013)
Dry matter soap stock	g/kg	1,000	1,000	-	
Dry matter fatty acid distillate	g/kg	-	-	1,000	
Energy allocation:					
LHV refined oil	MJ/kg	37	37	37	(Schneider and Finkbeiner, 2013)
LHV soap stock	MJ/kg	20	20	-	
LHV fatty acid distillate	MJ/kg	-	-	30	

Economic allocation:					
Value refined oil	€/kg	0.843	0.809	0.803	(Schneider and Finkbeiner, 2013)
Value soap stock	€/kg	0.200	0.350	-	
Value fatty acid distillate	€/kg	-	-	0.632	

Table 6-9: Estimated key parameters required for mass, energy and economic allocation for other refined oils and soap stock.

		Other refined oil	Comment
Mass allocation:			Applies to maize germ oil, rice bran oil, coconut oil, palm kernel oil and sunflower oil
Dry matter refined oil	g/kg	1,000	
Dry matter soap stock	g/kg	1,000	
Energy allocation:			Based on values for rapeseed and soybean oil
LHV refined oil	MJ/kg	37	
LHV soap stock	MJ/kg	20	
Economic allocation:			Based on values for rapeseed and soybean oil
Value refined oil	€/kg	0.826	
Value soap stock	€/kg	0.275	

6.5 Pulse products

Broad beans crushing into meal and hull was based on (Broekema and Smale, 2011). Lupins, pea and soybean processing into protein-concentrate and protein-isolate was based on the internship report by (van Veghel, 2017) at Blonk Consultants. The LCAs are based on literature and company communication. When possible, the literature data were verified by expert/industries. Table 6-10 shows the dry matter (DM) content, prices and gross energy (GE) content used for allocation purposes for all pulse outputs.

Table 6-10: Key parameters for mass, energy and economic allocation.

Output	DM content (g/kg)	GE content (MJ/kg)	Price (€/ton)
Broad bean, meal	900	18.0	550
Broad bean, hulls	900	9.2	130
Lupins fibre	600	9	495
Lupins hull	960	10.6	285
Lupins okara	410	3	140
Lupins protein slurry	35	0.3	489
Lupins oil	100	39.1	759
Lupins protein-concentrate	900	19.7	1600
Lupins protein-isolate	900	19.7	2785
Pea wet animal feed	220	5.5	46
Pea starch-concentrate	905	16.3	495
Pea slurry	330	3	35
Pea protein-isolate	900	17	3500
Pea protein-concentrate	905	119.7	1600
Pea starch slurry	400	3	274
Soybean okara	410	3	140
Soybean slurry	110	0.3	372
Soybean fines	910	9	313
Soybean molasses	600	11.2	35
Soybean protein-concentrate	930	19.7	2000
Soybean protein-isolate	950	19.7	4350

6.5.1 Pulse protein-concentrates

The protein-concentrates production a dry fractionation/air classification for pea and lupin, while a traditional ethanol water extraction for soybean. While the latter is an established industrial process, the dry fractionations of legume is still a new product. Still, the growing interest in meat substitutes could potentially boost these markets.

Figure 11: Lupin protein-concentrate production process (van Veghel, 2017). Figure 12 and Figure 13 show the graph used to extrapolate the data for LCIs.

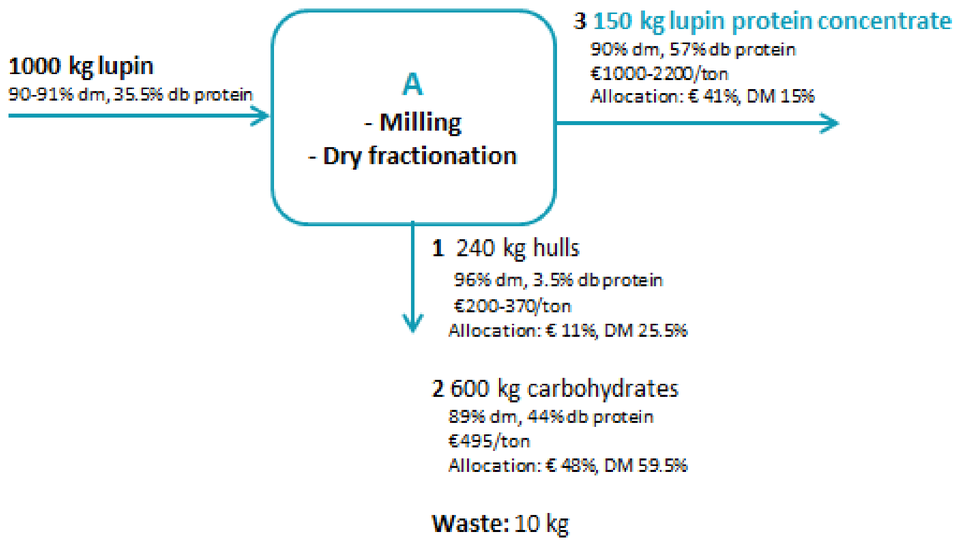


Figure 11: Lupin protein-concentrate production process (van Veghel, 2017).

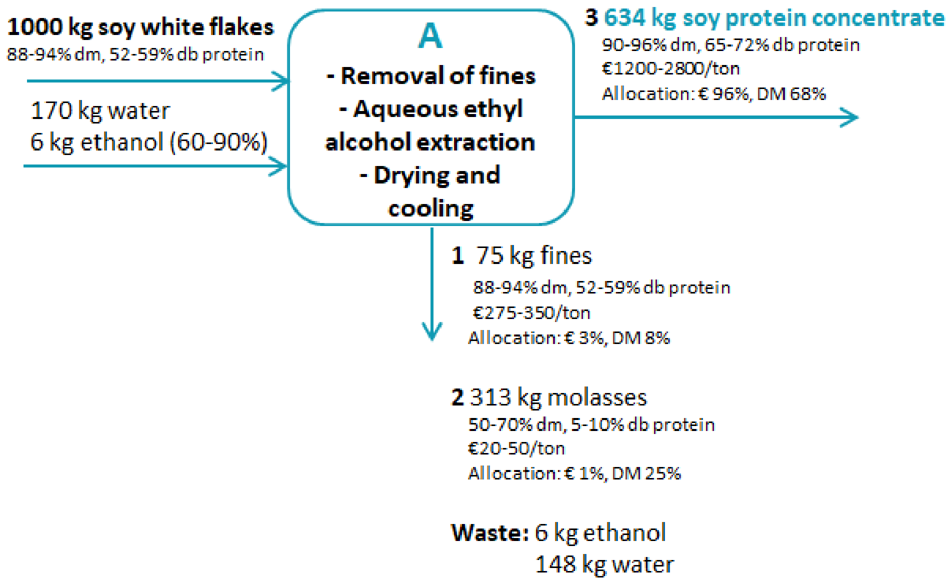


Figure 12: Soy protein-concentrate production process (van Veghel, 2017).

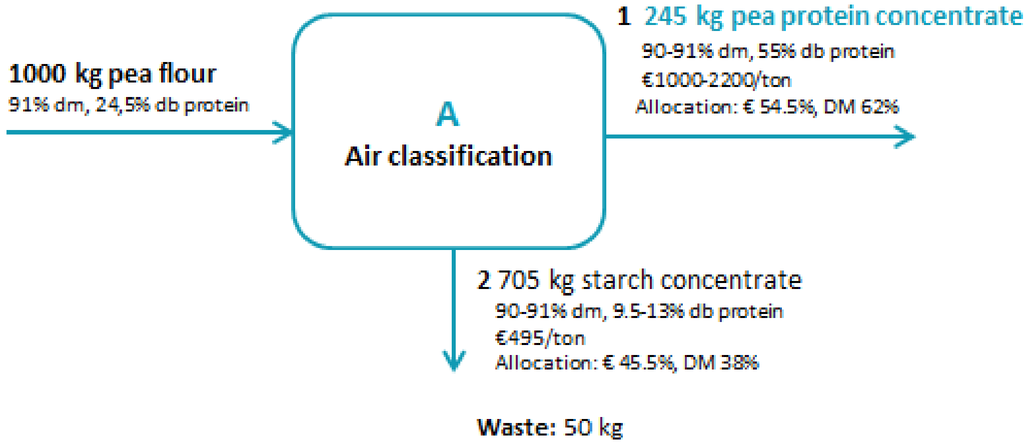


Figure 13: Pea protein-concentrate production process (van Veghel, 2017).

6.5.2 Pulse protein isolates

Isolates are produced trough a two steps process. Soybean isolate processing is a wet treatment on soybean meal, also called white flakes (Figure 14). Through acid and basic treatment, the proteins are separated. The second step is spray drying of the protein slurry. Same process is considered for lupin protein-isolate (Figure 15).

Production of pea protein isolate is shown in Figure 16 and occurred through separation of starch by hydrocyclones, followed by separation of fibres by a decanter centrifuge. After which precipitation of the soluble proteins occurred upon addition of phosphoric acid. These precipitated proteins were neutralized by sodium hydroxide and then spray dried. In Agri-footprint has been assumed as input directly pea, dried, since no data were available on pea milling into flour.

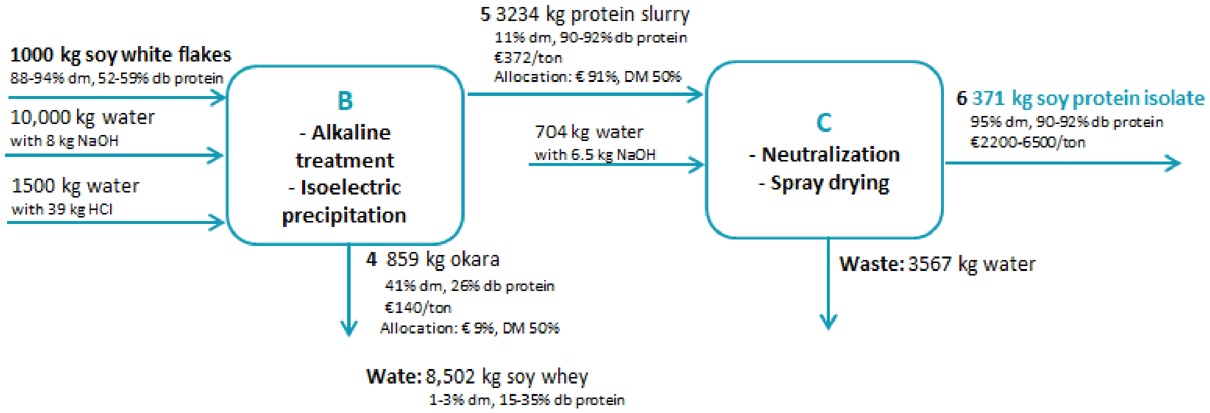


Figure 14: Soy protein-isolate production process (van Veghel, 2017).

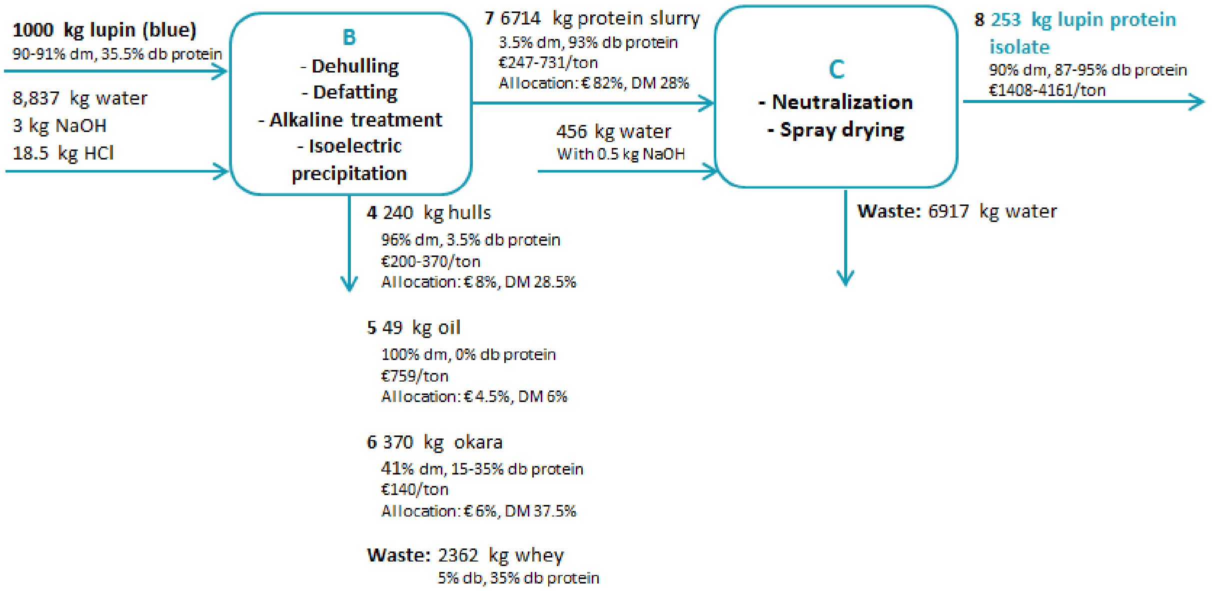


Figure 15: Lupin protein-isolate production process (van Veghel, 2017).

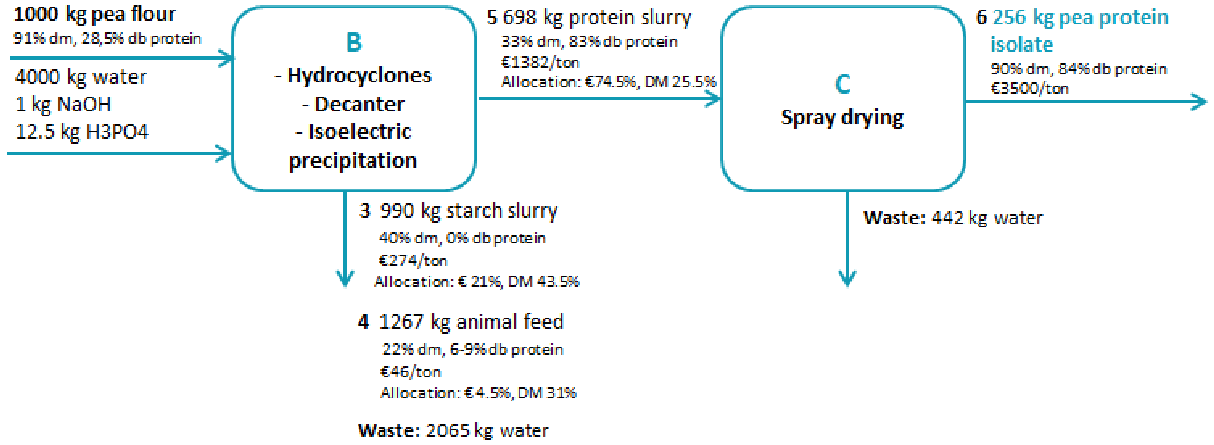


Figure 16: Pea protein-isolate production process (van Veghel, 2017).

6.6 Roots & tuber products

The potato wet milling into protein, juice concentrated, pulp pressed and dried starch is based on Feedprint (van Zeist et al., 2012c) and is aggregated in one LCI. Water use is based on (European Commission, 2006).

Cassava root processing was included in the original inventory of Feedprint, but this process did not take into account the use of co-products. When co-products like peels and fibrous residues (e.g. pomace) are not used, it results in heavy water pollution as it generates large amounts of solid waste and wastewater with high organic content. Based on literature, it is known that co-products are sold as animal feed at some plants. Because of this, two tapioca starch production processes are now included in Agri-footprint:

- Tapioca starch, from processing with use of co-products
- Tapioca starch, from processing without use of co-products

Both inventories are based on (Chavalparit and Ongwandee, 2009). The energy and sulfur are not included in the tables of this paragraph but are identical to the amounts mentioned in (Chavalparit and Ongwandee, 2009). The amount of fibrous residue (mainly pomace) was adapted to 15% of the cassava root because it can be up to 17% of the tuber (Feedipedia, 2014).

19.1 m3 of wastewater is generated to produce 1 tonne of tapioca starch output. This is identical to 454 kg of wastewater per tonne of cassava root input. The amount of peels is subtracted (454 kg – 90 kg) from the wastewater because peels are used as feed and do not end up in the wastewater. The pomace will end up in the wastewater, so the wastewater amount increased (454 kg + 150 kg).

6.7 Sugar products

6.7.1 Sugar from sugar beet

In 2012 the European Association of Sugar Producers (CEFS) published a report on the carbon footprint of EU sugar from sugar beets (Klenk et al., 2012). It is a detailed publication, containing the mass balance as well as energy requirements with a division between the sugar factory and the pulp drier. Average EU beet sugar factory emissions were calculated based on an EU-wide study conducted by ENTEC for the CEFS in 2010. The data covered the period 2005–2008.

6.7.2 Sugar from sugar cane

Several inputs are necessary during sugar cane processing. As (Renouf et al., 2010) has the most transparent references this is the main data provider and the report of (ETPi, 2011) was used when the required data was not available in the article of Renouf et al.

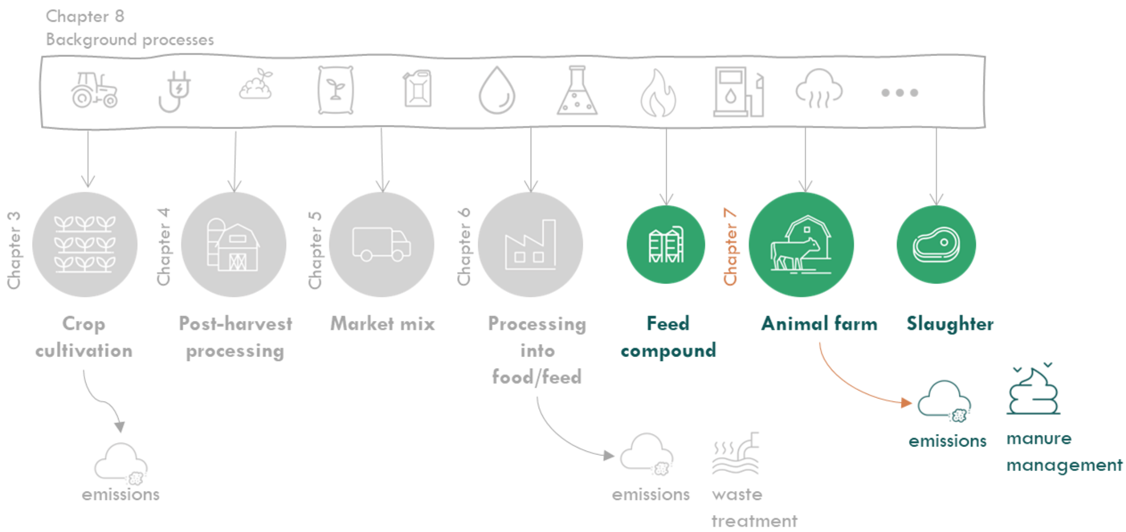
In the Feedprint data, the combustion of bagasse during sugar cane processing was not modelled (as the focus of the Feedprint project was on fossil carbon emissions). However, the emissions from bagasse combustion are included in Agri-footprint. When one tonne of sugarcane is processed, 280 kg of bagasse is created, which is combusted in the processing plant to provide heat and electricity. It is assumed that all the energy is used internally, and none is exported to a (heat or electricity) grid. The emissions are calculated from the emissions listed in (Renouf et al., 2010) and by the Australian (National Greenhouse Gas Inventory Committee, 2007) and are provided in Table 6-11. Although it is possible for sugar mills to produce electricity as surplus for the market, there is no data on how common this practice is, so the assumption was made that no surplus electricity is delivered to the market.

Table 6-11: Gas emissions from combustion of 280 kg of bagasse 'as is' (wet-mass).

Emission	Unit	Quantity
Carbon dioxide, biogenic	kg	218.9
Methane, biogenic	g	23.9
Dinitrogen monoxide	g	10.5
Carbon monoxide, biogenic	kg	4.2
Sulfur dioxide	g	84.0
Particulates, < 10 um	g	134.4

(Renouf et al., 2010) mention that the water evaporated from the cane is enough for what is needed. COD is described as 23 kg per 100 tonnes cane input. (European Commission, 2006) only notes that the water consumption is 'less' than sugar beet.

7. Animal Farm Systems



Please note that all farms here described are single enterprise, 'conventional' animal production systems. High welfare and organic systems are not included.

Table 7-1: Summary of animal production systems/country combinations included in Agri-footprint 6.

Animal production system	Country/regions included	Comment
Dairy farm system	BE, BR, DE, DK, ES, FR, GB, IE, IT, NL, NZ, PL, RER, US	RER as production mix
Beef system	IE	
Pig system	BE, BR, DE, DK, ES, FR, GB, NL, RER, RNA	Including breeding and fattening
Broiler system	BR, CN, FR, JP, NL, RER, TH, US	Including parent rearing, one day-chicken breeding and broiler fattening
Layer system	NL, RER, RNA	Including pullet rearing and egg production

7.1 Dairy Farm Systems

Raw milk production has been modelled for different countries worldwide, modelling typical conventional farm systems. Countries in scope are Belgium, Germany, Denmark, Spain, France, Ireland, Italy, New Zealand, Poland, Great Britain, United States of America. For Europe, a production mix of various European countries is compiled.

In the case of Belgium, the dataset is developed based on Flanders statistical data, therefore excluding the Wallonia productions. The distinction between Flanders and Wallonia is necessary due to the large differences in farm management practices (e.g., grazing, milk yield) and legal framework between these two regions in Belgium. The share of Flanders in BE dairy production is around 70%.

In the case of USA, the dataset is based on California data, since this is of higher availability compared to data at overall country level. The share of California in US dairy production is around 35%.

The datasets were originally developed during the Environmental Footprint (EF 3.0) (European Commission, 2022) agro-food database development (2021), and most of the datasets were developed in partnership with the European Dairy Association (EDA). This was done through involving country specific experts reviewing datapoints and providing alternative sources to improve the representativeness of the dataset.

Dairy farms are mixed and animal (housing system) and cultivation systems. Most of the farms has been normalized to a 100 dairy cows herd.

Raw milk is the main product that is produced on dairy farms. In addition, calves are produced (kept partly for herd replacement and partly sold to the veal industry), and unproductive cows are sent to slaughter. Also, in some countries it is typical to sell heifers and calves after being reared.

Table 7-2: Data sources for dairy farm parameters

Parameter	Country	Source
Milk yield and characteristics	BE, DE, PL, GB	(UNFCCC, 2021)
	BR	(Maciel, 2019)
	DK	(SEGES, 2021)
	ES	(CONAFE, 2021)
	FR	(Thomas and Bourrigan, 2019)
	IE	(CSO, 2021)
	IT	(Eurostat, 2021b; UNFCCC, 2021)
	NL	(Wageningen UR, 2021a)
	NZ	(LIC, 2021a; NZ Dairy, 2019)
	US	(CDFA, 2016; UNFCCC, 2021)
Animal mortality	BE	(FAO, 2018c; Landbouwmonitoringnetwerk (LMN), 2019)
	BR	(Maciel, 2019)
	DE, ES, IT, PL, GB, US	(FAO, 2018c)
	DK	(FAO, 2018c; SEGES, 2021)
	IE, NL, FR	(Wageningen UR, 2021b)
	NZ	(FAO, 2018c; Harris, 1989)
Herd composition and sold animals	BE	(Van Mierlo and Bracequené, 2020)
	BR	(Maciel, 2019)
	DE, IT, PL, GB	(FAO, 2018c; UNFCCC, 2021)
	DK	(Mogensen et al., 2015; SEGES, 2021; UNFCCC, 2021)
	ES	(MAPA, 2020)
	FR	(Thomas and Bourrigan, 2019)
	IE	(Dillon et al., 2021; ICBF, 2021)
	NL	(Wageningen UR, 2021a)
	NZ	(LIC, 2021b; NZ Dairy, 2019)
	US	(Thoma et al., 2013)
Feed intakes	BE	(Landbouwmonitoringnetwerk (LMN), 2019; Leip, 2017)
	BR	(Maciel, 2019)
	DE, DK, ES, FR, IT, NL, PL, GB	(Leip, 2017)
	IE	(Dillon et al., 2021)
	NZ	(DairyNZ, 2016)
	US	(Thoma et al., 2013)

Bedding materials	BE, DE, FR, NL, PL, GB, US	(Wageningen UR, 2021b)
	DK	(SEGES, 2021)
	ES	(MAPA, 2020)
	IE	(Dillon et al., 2021)
	IT	(Famiglietti et al., 2018)
Water use	BE	(Van Mierlo and Bracequené, 2020)
	BR	(Maciel, 2019)
	DE, DK, ES, NL, NZ, PL, GB, US	(Wageningen UR, 2021b)
	FR	(Menard et al., 2012)
	IE	(Murphy et al., 2017)
	IT	(Famiglietti et al., 2018)
Energy use	BE	(Van Mierlo and Bracequené, 2020)
	BR	(Maciel, 2019)
	DE, DK, ES, FR, NL, PL, GB	(Wageningen UR, 2021b)
	IE	(Upton et al., 2013)
	IT	(Famiglietti et al., 2018)
	NZ	(Chobtang et al., 2016; Stats NZ, 2021)
	US	(Thoma et al., 2012)
Time spent on pasture and manure management system	BE, DE, DK, ES, IE, IT, NZ, PL, GB, US	(UNFCCC, 2021)
	BR	(Maciel, 2019)
	FR	(IDELE, 2021; INOSYS Réseaux d'Elevage, 2021)
	NL	(CBS (Centraal Bureau voor de Statistiek), 2019; UNFCCC, 2021)
Compound feed formulation	BE, DE, FR, IE, IT, PL, GB	(Leip, 2017)
	BR	(Guimarães Júnior et al., 2007; Salman et al., 2011)
	DK	(Leip, 2017; Nielsen, 2021)
	ES	(MAPA, 2020)
	NL	(Personal Communication, 2013)
	NZ	(Ledgard et al., 2020)
	US	(Thoma et al., 2013)

The herd at the farm consists of dairy cows, and replacement animals (calves < 1 year, calves 1-2 years and heifers). In most cases, for comparability or data gaps, 100 dairy cows was used as a reference values, not representative of the actual typical country specific herd size. Heifers are defined as animals that are older than 2 years, but before their first calving. Male animals are assumed to be completely sold after birth, and the presence of bulls for reproduction is neglected in the system. The amount of the replacement animals is dependent on the dairy cows replacement rates, various animal mortalities, age of calving and age of slaughtering.

Table 7-3: Herd size at various country dairy farms, and other herd dynamics parameters.

Herd size and dynamics	BE	BR	DE	DK	ES	FR	IE	IT	NL	NZ	PL	GB	US

Female Calves < 1	36	49	38	50	37	40	38	38	29	24	38	38	23
Female Calves 1-2	32	48	35	46	33	37	35	35	25	24	35	35	21
Heifers	5	0	11	7	3	18	10	13	3	0	10	10	5
Dairy cows	100	120	100	100	100	100	82	100	102	100	100	100	51
Dairy cows replacement rate (%)	33	17	33	35	27	30	21	32	28	22	32	32	31
Dairy cows mortality (%)	4.4	1.8	4.0	5.4	4.0	2.0	2.0	4.0	2.0	1.2	4.0	4.0	4.0
Dairy cows average weight mortality	600	400	650	653	675	700	535	603	625	449	540	608	680
Heifer mortality (%)	4.0	0.0	4.0	4.0	4.0	2.0	2.0	4.0	2.0	1.2	4.0	4.0	4.0
Heifers average weight mortality (kg)	501	400	552	555	574	587	455	540	531	382	500	517	578
Calves 1-2 yr mortality (%)	4.0	1.0	4.0	4.0	4.0	3.0	2.0	4.0	2.0	2.0	4.0	4.0	1.6
Female Calves 1-2 yr average weight mortality (kg)	412	300	325	327	338	412	268	405	313	225	405	304	340
Calves <1 yr mortality (%)	8.0	3.0	8.0	8.0	8.0	8.0	5.0	8.0	3.0	6.0	8.0	8.0	6.4
Female Calves <1 yr average weight mortality (kg)	229	200	185	186	40	229	45	225	180	132	225	175	193
Age at first calving (years)	2.3	2.0	2.3	2.2	2.1	2.5	2.2	2.3	2.1	2.0	2.0	2.0	2.3
Age at slaughtering (years)	5.8	8.0	5.4	5.6	5.3	6.0	7.1	6.9	6.1	6.8	6.0	6.0	5.1

Dairy farms are a multi output systems, where together with milk, also sold animals are leaving the farm. In all cases, part of the dairy cows herd is replaced each year: these cows, that reached the end of their productive life, are typically culled and sent directly to the slaughterhouse. Most of male calves and part of female calves (not needed for replacement) are sold for further rearing or sometimes directly for slaughtering. In some countries, it is also typical to sell part of the grown animals (e.g., grown calves or heifers).

For allocation purposes, the dry matter, energy content and prices of the various co-products need to be defined. These values are based on the Dutch situation and are not country specific. The prices in particular are based on a 5 year averages from Binternet (2007-2011) (Wageningen UR, 2015b). FPMC milk is considered to have a 13.4% dry matter, an energy content of 3.34 MJ/kg and a value of €0.339 per liter. Liveweight is considered to have a 42.6% dry matter, an energy content of 11.28 MJ/kg liveweight. Prices for culled cows and sold calf are €0.888 and €3.182 per kg liveweight, respectively. The price for sold heifer and calves 1-2 years has been derived as an average of the two previous datapoints (€2.035 per kg liveweight).

Table 7-4: Milk output (and its characteristics) and sold animals at various country dairy farms.

Outputs and characteristics	BE	BR	DE	DK	ES	FR	IE	IT	NL	NZ	PL	GB	US
Milk (kg dairy cow^{-1})	9097	4869	7748	10068	8310	7373	5443	7329	8652	4359	5511	8071	10418
Milk protein content (%)	3.7	3.2	3.4	3.5	3.3	3.2	3.5	3.5	3.6	3.9	3.2	3.3	3.4
Milk Fat content	4.5	3.9	4.1	4.3	3.7	4.0	4.1	4.0	4.4	5.0	4.1	4.0	3.8
FPCM Milk (kg dairy cow^{-1})	10048	4782	7902	10593	7990	7315	5620	7442	9277	5096	5535	8070	10323
Culled dairy cows	28.3	20	28.5	29.5	30.7	33	16.9	28	26	21	28	28	31
Culled dairy cows average weight (kg)	600	500	650	653	675	700	535	603	625	449	540	608	680
Sold Calves < 1 yr	46.6	50	37.7	26.8	45.3	39	57.7	38.6	66.5	71	38.6	38.6	64
Sold Calves < 1 yr average weight (kg)	45	100	45	45	40	45	45	45	47	40	45	45	45
Sold Calves 1-2 yr	-	28	-	-	-	-	-	-	-	-	-	-	-
Sold Calves <1-2 yr average weight (kg)	-	300	-	-	-	-	-	-	-	-	-	-	-
Sold Heifers	-	-	-	14.3	-	-	-	-	-	-	-	-	-
Sold Heifers average weight (kg)	-	-	-	555	-	-	-	-	-	-	-	-	-

Energy consumption at a dairy farm consists of electricity, diesel, and natural gas, see Table 7-5 for the consumption of electricity and natural gas. The diesel consumption for land management is incorporated in the cultivation and production of roughage. Also, water is used at the dairy farm, both as drinking water and cleaning water. The source of drinking water is commonly groundwater. Irrigation water is considered in the pasture and roughages cultivation inventory. Bedding materials, in the form of wheat straw and saw dust, are considered in dairy cows' housing.

Table 7-5: Energy consumption and water use at various country dairy farms.

Country	Electricity	Natural	Fuel	Water	Wheat	Saw dust
	MJ/dairy cow			m3/dairy	kg/dairy cow	
BE	1364	0	1.1	40.6	55	125
BR	1387	0	0	83.6	0	0
DE	1432	417	0	41.8	55	125
DK	1480	0	0	41.8	44	6.25
ES	1480	0	0	41.8	730	1825
FR	1362	0	0	50.5	55	125
IE	1629	0	1068	36.0	50	0
IT	1963	0	0	47.6	675	0
NL	1599	408	0	41.8	55	125
NZ	285	10	0	41.8	0	0
PL	1480	0	0	41.8	55	125
GB	1480	0	0	41.8	55	125
US	2175	0	0	41.8	250	125

The feed intakes of the various countries dairy farms are displayed in Table 7-6. The various animals ration consists of (1) concentrates, also called compound feeds, (2) fresh grass, which animals eat in pastures, (3) farm grown feed, that mostly consists of grass silage and maize silage, and (4) single ingredients, like for instance straw. For calves, the feed ration depends on their age. When calves are very young and stabled, they are usually fed with raw milk directly from the cows. This milk is produced by the cows but does not end up in the milk tank. Because the dairy farm is modelled as one animal system which produces calves, milk and meat, the milk which is fed to the calves is accounted for in this manner. The rest of the ration consists of concentrates, grass silage and maize silage. When calves are older, they spend relatively much time in the pasture where they eat mainly grass. The heifers were assumed to be fed the same ration as the female calves 1-2 years of age.

The overall diet fed to the various animal types is assumed to have a 70% digestibility (DE % of GE) with the exception of calves < 1 year, for which a 80% DE% is assumed. These were based on (IPCC, 2006b). Based on the same source, we assumed the GE content of the overall animals' diet to be 18.45 MJ/kg DM.

For the United States system, the feed intakes are simplified. Due to the aggregated form in which the data on feed intake were available, the feed fed to the various replacement animals is fully allocated to heifers. This results in an unbalanced hotspot analysis.

Table 7-6: Dry Matter Intake (DMI, kg/animal/year) of the animals on the various countries' dairy farms per various feed fed. Dry matter (DM, %) content and Crude Protein (CP, % of DM) content of the overall diet.

Type of animal	Compound feeds intake	Fresh grass intake	Farm grown feed intake	Single ingredients intake	Overall diet dry matter content	Overall diet crude protein content
BE		DMI, kg/animal/year			DM, %	CP, % of DM
Calves < 1 yr	458	10	936	0	42.4	12.1
Calves 1-2 yr	377	1743	921	0	22.2	20.8
Dairy cows	1441	3460	1375	225	32.7	18.1
Heifers	377	1743	921	0	22.2	20.8
BR		DMI, kg/animal/year			DM, %	CP, % of DM
Calves < 1 yr	659	0	0	0	90.2	31.2
Calves 1-2 yr	659	1120	2424	0	27.5	24.1
Dairy cows	2635	455	4088	0	38.7	25.8
Heifers	1317	2262	2920	0	26.3	24.6
DE		DMI, kg/animal/year			DM, %	CP, % of DM
Calves < 1 yr	24	952	384	0	18.8	20.0
Calves 1-2 yr	73	2897	1119	0	19.0	20.6
Dairy cows	781	587	5379	430	31.1	14.8
Heifers	73	2897	1119	0	19.0	20.6
DK		DMI, kg/animal/year			DM, %	CP, % of DM
Calves < 1 yr	67	6	2029	0	47.1	18.3
Calves 1-2 yr	279	1807	956	0	24.2	18.5
Dairy cows	2480	29	4049	736	52.4	16.7
Heifers	279	1807	956	0	24.2	18.5
ES		DMI, kg/animal/year			DM, %	CP, % of DM
Calves < 1 yr	522	265	175	0	35.3	27.1
Calves 1-2 yr	233	1215	2125	0	27.4	26.8
Dairy cows	2095	2269	1710	0	27.7	26.9

Heifers	233	1215	2125	0	27.4	26.8
FR		**DMI, kg/animal/year**			**DM, %**	**CP, % of DM**
Calves < 1 yr	602	55	447	0	41.4	17.1
Calves 1-2 yr	166	1970	2293	0	25.4	20.6
Dairy cows	1885	634	4850	557	41.2	16.8
Heifers	166	1970	2293	0	25.4	20.6
IE		**DMI, kg/animal/year**			**DM, %**	**CP, % of DM**
Calves < 1 yr	333	487	320	0	23.9	16.2
Calves 1-2 yr	182	1339	814	0	19.2	16.2
Dairy cows	1026	2797	1144	23	21.1	16.3
Heifers	182	1339	814	0	19.2	16.2
IT		**DMI, kg/animal/year**			**DM, %**	**CP, % of DM**
Calves < 1 yr	779	108	568	0	65.1	22.1
Calves 1-2 yr	493	1423	2228	0	28.7	22.1
Dairy cows	1320	1108	4850	257	39.4	20.3
Heifers	493	1423	2228	0	28.7	22.1
NL		**DMI, kg/animal/year**			**DM, %**	**CP, % of DM**
Calves < 1 yr	173	563	702	0	26.5	20.9
Calves 1-2 yr	257	1729	598	0	20.9	21.9
Dairy cows	1732	1906	2825	69	30.3	21.5
Heifers	257	1729	598	0	20.9	21.9
NZ		**DMI, kg/animal/year**			**DM, %**	**CP, % of DM**
Calves < 1 yr	0	1048	0	0	16.0	23.1
Calves 1-2 yr	0	1968	0	0	16.0	23.1
Dairy cows	668	4040	222	0	18.4	21.2
PL		**DMI, kg/animal/year**			**DM, %**	**CP, % of DM**
Calves < 1 yr	893	47	104	0	63.1	14.5
Calves 1-2 yr	479	2187	827	0	24.6	20.3
Dairy cows	2842	762	1034	604	42.6	15.0
Heifers	479	2187	827	0	24.6	20.3
GB		**DMI, kg/animal/year**			**DM, %**	**CP, % of DM**
Calves < 1 yr	101	1070	199	0	18.8	22.0
Calves 1-2 yr	391	3213	262	0	18.4	23.4
Dairy cows	1457	2810	4169	205	30.4	20.3
Heifers	391	3213	262	0	18.4	23.4
US		**DMI, kg/animal/year**			**DM, %**	**CP, % of DM**
Dairy cows	3226	3018	992	571	48.4	26.3
Heifers	6216	10649	3557	2835	39.7	30.2

Calculated emissions are CH_4 from enteric fermentation and various manure management related emissions: CH_4, N_2O direct and indirect, NH_3, NO_X, NMVOC and $PM_{2.5}$. Also, NMVOC emissions from silage feeding are included. All these emissions have been calculated with the APS-footprint tool (Blonk Consultants, 2020a, 2020b).

For each country specific dairy farm, animal-specific manure management shares have been considered (UNFCCC, 2021) accounting for the time share that animals spend outside in the pasture. This has an effect on the ration of excretions dropped in the stable and on the pasture. Days spent on the pasture reflect full 24 hours spent outside.

Since the Anaerobic digestor is not available as manure management system in APS-footprint tool (due to lack of a fixed emissions factors in IPCC guidelines), we assumed the CH_4 and N_2O emissions from manure management are equivalent to 50% of the emissions of the pit storage >1 month manure management system, based on extrapolated values from literature (Evers et al., 2019).

Table 7-7: Yearly excretion of nitrogen, phosphorous, manure, and methane emission due to enteric fermentation for each animal type on the average Dutch dairy farm.

Type of animal	Calves < 1 yr	Calves 1-2 yr	Dairy cows	Heifers
BE	%	%	%	%
Percentage of time spent outside	6	6	14	0
Pit storage > 1 month	9	66	70	22
Solid storage	28	9	10	9
Dry lot	64	26	20	69
BR	%	%	%	%
Percentage of time spent outside	0	50	50	50
Daily spread	100	100	100	100
DE	%	%	%	%
Percentage of time spent outside	0	20	11	20
Solid storage	27	27	17	27
Liquid/Slurry without natural crust	42	42	60	42
Anaerobic digester	13	13	23	13
Cattle and Swine deep bedding (>1	18	18	0	18
DK	%	%	%	%
Percentage of time spent outside	0	36	5	36
Liquid/Slurry with natural crust	100	100	86	100
Anaerobic digester	0	0	14	0
ES	%	%	%	%
Percentage of time spent outside	63	63	0	63
Daily spread	0	0	9	0
Solid storage	60	60	46	60
Liquid/Slurry with natural crust	40	40	45	40
FR	%	%	%	%
Percentage of time spent outside	30	55	39	55
Solid storage	97	90	58	89
Liquid/Slurry with natural crust	3	10	42	11
IE	%	%	%	%
Percentage of time spent outside	39	58	70	65
Pit storage > 1 month	79	68	94	100
Cattle and Swine deep bedding (>1	21	32	6	0
IT	%	%	%	%
Percentage of time spent outside	5	5	5	5
Solid storage	0	70	56	70
Liquid/Slurry without natural crust	100	30	44	30
NL	%	%	%	%
Percentage of time spent outside	3	8	12	8
Pit storage > 1 month	100	100	100	100

NZ	%	%	%	%
Percentage of time spent outside	100	100	92	100
Uncovered anaerobic lagoon	-	-	12	-
Daily spread	-	-	88	-
PL	**%**	**%**	**%**	**%**
Percentage of time spent outside	12	12	10	12
Solid storage	88	88	88	88
Liquid/Slurry with natural crust	5	5	5	5
Liquid/Slurry without natural crust	6	6	6	6
GB	**%**	**%**	**%**	**%**
Percentage of time spent outside	54	71	21	71
Daily spread	2	100	8	2
Solid storage	80	0	20	80
Liquid/Slurry with natural crust	14	0	58	14
Liquid/Slurry without natural crust	4	0	14	4
US	**%**	**%**	**%**	**%**
Percentage of time spent outside	0	0	0	1
Uncovered anaerobic lagoon	70	0	0	0
Solid storage	30	0	0	0
Dry lot	0	88	88	88
Daily spread	0	12	12	12

The feed material compositions of the daily ration have been mostly based on a model shared by (Leip, 2017), where, based on import/export feed ingredients statistics and allocation to various animal types. For the Netherlands, compound feeds have been based on the analysis of the yearly throughput of feed raw materials, specifically for dairy, of Agrifirm - the market leader in animal feed production in the Netherlands (Personal Communication, 2013). Due to the large amount of rations (animal and country specific), the exact composition has not been included in this documentation and can be found directly in the Unit LCI database.

The energy consumption for the manufacturing of the compound feed is based on the Feedprint study (315 MJ of electricity and 135 MJ of natural gas). Transportation of compound feed to the animal farm is not included and will be implemented in future versions of the database.

Roughage is produced on the dairy farm, with a fraction of the manure which is excreted by the dairy cattle. These are in principle with the same methodology described previously for other types of cultivations.

7.2 Beef System

Only Irish production is included in Agri-footprint 6.

The Irish beef system is based on a study by (Casey and Holden, 2006). In the Irish beef system, beef is produced; It is not a dairy system. In this system, beef calves are primarily fed on grass in pasture for a large part of the year (214 days), and grass silage and compound feed in stable (151 days). Calves are weaned after approximately 6 months;

therefore, no additional feed is required for the first 6 months. The feed regime is listed in Table 7-8, and generic farming parameters in Table 7-9. Table 7-10 lists the feed intake over the whole lifetime of a beef animal as described in the study, and Table 7-11details the composition of the compound feed. The meat calves are slaughtered after two years. However, the dietary requirements of cows that produce new calves are not mentioned in the study. Therefore, the feed ration intake of the calves in their second year has been used as a proxy for the feed intake of cows that are kept for breeding and herd replacement. The feed intake from Table 7-10 has been linearly scaled to the time spent in pasture and indoors (e.g. total time in pasture = 244 days, therefore grass intake in 30 days in year 1 is 30/244*12,355= 1,519 kg).

A herd consists of 20 cows, giving birth to 18 calves (a birth rate of 90%). 3 cows and 15 two-year old calves are slaughtered every year
Table 7-12), 3 heifers are kept for herd replacement and 1 bull is also kept on pasture. These data can be used to develop an inventory for Irish beef production, which is presented below in Table 7-13.

Table 7-8: Rations for cows and calves per animal for one year.

Animal type	# on farm	Cow milk in pasture		Grazing in pasture		Grass silage and supplement in stable		
		Time (days)	**Feed intake**	**Time (days)**	**Feed intake (kg grass)**	**Time (days)**	**Feed intake (kg grass silage)**	**(kg supplement)**
Calves age 0-1	18	184	-	30	1,519	151	2,491.5	508
Calves age 1-2	18	-	-	214	10,796	151	2,491.5	508
Cows	20	-	-	214	10,796	151	2,491.5	508
Bulls	1	-	-	214	10,796	151	2,491.5	508
Heifers	3	-	-	214	10,796	151	2,491.5	508

Table 7-9: Farming practices for Irish beef.

Farming practices	Unit	Quantity
Target live weight	kg	647
Average daily gain	kg/day	0.87
Lifetime	days	730
Time grazing in pasture	days/year	214
DMI	kg	5,406
DMI/day	kg	7.4

Table 7-10: Lifetime consumption of dietary components per beef animal (Casey and Holden, 2006).

Ingredient	Ration weight (kg as fed)	DM (%)	DM intake (kg)
Fresh Grass	12,355	20.6	2,545.1
Grass silage	4,983	38.4	1,913.5
Supplement	1,016	86.6	879.9
Total consumed	18,354	29 (average)	5,337.9*

**In the original publication, the authors report a different total DM consumed, but this seems to be a type error (as it is identical to the total for the diet listed below).*

Table 7-11: Compound feed composition (Casey and Holden, 2006).

Supplement ingredients	DM (%)	Mass proportion in supplement (%)	Product origin	Comment
Barley	86	29	IE / UK	Assuming 50% UK - 50% IE
Wheat	86	9	IE / UK	Assuming 50% UK - 50% IE
Molasses	75	5	India / Pakistan	Assuming 50% IN - 50% PK
Rapeseed meal	90	15	US / Uzbekistan	Assuming 100% USA
Oats	84	9	US	-
Soya	90	12	Brazil	-
Maize	87	21	US	-
Total	86.6 (average)	100	-	-

Table 7-12: Farm outputs in one year in the Irish beef system

Farm output	Unit	Mass	Comment
Cows for slaughtering	kg	1,995	3 Cows @ 665 kg, replaced by heifers
2-year-old calves for slaughtering	kg	9,705	15 Calves @ 647 kg
Total	kg	11,700	Live weight

Table 7-13: Inventory for Irish beef production

	Unit	Quantity	Comment
Products			
Beef cattle, at farm/IE Economic	kg	11,700	Total live weight to slaughter per year: 15 x 2-year old calves @647 kg live weight + 3 x cows @665 kg
Resources			
Water, unspecified natural origin/m3	m^3	587.42	Water for drinking
Materials/fuels			
Grass, at beef farm/IE	kg	618,996.5	
Grass silage (beef), at farm/IE	kg	122,137	
Beef cattle compound feed, at processing/IE	kg	32,803	
Energy, from diesel burned in machinery/RER	MJ	68,043.7	
Transport, truck >20t, EURO4, 80%LF, default/GLO	tkm	3,280.3	Transport of feed from feed compound plant to farm
Electricity/heat			
Electricity mix, AC, consumption mix, at consumer, < 1kV NL S	kWh	3,555	
Emissions to air			
Methane, biogenic	kg	2,279.68	CH_4 emissions due to enteric fermentation
Methane, biogenic	kg	642.54	CH_4 emissions due to manure management in stable
Dinitrogen monoxide	kg	4.25	direct N_2O emissions from the stable
Dinitrogen monoxide	kg	5.95	indirect N_2O emissions from the stable
Ammonia	kg	459.69	NH_3 emissions from the stable

Particulates, < 10 um	g	10,200

7.3 Pig system

Pig fattening and pig breeding productions here described are single enterprise, 'conventional' animal production systems. High welfare and organic systems are not included. Countries/regions in scope are Belgium, Brazil, Denmark, France, Germany, Great Britain, the Netherlands, Spain, Europe and North America (Table 7-14).

Brazil data points are weighted averages of Mato Grosso and Santa Carolina regions (83% and 17% production share, respectively). North America data points are weighted averages of United States of America and Canada (84% and 16% production share, respectively, based on (FAO, 2021d)). Europe data points are weight averages of various European countries, based on (Eurostat, 2021c) production shares on piglets (25% Spain, 24% Germany, 16% Netherlands, 13% Denmark, 11% France, 5% Belgium, 4% Great Britain, 2% Hungary and 1% Czechia) and pig (27% Spain, 25% Germany, 11% Netherlands, 11% Denmark, 12% France, 6% Belgium, 4% Great Britain, 3% Hungary and 1% Czechia).

Table 7-14: Data source used for the pig breeding and fattening LCIs.

Source	Parameter
(Hoste, 2020), country specific information	Pig reared per sow (every year), sow replacement rate, piglet weight at transfer, fattener target liveweight, fattener and gilt FCR, length of fattener production period, sow feed intake per year, gilt and pig mortality, feed consumption rearing phase.
(Wageningen UR, 2021b), NL specific data	Sow and piglet mortality, gilt removals to slaughtering, price of sold animals, slaughtering weight of spent sow.
(UNFCCC, 2021), country specific	Manure management systems
(Wageningen UR, 2021a), NL specific data	Energy and water use.
(Kebreab et al., 2016)	Compound feed formulations
(Personal Communication, 2013), NL specific data	Compound feed formulation for the systems "Pig fattening, dutch feed formulation, at farm/NL Economic" and "Piglet, dutch feed formulation, at farm/NL Economic"
(Feedipedia, 2021)	Nutritional characteristics of compound feeds ingredients
(Centraal Veevoeder Bureau, 2016)	Nutritional characteristics of compound feeds ingredients for the systems "Pig fattening, dutch feed formulation, at farm/NL Economic" and "Piglet, dutch feed formulation, at farm/NL Economic"
Assumed	Weight at weaning, piglet production period,

The production of pigs for slaughter is organized in two production stages.

In the first stage, sows are reared, inseminated and then goes through a gestation period that concludes with the farrowing. New-born piglets are weaned with the mother sow, and then (after separation) reared up to a target weight for transfer. The second stage of the production system, the pig fattening stage, pigs are fattened to a target live weight. When the pigs have achieved the target weight, they are sent to slaughter.

The data points in the first stage are rescaled to be representative of 1 sow animal place, while the LCIs for the second stage are rescaled to 1 fattener animal place (

Table 7-15).

Table 7-15: Piglet breeding and pig fattening animal average population and various population dynamic metrics.

Animal population and dynamics	BE	BR	DK	FR	DE	GB	NL	ES	RER	RNA
Gilt average population	0.16	0.13	0.13	0.14	0.12	0.13	0.13	0.17	0.14	0.15
Gilt removals to slaughtering (%)	5	5	5	5	5	5	5	5	5	5
Sow feed intake (kg/year)	125	115	144	133	131	137	132	114	129	122
Sow mortality (%)	6	6	6	6	6	6	6	6	6	6
Sow replacement rate (%)	42	45	53	45	39	55	41	45	45	44
Sow slaughtering weight (kg)	230	230	230	230	230	230	230	230	230	230
Weaning piglet mortality (%)	16	16	16	16	16	16	16	16	16	16
Weaned piglet weight (kg)	8	8	8	8	8	8	8	8	8	8
Rearing piglet average population (#/sow)	3.93	4.13	6.00	5.28	5.34	5.91	4.51	3.00	4.59	4.00
Piglet rearing mortality (%)	0	0	0	0	0	0	0	0	0	0
Piglet rearing feed intake (kg/animal)	26.7	30.6	39.6	39.3	39.1	53.3	28.3	20.8	32.7	29.2
Piglet rearing production length (days)	52	55	68	67	67	82	56	42	59	55
Piglet weight at transfer (kg)	23.1	24.5	30.2	30.1	30.0	36.5	25.0	18.7	26.2	24.6
Pig reared per sow (#/year)	27.7	27.5	32.4	28.6	29	26.4	29.4	26.1	28.6	26.5
Fattener (and gilt) FCR	2.70	2.48	2.60	2.80	2.80	2.70	2.60	2.50	2.66	2.75
Fattener (and gilt) production length (days)	133	100	85	112	109	86	115	130	113	121
Fattener (and gilt) mortality	3.2	2.5	3.4	3.8	2.7	3.2	2.4	4.1	3.2	5.0
Fattener (and gilt) target weight (kg)	116	112	115	121	122	111	122	115	118	128

For allocation between spent sows and piglets, the dry matter, energy content and prices of the various co-products needs to be defined. These values have been based on Dutch values and are not country specific. The prices in particular are based on (Wageningen UR, 2021b). The considered dry matter and gross energy content is 62% and 11.44 MJ/kg respectively. Prices considered for spent sow and piglets are 888 euro/ton and 1767 euro/ton, respectively.

Energy and water use was based on NL yearly data (KWIN SOURCE): 1828 MJ electricity/sow, 137 MJ electricity MJ/ fattener, 1293 MJ natural gas/sow, 41 MJ natural gas/fattener, 459 MJ diesel/sow, 34 MJ diesel/fattener, 7880 kg water/sow and 650 kg water/fattener. Only in the case of Brazilian production, no natural gas use was assumed.

For each country, a manure management mix has been considered (

Table 7-16). In the case of Brazil, due to lack of a representative data, anaerobic lagoon manure management was assumed. Calculated emissions are CH_4 from enteric fermentation and various manure management related emissions: CH_4, N_2O direct and indirect, NH_3, NO_X, NMVOC, PM_{10} $PM_{2.5}$ and TSP (Total Suspended Particle). All these emissions have been calculated with the APS-footprint tool (Blonk Consultants, 2020c, 2020b).

Table 7-16: Manure management system mix for various countries pig farms.

Manure management systems	BE	BR	DK	FR	DE	GB	NL	ES	RER	RNA
Solid storage (%)						50			4	
Anaerobic lagoon (%)		100								
Pit storage (<1 month) (%)										11
Pit storage (>1 month) (%)	100							100	29	59
Liquid/Slurry without natural crust cover (%)			100	100	100	50	100		67	30

Emission reduction at housing (either due to housing design or mitigation technology such as air washers) are not considered in these typical systems. This means that emissions (in particular ammonia and particulate matter emissions) might be overestimated compared to the average country systems. This is especially relevant for countries where these systems are applied to a bigger extent such as the Netherlands.

Compound feed formulations, and their nutritional characteristics are described in Table 7-17. These are generic compound feed formulations, that are pre-defined weighted averages for different swine types (sow, piglet and growing pigs). This means that the feed ingredients and manure emissions are allocated to various animal stages in an approximated way.

For the process “Pig fattening, Dutch feed formulation, at farm/NL Economic” and “Piglet, Dutch feed formulation, at farm/NL Economic” compound feeds (Dutch and animal type specific) as implemented in previous Agri-Footprint versions is incorporated in the LCI (Table 7-18).

The energy consumption for the manufacturing of the compound feed is based on the study that was performed for the Dutch Product Board Animal Feed (PDV) by Wageningen University and Blonk Consultants, in which life cycle inventories (LCIs) were developed for crop cultivations used in compound feeds. For one tonne of compound feed, 315 MJ of electricity and 135 MJ of natural gas are required. Feed transport is not included in the LCIs.

Table 7-17: Compound feed formulations, regions and animal type aggregated.

Feed Ingredient	Unit	RER	RNA	BR
Wheat grain, dried	%	37.9	65	
Maize, dried, market mix	%	12.8		77.5
Barley grain, dried	%	31.1		
Wheat bran, from wet milling	%	2.2		0.1
Rapeseed meal (solvent)	%	5.1		
Soybean meal (solvent)	%	6.8	9.3	16.9
Crude rapeseed oil (solvent)	%	0.3		
Soybeans, dried	%	0.01		
Total minerals, additives, vitamins	%	1.1	1.2	2.1
Single superphosphate, as 35% Ca(H2PO4)2 (NPK 0-21-0)	%	0.2	0.1	0.2
Sodium chloride, powder	%	0.4	0.4	0.4
Calcium carbonate, precipitated	%	1.8	1.5	0.9
Whey powder dried	%	0.2	0.2	
Maize distillers grains dried	%		14.6	
Wheat middlings & feed	%		6.8	
Fat from animals	%		1	1.4

Sugar beet pulp dried	%			0.3
Total	**%**	**100**	**100**	**100**
Dry matter	%	87.5	87.7	87.1
Nitrogen content	% as is	2.2	2.4	2.4
Digestibility	% of GE	70.8	75.9	77.3

Table 7-18: Compound feed formulations, Dutch and animal type specific. Other ingredients have been excluded from the LCI.

Feed Ingredient	Unit	Piglets	Sows	Pigs
Wheat grain, dried	%	26	13	25
Barley grain, dried	%	36	21	29
Rye grain, dried	%	0	4	3
Maize, dried	%	6	4	2
Triticale grain, dried	%	0	0.5	2
Oat grain, dried	%	1	0	0
Wheat middlings & feed	%	2	17	6
Wheat gluten feed	%	1	4	1
Maize middlings	%	0	2	1
Molasses	%	1	1	1
Sugar beet pulp dried	%	1	5	1
Crude palm oil	%	1	1	1.5
Soybeans, dried	%	4	0	0
Soybean meal (solvent)	%	13	4.5	8
Soybean hulls	%	0	5.5	0.5
Rapeseed meal (solvent)	%	2	4	10
Sunflower seed meal (solvent)	%	2	3	4
Palm kernel expeller	%	0	8	2.5
Fat from animals	%	0	0.5	0.5
Other	%	4	2	2
Total	**%**	**100**	**100**	**100**
Dry matter	%	87.2	88.3	87.5
Nitrogen content	% as is	2.8	2.8	2.8
Digestibility	% of GE	85	75	85

7.4 Poultry system

7.4.1 Laying hens system

Egg production here described are single enterprise, ‘conventional’ animal production systems. High welfare and organic systems are not included. Countries/regions in scope are the Netherlands, Europe and North America (Table 7-19). All datapoints used for the North American systems were provided, though personal communication, by (Guyonnet, 2020)

The European dataset is representative of an enriched cage system. The data points are weighted averages of various European countries (26% Spain, 19% Poland, 19% France, 15% Great Britain, 15% Italy, 4% the Netherlands, 2% Germany, 0.4% Denmark), based on production share of eggs produced in enriched cages (calculated from (FAO, 2021d) and (European Commission, 2018b)).

Dutch egg LCI is representative of an aviary system.

For North American productions (cage), we distinguished two types of farms characterized by a different type of manure management (dry and wet).

Table 7-19: Data source used for the egg production LCIs.

Source	Country	Parameter
(Van Horne, 2018), country specific	RER	Laying period length, number of eggs per hen, egg average weight, laying hen feed conversion ratio
(Wageningen UR, 2021b), NL specific	NL	Laying period length, number of eggs per hen, egg average weight, laying hen feed conversion ratio
	NL, RER	Pullet feed intake, reared pullet average liveweight, pullet rearing production length, pullet mortality, spent hen average weight, laying hen mortality, electricity use, water use, bedding material use
(Wageningen UR, 2021a), NL specific	NL, RER	Diesel use, natural gas use
(IPCC, 2006b), default	NL, RER	Feed metabolizable energy, ash content, manure management systems
(Centraal Veevoeder Bureau, 2016), default	RER	Compound feed nutritional N content and dry matter content
(Raamsdonk et al., 2007), NL specific	NL, RER	Pullet and laying hen feed formulation

The production of consumption eggs consists of two animal production stages. In the first stage the laying hens are reared up to approximately 17 weeks (pullet). In the second stage the laying hens start to produce eggs. After a production period they are slaughtered (

Table 7-20).

Breeding of one-day chicken for pullet rearing is assumed to be the same as for animal meant for broiler production. It is described in the subsequent broiler chapter.

The stables are not filled with animals throughout the whole year, but they remain empty for cleaning in between production rounds.

Table 7-20: egg production (and pullet rearing) population dynamic metrics.

Animal population dynamics		NL	RER	RNA
Pullet feed intake	Kg/animal	4.01	4.01	5.94
One-day chicken weight	g/animal	42	42	42
Reared pullet weight	Kg/animal	1.29	1.29	1.29
Pullet mortality	%	4	4	2.9
Pullet rearing period length	days	112	112	126
Laying hen feed conversion ratio	Kg/kg egg	2.09	2.04	1.97
Spent hen average weight	Kg/animal	1.60	1.60	1.71
Hen mortality	%	7.8	7.8	9
Laying period length	days	490	420	525
Number of eggs per hen	#/year	323	316	293
Egg average weight	g/egg	61.5	62.9	61.5

Utilities are used at the animal farms. Values for North American LCIs are 8.5 MJ electricity/pullet, 1.5 MJ diesel/pullet, 3.0 MJ natural gas/pullet, 557 MJ electricity/1000 eggs, 159 MJ diesel/1000 eggs and 4 MJ natural gas/1000 eggs. Diesel is an aggregate of various fuels used. For the Dutch and European LCIs values for utilities use are 2.4 MJ electricity/pullet, 0 MJ diesel/pullet, 0 MJ natural gas/pullet, 1.1 MJ diesel//(hen year) and 1.5 MJ natural gas//(hen year). Electricity use is differentiated between NL (7.1 MJ electricity/(hen year)) and RER (2.6 MJ electricity/(RER hen year)).

Poultry manure without litter was assumed for all three regions, except that for the North American LCIs an additional system was modelled were an anaerobic lagoon manure management was considered. This is a common manure management in North Aamerica, while rarely implemented at European farms.

Calculated emissions are only connected to manure management: CH_4, N_2O direct and indirect, NH_3, NO_X, NMVOC, PM_{10} $PM_{2.5}$ and TSP (Total Suspended Particle). All these emissions have been calculated with the APS-footprint tool (Blonk Consultants, 2020d, 2020b).

Emission reduction at housing (either due to housing design or mitigation technology such as air washers) are not considered in these typical systems. This means that emissions (in particular ammonia and particulate matter emissions) might be overestimated compared to an average country system.

The feed composition of laying hens <17 weeks and >17 weeks for the Dutch and European LICs is based on (Raamsdonk et al., 2007) from RIKILT, see Table 7-21. Feed formulations for North American production is based on (Guyonnet, 2020).

The energy consumption for the manufacturing of the compound feed is based on a study that was performed for the Dutch Product Board Animal Feed (PDV) by Wageningen University and Blonk Consultants, in which life cycle inventories (LCIs) were developed for crop cultivations used in compound feeds. For one tonne of compound feed, 315 MJ of electricity and 135 MJ of natural gas are required. Feed transport is not included in the LCIs.

Table 7-21: laying hen (>17 weeks) and pullet (<17 weeks) compound feed formulations.

Feed Ingredient	Unit	Laying hen <17		Laying hen >17	
		NL/RER	RNA	NL/RER	RNA
Barley grain, dried	%	1.51	0	1.11	7.02
Maize, dried	%	38.6	60.14	32.80	36.14
Wheat grain, dried	%	13.26	0	20.92	28.97
Wheat bran	%	3.69	0	4.06	0
Wheat gluten feed	%	0	0	0.65	0
Wheat middlings & feed	%	0	0	0	2.35
Rapeseed meal (solvent)	%	0	0	0	1
Maize gluten feed, dried	%	1.61	0	1.50	0
Soybean meal (solvent)	%	15.53	26.69	13.45	16.36
Sunflower seed meal (solvent)	%	2.61	0	3.22	0
Cassava root, dried	%	0.91	0	1.46	0
Molasses	%	0.05	0	0.11	0
Animal meal	%	0	0	0	2.69
Maize distillers grains dried	%	0	0	0	2.52
Crude palm oil	%	0	0	0.004	0

Crude soybean oil (solvent)	%	0	1.82	0	0
Crude rapeseed oil (solvent)	%	0	0	0	0.45
Sodium chloride, powder	%	0	0.29	0	0.39
Fat from animals	%	3.44	0	3.41	0.05
Peas, dry	%	1.17	0	2.15	0.57
Soybean, heat treated	%	5.62	0	2.67	0
Soybeans, dried	%	0	0	0.26	0
Limestone, unprocessed	%	8.82	9.59	9.09	1.07
Total minerals, additives, vitamins	%	0	1.5	0	0.5
Other	%	3.18	0	3.12	0
Total	%	100	100	100	100
Dry matter	%	88.0	87.6	87.0	88.6
Nitrogen content	%	3.68	2.72	2.39	2.80
Metabolizable energy	%	75.0	73.5	75.0	73.5

7.4.2 Broilers system

Broiler production here described are single enterprise, 'conventional' animal production systems. High welfare and organic systems are not included. Countries/regions in scope are the Brazil, China, France, Japan, the Netherlands, Thailand, United States and Europe (Table 7-22). The modelling of parent rearing, one-day-chicken breeding and eggs hatching has been fully based on (Wageningen UR, 2021b).

Table 7-22: Data sources used for the broiler production LCIs.

Source	Country	Parameter
(Putman et al., 2017)	US	Broiler average target weight, broiler energy use, broiler water use, broiler bedding material use
		Broiler production length, broiler mortality rate
(Prudêncio da Silva et al., 2014)	BR, FR	Broiler production length, broiler mortality rate
	BR	Broiler FCR, broiler average target weight
(van Horne, 2019)	FR, RER	Broiler FCR, broiler average target weight
(Kebreab et al., 2016)	US	Broiler FCR
(Wageningen UR, 2021b), NL specific	All but US	Broiler bedding material use, broiler energy use, broiler water use
Personal communication with regional industry experts (2020)	NL, JP, CN, TH, RER	Broiler production length
	NL, JP, CN, TH	Broiler FCR, broiler average target weight
(CBS (Centraal Bureau voor de Statistiek), 2019)	All	One day-chicken weight
(Personal Communication, 2013)	All	Broiler parents (rearing and one-day chicken breeding) compound feed formulations
(FAO, 2018c)	All	Broiler compound feed formulation
Assumed	All	Broiler cleaning period length, broiler mortality rate

(Prudêncio da Silva et al., 2014)

The production of broilers for chicken meat consists of three animal production stages and a hatchery. In the first stage the bird parents are bred up to 20 weeks. In the second stage bird parents are reared and they start to produce eggs for hatching. After a production period they are slaughtered. The eggs are hatched in a hatchery, producing one-day-chicks. This system is assumed to the same for one-day chicken that are meant for broiler production and pullet rearing into laying hens (previous chapter). In the third system the one-day-chicks are reared in a couple of weeks and slaughtered to produce chicken meat. The stables are not filled with animals throughout the whole year, but they remain empty for cleaning in between production rounds.

Table 7-23: Key parameters for the parent rearing and on day chicken breeding production systems.

Parameter	Unit	Value
Parent rearing period length	days	140
Parent rearing empty period length	days	21
Reared pullet liveweight	Kg/animal	2.27
On-day chicken weight	g/animal	42
Pullet mortality rate	%	11
Pullet compound feed intake	Kg/reared pullet	4.96
One-day chicken breeding period length	days	286
One-day chicken breeding empty period length	days	40
Egg weight	g/egg	61.5
Parent mortality during one-day chicken breeding	%	2.2
Infertile egg output	Eggs/reared pullet	10
Hatching egg output	Eggs/reared pullet	174
Parent weight at the end of the cycle	Kg/animal	3.93
Parent FCR during one-day chicken breeding	Kg/kg egg	4.21
One day chicken per hatched egg	#/#	0.8

Table 7-24: Key parameters for the broiler production system.

Parameter	Unit	FR	NL	BR	RER	US	JP	CN	TH
Broiler period length	Days	40	42	42	42	47	46	29	38.5
Broiler empty period length	Days	8	8	8	8	8	8	8	8
Broiler target weight	Kg/animal	1.9	2.8	2.4	2.3	2.6	3.0	1.6	2.2
Broiler mortality rate	%	4.1	3.2	4.3	3.2	4.0	3.2	3.2	3.2
Broiler FCR	Kg/kg	1.67	1.55	1.88	1.63	1.70	1.55	1.67	1.44

The breeding of one-day chickens system produces hatching eggs, infertile eggs as well as spent parents which are slaughtered for meat. This requires allocation of the environmental impact to the products. Considered dry matter contents are 21% and 70% for eggs and spent animals, respectively. Gross energy contents are set at 4.73 MJ/kg and 13 MJ/kg for eggs and spent animals, respectively. Considered prices are 3036 euro/kg, 81 euro/kg and 449 euro/kg for hatching eggs, infertile eggs and spent animals, respectively.

Each of the various stage requires input of bedding material, water and energy. The parent rearing to 20 weeks uses 2.27 kg straw/pullet reared, 22.5 kg water/pullet reared, 3.0 MJ electricity/pullet reared, and 17.8 MJ heat/pullet reared. The parent stage (one-day chicken breeding) requires 1.2 kg straw/parent, 57.5 kg water/100 hatching eggs, 8.3 MJ electricity/100 hatching eggs and 5.1 MJ heat/hatching eggs. The egg hatchery is considered to be using 53.3 MJ heat/100 one-day chicken. For the broiler fattening stage, all countries (except US) were assumed to require 0.34 kg straw/broiler place, 51.1 kg water/ broiler place, 2.9 MJ electricity/ broiler place and 19.8 MJ heat/ broiler place. The US broiler farm has an input of 1.33 kg straw/broiler place, 64.0 kg water/broiler place, 5.2 MJ electricity/broiler place, 5.0 MJ heat/broiler place, and 1.1 MJ diesel/broiler place.

As manure management system "Poultry manure with litter" is assumed for all the stages and countries. Calculated emissions are connected to manure management: CH_4, N_2O direct and indirect, NH_3, NO_X, NMVOC, PM_{10} $PM_{2.5}$ and TSP (Total Suspended Particle). All these emissions have been calculated with the APS-footprint tool (Blonk Consultants, 2020d, 2020b).

Emission reduction at housing (either due to housing design or mitigation technology such as air washers) are not considered in these typical systems. This means that emissions (in particular ammonia and particulate matter emissions) might be overestimated compared to an average country system.

The feed composition of broiler parents (<20 weeks & >20 weeks) and broilers (Table 7-25) is based on confidential information from major feed producer in the Netherlands (data from 2010) and data derived from GLEAM model (FAO, 2018c), respectively.

The energy consumption for the manufacturing of the compound feed is based on the study that was performed for the Dutch Product Board Animal Feed (PDV) by Wageningen University and Blonk Consultants in which life cycle inventories (LCIs) were developed for the cultivation of crops used in compound feeds. For one tonne of compound feed 315 MJ of electricity and 135 MJ of natural gas are required. The assumption was made that the feed is transported over 100 kilometers from the factory to the farm with a truck.

Table 7-25: Feed rations for broiler parents and broilers.

Feed Ingredient	Unit	Broiler parents		Broilers					
		<20 weeks	>20 weeks	RER	FR	NL	JP/CN	BR/TH	US
Barley grain, dried	%	3	7	0	0	0	5	0	0
Maize, dried	%	26	17	22.5	25	0	39	71	63
Sorghum grain, dried	%	0	0	3.5	0	0	9	0	0
Wheat grain, dried	%	28.5	34	41.9	41	48	18	0	0
Wheat bran	%	7.5	12	0	0	0	0	0	0
Wheat gluten meal	%	1.5	1.25	0	0	0	0	0	0
Maize gluten meal	%	1.5	0.5	0	0	20	0	0	0
Soybean meal (solvent)	%	6.5	3	25.2	24	25	23	27	25
Sunflower seed meal	%	6	13	0	0	0	0	0	0
Rapeseed meal (solvent)	%	5.5	6	4.8	8	5	2	0	5
Oat grain, dried	%	0.5	1	0	0	0	0	0	0
Crude palm oil	%	0.5	0.25	0	0	0	0	0	0
Fat from animals	%	2.5	1	0	0	0	0	0	0
Peas, dry	%	0.5	0	0	0	0	0	0	0
Fish meal	%	0	0	0	0	0	2	0	5
Meat bone meal	%	0	0	0	0	0	0	0	0

Citrus pulp dried	%	6.5	0	0	0	0	0	0	0
Calcium carbonate,	%	0	0	1	1	1	1	1	1
Total minerals, additives,	%	0	0	1	1	1	1	1	1
Other	%	3.5	4	0	0	0	0	0	0
Total	%	100	100	100	100	100	100	100	100
Dry matter	%	88.1	87.7	87.9	88.1	88.0	87.6	87.0	88.0
Nitrogen content	%	2.65	2.75	3.00	3.00	3.00	3.10	3.00	3.30
Metabolizable energy	%	75.0	75.0	76.4	78.0	77.4	74.5	74.5	81.7

7.5 Slaughterhouse

Animals are slaughtered for meat production in a slaughterhouse. The live weight of the animals is separated into fresh meat, food grade, feed grade and other products (non-food and non-feed) (Luske and Blonk, 2009), according to the mass balance shown in Table 7-26.

Table 7-26: Mass balances of the slaughterhouses for different animal types (Luske and Blonk, 2009).

		Pigs	Chickens	Beef cattle	Dairy cattle
Fresh meat	%	57.00	68.00	45.8	40.4
Food grade	%	10.32	4.48	18.7	20.6
Feed grade	%	27.95	13.76	14.1	15.5
Other	%	4.73	13.76	21.4	23.6
Total		100.00	100.00	100.00	100.00

The energy consumption and water consumption at slaughtering is based on Dutch data (www.routekaartvlees.nl, 2012). They are shown in Table 7-27 to Table 7-29.

The water use is not split up transparently in the 'ketenkaarten[12]' (www.routekaartvlees.nl, 2012), so the remainder of the total is assumed to be for general facilities, but some of this can probably be attributed to the slaughterhouse processes directly.

The production of four products from the slaughterhouse (fresh meat, food grade, feed grade and other - non-food & non-feed) requires allocation. This is done based on mass (as is), energy content as well as financial revenue. The results are highly dependent on the choice of allocation. The fresh meat and food grade will have the highest financial revenue, but the feed grade and other non-food and non-feed products represent a significant amount of the mass of all final products. See Table 7-30.

[12] Ketenkaarten is the name used for the maps from www.routekaartvlees.nl made to display the overview of the supply chain.

Table 7-27: Energy and water consumption for chicken meat in the slaughterhouse.

Production line	Action	Electricity (MJ/kg LW)	Natural gas (MJ/kg LW)	Water (l/kg LW)
Slaughter line	Culling	0.001	-	0.025
	Slaughtering process	0.05	-	-
	Conveyor belt	0.01	-	-
	Cleaning the truck	-	-	0.038
	Washing	-	-	1.09
Cooling line	Dry air cooling	0.19	-	-
	Spray cooling	0.155	-	0.05
	Cooling the workspace	0.03	-	-
	Water bath	-	-	0.25
General facilities		0.03	0.13	0.73
Total		0.466	0.13	2.19

Table 7-28: Energy and water consumption for pig meat production in the slaughterhouse.

Production line	Action	Electricity (MJ/kg LW)	Natural gas (MJ/kg LW)	Water (l/kg LW)
Slaughter line	slaughtering process	0.01	-	0.16
	heating tray	-	0.03	-
	oven	-	0.15	-
	washing	-	-	-
Cooling line	dry air cooling	0.14	-	-
	spray cooling	0.11	-	0.16
	cooling the workspace	0.09	-	-
	cutting and deboning	0.001	-	-
General facilities		0.032	0.06	2.15
Total		0.383	0.24	2.47

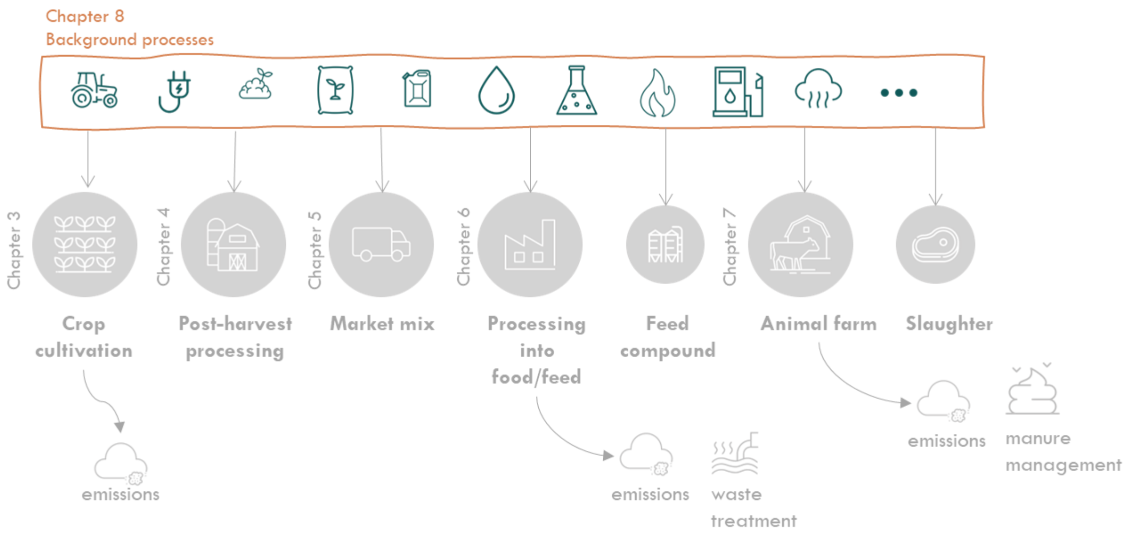
Table 7-29: Energy and water consumption for beef in the slaughterhouse.

Production line	Action	Electricity (MJ/kg LW)	Natural gas (MJ/kg LW)	Water (l/kg LW)
Slaughter line	slaughtering process	0.01	-	0.29
	heating of water	-	0.11	-
	removing the skin	-	-	0.36
Cooling line	dry air cooling	0.27	-	-
	spray cooling	-	-	-
	packing	0.001		-
	cooling the workspace	0.06	-	0.01
	cutting and deboning	0.002	-	0.08
Cleaning line	removing the organs	-	-	0.07
General facilities		0.048	0.04	1.19
Total		0.391	0.15	2.0

Table 7-30: Key parameters required for economic allocation and allocation based on energy content (Blonk et al., 2007), (Kool et al., 2010).

Type of animal	Parameter	Economic allocation (€/kg)	Allocation on energy content (MJ/kg)
Chicken	Fresh meat	1.50	6.14
	Food grade	0.60	7.39
	Feed grade	0.10	6.95
	Other	0.10	7.39
Pig	Fresh meat	1.90	7.00
	Food grade	0.15	14.19
	Feed grade	0.04	9.63
	Other	0.00	7.86
Dairy cattle	Fresh meat	3.00	7.00
	Food grade	0.30	23.68
	Feed grade	0.05	13.15
	Other	0	8.23
Beef cattle	Fresh meat	4.00	7.00
	Food grade	0.30	23.68
	Feed grade	0.05	13.15
	Other	0	8.23

8. Background processes



8.1 Adjustment in wastewater process

All Ecoinvent background processes that are used in Agri-footprint are exact copies from the Ecoinvent v3.10 database, except for the wastewater process. In the copied wastewater process from Ecoinvent (Wastewater, average {RoW}| market for wastewater, average | Cut-of, S), all water flows have been deleted. The original wastewater process in Ecoinvent itself “produces” water, which from a material balance point of view is correct. But this can result in negative water consumption for agricultural products in case the crop is cultivated without irrigation. To avoid negative water consumption of agricultural products and to comply with the with the ISO 14046 on water footprint (ISO 14046, 2014), it was chosen to remove all water flows from the wastewater background dataset. Hereby no water “credits” are given to wastewater processing, but the other impacts related to wastewater processing (electricity, chemical use, etc.) are still included.

8.2 Transport processes

8.2.1 Road

Fuel consumption for road transport is based on primary activity data of multiple types of vehicles (Table 8-1). These data have been categorized into three types of road transport: small trucks (<10t) medium sized trucks (10-20t) and large trucks (>20t). Small trucks have an average load capacity of 3 tonnes, medium trucks have an average load capacity of 6.2 tonnes and large trucks have an average load capacity of 24 tonnes average.

Small, medium and large trucks have a fuel consumption that is the average within the category of the primary activity data (Table 8-2). Because the fuel consumption has been measured for fully loaded as well as for empty vehicles, the fuel consumption can be adapted to the load factor (share of load capacity used) by assuming a linear relationship between load factor and marginal fuel use.

Table 8-1: Primary activity data for the fuel consumption of road transport.

Type op truck	Classification	Total weight (kg)	Load capacity (tonnes)	Fuel consumption - fully loaded (l/km)	Fuel consumption - empty (l/km)
Atego 818	small truck	7,490	1.79	0.22	0.17
Unknown	small truck	7,100	4.4	0.13	0.10
Atego 1218 autom,	medium truck	11,990	4.99	0.21	0.16
Atego 1218 autom,	medium truck	11,990	4.99	0.21	0.16
Eurocargo 120E18	medium truck	12,000	4.89	0.26	0.19
Eurocargo 120E18	medium truck	12,000	4.89	0.27	0.20
Eurocargo 120E21	medium truck	12,000	4.39	0.27	0.20
Eurocargo 120E21	medium truck	12,000	4.39	0.25	0.19
LF 55,180	medium truck	15,000	4.49	0.26	0.20
LF 55,180	medium truck	15,000	4.49	0.27	0.21
Unknown	medium truck	14,500	9.6	0.24	0.13
Atego trailer 1828	medium truck	18,600	15	0.31	0.24
Unknown	large truck	36,400	25	0.38	0.30
Unknown	large truck	24,000	14	0.35	0.28
Unknown	large truck	40,000	26	0.35	0.25
Unknown	large truck	60,000	40	0.49	0.31

Table 8-2: Categorized primary activity data for vans, small trucks and large trucks.

		Truck <10t (LC 3 tonnes)	Truck 10-20t (LC 6.2 tonnes)	Large truck >20t (LC 24 tonnes)
Fuel use when fully loaded per km	l/km	0.18	0.26	0.39
Fuel use when empty per km	l/km	0.13	0.19	0.28

The emissions due to the combustion of fuels and wear, and tear of roads, and equipment of road transport are based on the reports from (Klein et al., 2012a) of www.emisieregistratie.nl, which are based on the methodology by (Klein et al., 2012b). The emissions have been monitored in the Netherlands and they are assumed to be applicable for all locations.

Three types of roads are defined: urban area, country roads and highways. In 2010 trucks spent 17.5% of their distance in urban areas, 22.1% of their distance on country roads and 60.4% on highways. These percentages were used for the calculation of emissions when emissions were given per type of road.

Five types of emissions standards are defined: EURO1, EURO2, EURO3, EURO4 and EURO5. These emissions standards correspond with the European emission standards and define the acceptable limits for exhaust emissions of new vehicles sold in EU member states. The emission standards were defined in a series of European Union directives staging the progressive introduction of increasingly stringent standards. Currently, emissions of nitrogen oxides (NO_x), carbon monoxide (CO) and particulate matter (PM) are regulated for most vehicle types. The emissions decrease from EURO1 to EURO5.

The naming of the processes is built up of several types of information. First of all, it is a 'Transport, truck,' process. The load capacity is given in tonnes (t), and the emission standard is also given (EURO1-EURO5). The load factor, which is the percentage of the load capacity, which is being occupied, is given in % (%LF). Finally, there are two options related to the return trip. A vehicle can make a complete empty return trip, indicated by 'empty return'. This means that the emissions include a return trip of the same distance but instead of the load factor, which was applied to the first trip, the load factor for the return trip is 0%. In many cases there is no information in the return trip. The vehicle can drive a couple of kilometers to another location to pick up a new load or may have to drive a long distance before loading a new load. Usually the vehicle will not directly be reloaded on the site of the first destination. As a 'default' the assumption has been made that an added 20% of the emissions of the first trip are dedicated to the return trip. Indirectly the assumption is made that a certain amount of the trip to the next location is dedicated to the first trip.

8.2.2 Water

8.2.2.1 Barge

The fuel consumption of barge ships is based on a publication of CE Delft (den Boer et al., 2008). There are barge ships which transport bulk (5 types) and barge ships which transport containers (4 types). The types of ships differ in the load capacity and in the fuel consumption (Table 8-3).

Table 8-3: Fuel consumption of 5 types of bulk barges and 4 types of container barges. Based on (den Boer et al., 2008).

		Load capacity (tonnes)	Difference energy use per load % (MJ/km)	Energy use at 0% load (MJ/km)	Energy use at 66% load (MJ/km)
Bulk	Spits	350	0.88	54.92	113
	Kempenaar	550	0.96	114.64	178
	Rhine Herne canal ship	1,350	2.3	260.2	412
	Koppelverband	5,500	3.6	418.4	656
	Four barges convoy set	12,000	4.5	673	970
Container	Neo Kemp	320	1	83	149
	Rhine Herne canal ship	960	2.3	211.2	363
	Rhine container ship	2,000	3.8	319.2	570
	JOWI class container ship	4,700	7.4	551.6	1.040

Most barges run on diesel, and thus the fuel type of barges is set on diesel. The naming of the processes is built up of a couple of types of information. First of all, it is a 'Transport' process. Secondly it is either a 'bulk' barge ship or a 'container' barge ship. The load capacity is given in tonnes (t), and the load factor is given in % (%LF). As in the case of the trucks on the road, there are two options related to the return trip. A barge ship can make a completely empty return trip, indicated by ‘empty return’, in which emissions include a return trip of the same distance of the first trip but with a load factor of 0%. In many cases there is no information in the return trip. The barge ship can travel several kilometers to another location to pick up a new load or might have to travel a long distance before loading a new load. The barge ship might not directly be reloaded on the site of the first destination. As a ‘default’ the assumption has been made that and added 20% of the emissions of the first trip are dedicated to the return trip. Indirectly the assumption is made that a certain amount of the trip to the next location is dedicated to the first trip.

8.2.2.2 Sea ship

The fuel consumption of the sea ships is based on the model of Hellinga (Hellinga, 2002), and it depends on the load capacity of the ship, the load factor and the distance. The fuel type is heavy fuel oil. Load capacity is defined in DWT, which stands for 'dead weight tonnage'. It is the sum of the weights of cargo, fuel, fresh water, ballast water, provisions, passengers, and crew, and It measures the weight a ship is carrying or can safely carry.

The model distinguishes four different phases of a trip: a maneuvering phase, a slow cruise phase, a cruising phase and a hoteling phase. The cruising phase is the longest phase of a trip, and before that the ship goes through a maneuvering phase and slow cruise phase. After the cruising phase (before the ship can unload) the ship goes again through a slow cruise and a maneuvering phase. Once in the port the ship has a hoteling phase in which it consumes fuel, but it does not travel any distance. The cruising distance depends on the distance of the trip. The slow cruise distance is assumed to be 20 km (1hour) and the maneuvering distance is assumed to be 4 km (1.1 hour). The hoteling phase is assumed to be 48 hours.

The model calculates the maximum engine capacity based on the DWT. The amount of engine stress and the duration determine the fuel consumption during a phase. The engine stress is set at 80% for the cruise phase, 40% for the slow cruise phase and 20% for the maneuvering phase, but it is also related to the load factor of the ship. When the ship is not fully loaded the engine stress decreases depending on the actual weight and the maximum weight.

Besides the main engines, the sea ship also has auxiliary engines which are operational independently of the traveling speed. These engines power the facilities on the ship. During the cruising and the slow cruising phases, the auxiliary engines power 750 kW; in the maneuvering and the hoteling phases, they power 1250 kW.

The steps which the model uses to calculate the fuel consumption are displayed below (Hellinga, 2002):

<u>Step 1</u>: Calculate maximum engine power (P_{max})

$$P_{max}\text{ (kW)} = (6{,}726 + 0.0985 * DWT) * 0.7457$$

<u>Step 2</u>: Calculate empty weight (LDT)

LDT (tonnes) = 2431+0,109*DWT

<u>Step 3</u>: Calculate the maximum ballast weight (BWT)

BWT (tonnes) = IF (DWT < 50,853 ; 0.5314*DWT ; 13,626+0.26345*DWT)

Step 4: Calculate the cruising time

Cruising time (hr) = (distance – slow cruising distance – maneuvering distance) / (14*1.852)

Step 5: Calculate the load

Load (tonnes) = DWT * load factor

Step 6: Calculate the total weight of the ship

Total weight (tonnes)= TW = LDT + IF (load < BWT * 50%/100% ; BWT * 50%/100% ; load)

Step 7: Calculate the maximum total weight of the ship

Maximum weight (tonnes) = DWT + LDT

Step 8: Calculate the actual engine power used per phase

Engine power cruise (kW) = P = $K * TW^{\frac{2}{3}} * V_{cr}^3$

Engine power slow cruise (kW) = $K * TW^{\frac{2}{3}} * V_{scr}^3$

Engine power maneuvering (kW) = $K * TW^{\frac{2}{3}} * V_{man}^3$

Where K is a ship specific constant defined by K=$\frac{0.8 * P_{max}}{(TW_{max})^{\frac{2}{3}} * V_{def}^3}$; where V_{def} is the default cruising speed.

Step 9: Calculate the fuel consumption per phase

Fuel consumption (GJ) per phase i =

$$\left(\frac{14{,}12\left(\frac{P_i}{P_{max}}\right) + 205.717}{1000} * P_i + \frac{14.12 + 205.717}{1000} * P_{aux}\right) * cruising\ time_i * \frac{41}{1{,}000}$$

Step 10: Calculate the total fuel consumption by adding the fuel consumption of the cruise, the slow cruise, the maneuvering and the hoteling.

Step 11: Calculate the fuel consumption per tkm

Fuel consumption (MJ/tkm) = $\frac{total\ fuel\ consumption * 1{,}000}{distance * DWT * load\ factor}$

Because the trip distance has a large impact on the fuel consumption and the processes that are based on tkm, the trip distances have been categorized by: ‘short’, ‘middle’ and ‘long’. The short distance can be used for trips shorter than 5,000 km, and its fuel consumption has been calculated using a distance of 2,500 km. The middle distance can be used for trips which are 5,000 – 10,000 km and the fuel consumption has been calculated using a distance of 8,700 km. The long distance can be used for trips longer than 10,000 km, and the fuel consumption based on a distance trip of 20,500 km. The fuel type for sea ships is heavy fuel oil. The fraction of fuel used for cruising, slow cruising, maneuvering, and hoteling is displayed in Table 8-4. (Klein et al., 2012a).

Table 8-4: Fraction of fuel used for traveling phases for short, middle and long distances for sea ships.

Distance	Hoteling (%)	Slow cruise and maneuvering (%)	Cruise (%)
Short	12	34	53
Middle	9	25	66
Long	6	17	77

The naming of the processes is built up of several types of information. First, it is a 'Transport' process, and secondly it is sea ship. The load capacity is given in tonnes (DWT), and the load factor, which is the percentage of the load capacity that is being occupied, is given in % (%LF). The trip length can be selected among 'short', 'middle' or 'long'. Finally, there are two options related to the return trip. A sea ship can make a complete empty return trip, indicated by 'empty return'. This means that the emissions include a return trip of the same distance of the first trip but with a load factor set to 0%. In many cases there is no information in the return trip. The sea ship may not be directly reloaded on the site of the first destination, and it may travel few kilometers or long distances to pick up a new load. As a 'default', the assumption has been made that an added 20% of the emissions of the first trip are dedicated to the first trip. Indirectly the assumption is made that a certain amount of the trip to the next location is dedicated to the first trip.

8.2.3 Rail

The fuel consumption of freight trains is based on a publication of CE Delft (den Boer et al., 2011). There are some trains that run on diesel and others on electricity. Freight trains can transport bulk products as well as containers. The type of terrain also affects the fuel consumption. CE Delft differentiates three types of terrain: flat, hilly and mountainous, and fuel consumption increases as the terrain gets more hilly or mountainous.

Two general assumptions have been made:

- A freight train equals 33 wagons (NW)
- A freight container train never makes a full empty return

The specific energy consumption is calculated based on the gross weight (GWT) of the train. The GWT includes the wagons as well as the freight, but not the locomotive. GWT is calculated as follows:

- GWT for bulk trains (tonnes), loaded = NW × (LF × LCW) + NW × WW
- GWT for bulk trains (tonnes), unloaded = NW × WW
- GWT for container trains (tonnes), loaded = NW × TCW × UC × (CL*LF) + NW × WW

Where the abbreviations are explained as follows:

- NW: Number of wagons
- LF: Load factor
- LCW: Load capacity wagon

- WW: Weight of wagon
- TCW: TEU capacity per wagon
- UC: Utilization TEU capacity
- CL: Maximum load per TEU

Table 8-5 displays the values of the wagon specifications which have been used to calculate the fuel consumption of freight trains transporting bulk or containers.

Table 8-5 Wagon specifications required to calculate the gross weight of freight trains.

Characteristics of a wagon	Unit	Wagon specification for bulk	Wagon specification for containers
LCW	tonnes	42.5	-
WW	tonnes	17.25	16.3
TCW	TEU per wagon	-	2.5
UC	%	-	85
CL	tonnes per TEU	-	10.5

The emissions due to the combustion of fuels of rail transport are based on the reports (Klein et al., 2012a) of www.emisieregistratie.nl,which have been calculated based on the methodology by (Klein et al., 2012b).

The processes are named based on several types of information. First of all, it is a 'Transport' process. Secondly it is a freight train. The freight train either runs on diesel or on electricity, and it either carries bulk or containers. The load factor (the load capacity which is being occupied) is given in % (%LF). Three types of terrain can be selected: 'flat', 'hilly' or 'mountainous'. As explained for the other type of transports, there are two options related to the return trip: (1) a complete empty return trip, indicated by 'empty return', or (2) loaded. In the first case, the load factor for the return trip is set to 0%. In the second case, the train might not directly be reloaded on the site of the first destination, and it may travel short or long distances for new loads. As a 'default' the assumption has been made that and added 20% of the emissions of the first trip are dedicated to the first trip. Indirectly the assumption is made that a certain amount of the trip to the next location is dedicated to the first trip.

8.2.4 Air

The fuel consumption of airplanes is based on the a publication of the European Environment Agency (European Environment Agency, 2006). Three types of airplanes have been selected: Boeing 747-200F, Boeing 747-400F and Fokker 100. The specifications of these airplanes are given in Table 8-6.

Table 8-6: Specification of the airplanes Boeing 747-200F, Boeing 747-400F and Fokker 100.

Type of airplanes	Weight		Max fuel weight (kg)	Max payload weight (kg)	Max trip length when full (km)	Loading capacity (tonnes)
	When empty (kg)	**Max at starting (kg)**				
Boeing 747-200F	174,000	377,840	167,500	36,340	12,700	36.34
Boeing 747-400F	178,750	396,890	182,150	35,990	13,450	35.99

Fokker 100	24,500	44,000	11,500	2,800	11.5

Two assumptions have been made:

1. The airplane is always loaded to the maximum loading capacity.
2. The fuel consumption is not dependent on the weight of the load. The airplane itself and the fuel is much heavier and therefore a higher impact on fuel consumption.

The fuel consumption of the airplanes is shown in Table 8-7, Table 8-8 and Table 8-9. The data are used from the European Environment Agency (European Environment Agency, 2006), using the *simple methodology* described by them. The fuel consumption for Landing/Take-off (LTO) cycles does not depend on the distance for this methodology. An LTO cycle consists of taxi-out, take-off, climb-out, approach landing and taxi-in. The climb, cruise and descent depend on the distance of the flight.

The emissions due to the combustion of fuels of air transport are based on the reports (Klein et al., 2012a) from www.emisieregistratie.nl, which have been calculated based on the methodology by (Klein et al., 2012b).

Due to the large impact of trip distance on the fuel consumption and those processes based on tkm, trip distances have been categorized by ‘short’, ‘middle’ and ‘long’, to limit the number of process variants in the database to a practical quantity. The short distance can be used for trips shorter than 5,000 km, and the fuel consumption has been calculated using a distance of 2,700 km. The middle distance can be used for trips which are 5,000 – 10,000 km and the fuel consumption has been calculated using a distance of 8,300 km. The long distance can be used for trips longer than 10,000 km, and the fuel consumption has been calculated using a distance of 15,000 km. The fuel which is used for airplanes is kerosene.

For Boeing airplanes, the maximum payload depends on the maximum starting weight, which is dependent on the highest fuel weight. The amount of fuel that is taken aboard is determined by the trip distance. For the middle distance the loading capacity/ payloads for the Boeing 747-200F and Boeing 747-400F are respectively 69.84 tonnes and 72.42 tonnes; for the short distance, they are respectively 120.09 and 127.07 tonnes.

Table 8-6 shoes the payload for the long distance. Processes are named based on a couple of types of information. First of all, it is a ‘Transport’ process, and secondly it is an airplane. Three types of airplanes can be selected: Boeing 747-200F, Boeing 747-400F and Fokker 100. Finally, the trip length can be selected: ‘short’, ‘middle’ or ‘long’.

Table 8-7: Fuel consumption of a Boeing 747-200F

Distance (km)	232	463	926	1389	1852	2778	3704	4630	5556	6482	7408	8334	9260	10168
Flight total fuel (kg)	6,565	9,420	14,308	19,196	24,084	34,170	44,419	55,255	66,562	77,909	90,362	103,265	116,703	130,411
LTO	3,414	3,414	3,414	3,414	3,414	3,414	3,414	3,414	3,414	3,414	3,414	3,414	3,414	3,414
Taxi-out	702	702	702	702	702	702	702	702	702	702	702	702	702	702
Take-off	387	387	387	387	387	387	387	387	387	387	387	387	387	387
Climb-out	996	996	996	996	996	996	996	996	996	996	996	996	996	996
Climb/cruise/descent	3,151	6,006	10,894	15,782	20,671	30,757	41,005	51,841	63,148	74,495	86,948	99,852	113,289	126,997
Approach landing	626	626	626	626	626	626	626	626	626	626	626	626	626	626
Taxi-in	702	702	702	702	702	702	702	702	702	702	702	702	702	702

Table 8-8: Fuel consumption of a Boeing 747-400F

Distance (km)	232	463	926	1389	1852	2778	3704	4630	5556	6482	7408	8334	9260	10168	11112	12038
Flight total fuel (kg)	6,331	9,058	13,404	17,750	22,097	30,921	40,266	49,480	59,577	69,888	80,789	91,986	103,611	115,553	128,170	141,254
LTO	3,403	3,403	3,403	3,403	3,403	3,403	3,403	3,403	3,403	3,403	3,403	3,403	3,403	3,403	3,403	3,403
Taxi-out	661	661	661	661	661	661	661	661	661	661	661	661	661	661	661	661
Take-off	412	412	412	412	412	412	412	412	412	412	412	412	412	412	412	412
Climb-out	1,043	1,043	1,043	1,043	1,043	1,043	1,043	1,043	1,043	1,043	1,043	1,043	1,043	1,043	1,043	1,043
Climb/cruise/descent	2,929	5,656	10,002	14,349	18,695	27,519	36,865	46,078	56,165	66,486	77,387	88,584	100,209	112,151	124,769	137,852
Approach landing	624	624	624	624	624	624	624	624	624	624	624	624	624	624	624	624
Taxi-in	661	661	661	661	661	661	661	661	661	661	661	661	661	661	661	661

Table 8-9: Fuel consumption of a Fokker 100

Distance (km)	232	463	926	1389	1852	2778
Flight total fuel (kg)	1,468	2,079	3,212	4,285	5,480	7,796
LTO	744	744	744	744	744	744
Taxi-out	184	184	184	184	184	184
Take-off	72	72	72	72	72	72
Climb-out	185	185	185	185	185	185
Climb/cruise/descent	723	1,334	2,468	3,541	4,735	7,052
Approach landing	120	120	120	120	120	120
Taxi-in	184	184	184	184	184	184

8.3 Fertilizers production

The update regards the implementation of regionalized energy input/production for Ammonia and N_2O emissions for nitric acid. All the other fertilizers production was modelled based on (Kongshaug, 1998) and (Davis and Haglund, 1999). The energy use and block approach have been taken from Kongshaug, while additional data on emissions were sourced from Davis and Haglund. Background processed (such as steam and electricity) currently implemented in Agri Footprint are copied from Ecoinvent v3.10 database. Figure 17 shows the product flow diagram for fertilizer production. As can be seen in the figure, some fertilizers are produced using a combination of intermediate products and/or other fertilizer products. The updated inventories for fertilizer production are listed in Table 8-10 to Table 8-24. We show here only the inventories for European fertilizer products. Important intermediate product phosphoric acid is described in Table 8-10.

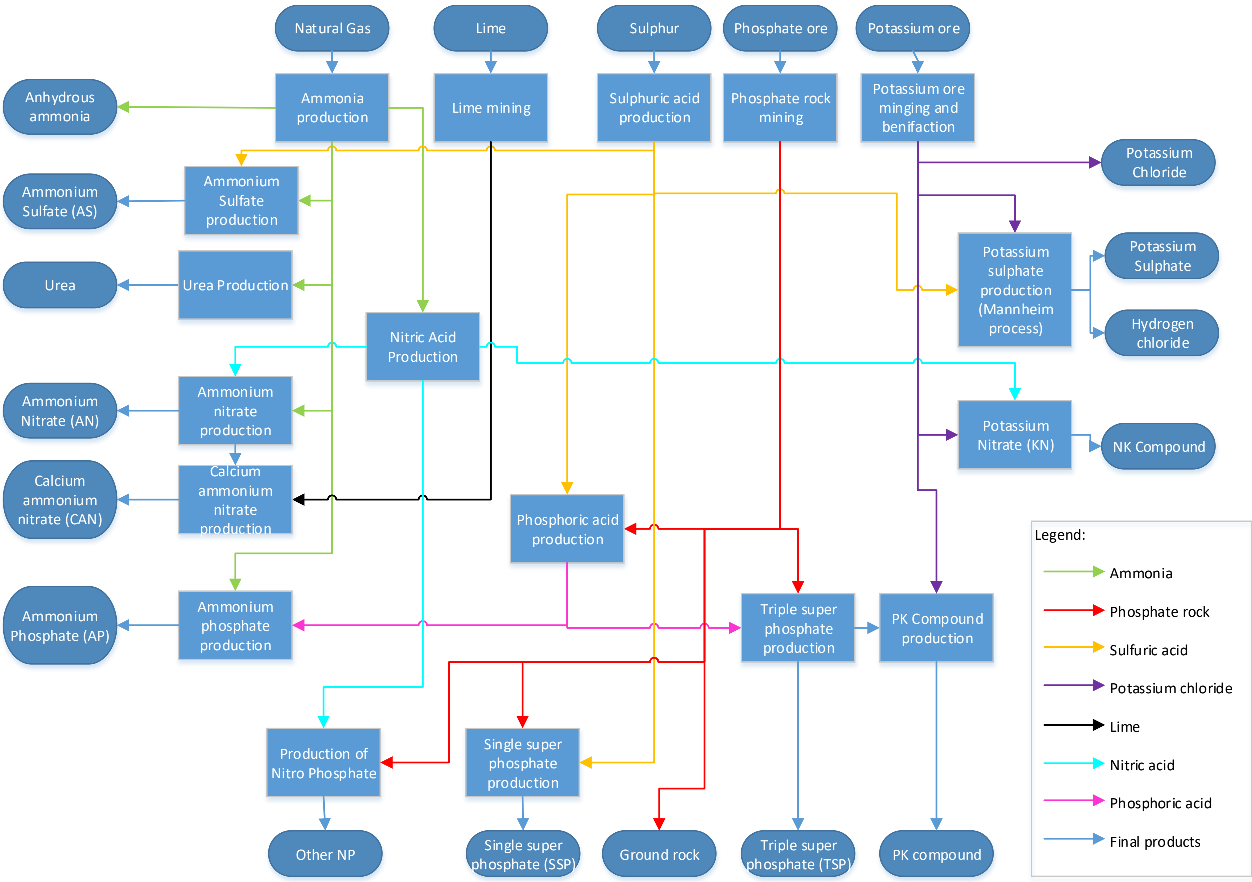


Figure 17: Product flow diagram for fertilizer production. The colored lines indicate specific intermediate flows (see legend). Raw materials are listed on the top of the figure, N fertilizers are listed on the left, P fertilizers on the bottom, K fertilizers on the right. Figure based on description in Kongshaug (Kongshaug, 1998)

Table 8-10 Inventory for phosphoric acid

	Unit	Quantity	Comment
Products			
Phosphoric acid, merchant grade (75% H_3PO_4) (NPK 0-54-0), at plant /RER	kg	1,000	
Materials/fuels			
Phosphate rock (32% P_2O_5, 50% CaO) (NPK 0-32-0) /RER	kg	1,687	based on P balance
Sulfuric acid (98% H_2SO_4), at plant /RER	kg	1,490	
De-ionised water	kg	420	
Process steam from natural gas	GJ	1.89	
Emission to air			
Water	kg	170	
Waste to treatment			
Inert waste	kg	3,865	landfill of gypsum data from Davis and Haglund

Table 8-11 Production of ammonia

	Unit	Quantity	Comment
Product			
Ammonia, as 100% NH_3 (NPK 82-0-0), at plant /RER	kg	1,000	-
Avoided products			
Process steam from natural gas	GJ	1.49	-
Inputs			
Process steam from natural gas	GJ	13.3	-
Natural gas	M^3	591	-
Electricity	MJ	840	-
Emissions to air			
Carbon dioxide, fossil	kg	1,138	CO_2 emissions from fuel incineration are included in the process 'Process steam from natural gas'. All CO_2 from feedstock is captured in absorbers and used in Urea making (if applicable). However, ammonia could be also used in other processes where CO_2 cannot be used (in the case it can be vented). Therefore, an input of CO_2 from nature is included in Urea making, to mass balance the CO_2 (no net emissions) and ensure that CO_2 emission is accounted for all other cases.

Table 8-12 Production of calcium ammonium nitrate (CAN)

	Unit	Quantity	Comment
Product			
Calcium ammonium nitrate (CAN), (NPK 26.5-0-0), at plant /RER	kg	1,000	-
Inputs			
Ammonium nitrate, as 100% $(NH_4)(NO_3)$ (NPK 35-0-0), at plant /RER	kg	756	-
Limestone	kg	244	-
Transport, freight train, electricity, bulk, 100%LF, flat terrain, empty return/GLO	tkm	0.732	transport of limestone to plant

Table 8-13: Production of nitric acid

	Unit	Quantity	Comment
Product			
Nitric acid, in water, as 60% HNO_3 (NPK 13.2-0-0), at plant /RER	kg	1,000	-
Avoided products			
Process steam from natural gas	GJ	1.05	-
Resources from nature			
Oxygen, in air	kg	626	-
Inputs			
Ammonia, as 100% NH_3 (NPK 82-0-0), at plant /RER E	kg	172	-
De-ionised water	kg	211.4	-
Electricity	MJ	18	
Emissions to air			
Dinitrogen monoxide	kg	0.42	-
Nitrogen	kg	6.6	-

Table 8-14: Production of ammonium nitrate

	Unit	Quantity	Comment
Product			
Ammonium nitrate, as 100% $(NH_4)(NO_3)$ (NPK 35-0-0), at plant /RER	kg	1,000	-
Inputs			
Ammonia, as 100% NH_3 (NPK 82-0-0), at plant /RER E	kg	219.07	-
Nitric acid, in water, as 60% HNO_3 (NPK 22-0-0), at plant /RER	kg	1,312.5	-
Process steam from natural gas	GJ	0.7	-
Emissions to air			
Ammonia	kg	6.57	losses due to conversion inefficiency
Water	kg	525	

Table 8-15: Production of di ammonium phosphate (DAP)

	Unit	Quantity	Comment
Product			
Di ammonium phosphate, as 100% $(NH_3)_2HPO_4$ (NPK 22-57-0), at plant /RER	kg	1,000	-
Inputs			
Ammonia, as 100% NH_3 (NPK 82-0-0), at plant /RER	kg	264	stoichiometric ratios
Phosphoric acid, merchant grade (75% H_3PO_4) (NPK 0-54-0), at plant /RER	kg	1,050	-
Process steam from natural gas	GJ	0.192	proxy natural gas
Process steam from natural gas	GJ	0.0525	-
Electricity	GJ	0.105	-
Transport, freight train, electricity, bulk, 100%LF, flat terrain, empty return/GLO	tkm	79.2	transport of ammonia to DAP production plant
Emissions to air			
Water	kg	314	-

Table 8-16: Production of Urea

	Unit	Quantity	Comment
Product			
Urea, as 100% $CO(NH_2)_2$ (NPK 46.6-0-0), at plant /RER	kg	1,000	-
Resources			
Carbon dioxide, in air	kg	733	From ammonia production, see note in ammonia inventory.
Inputs			
Ammonia, as 100% NH_3 (NPK 82-0-0), at plant /RER	kg	567	-
Process steam from natural gas	GJ	4.2	-
Emissions to air			
Water	kg	300	-

Table 8-17: Production of triple super phosphate

	Unit	Quantity	Comment
Product			
Triple superphosphate, as 80% $Ca(H_2PO_4)_2$ (NPK 0-48-0), at plant /RER	kg	1,000	Remainder is water
Inputs			
Phosphate rock (32% P_2O_5, 50%CaO) (NPK 0-32-0)	kg	450	30% P_2O_5 from rock
Phosphoric acid, merchant grade (75% H_3PO_4) (NPK 0-54-0), at plant /RER	Kg	622	70% from acid
Process steam from natural gas	GJ	2	energy used in drying, powder production and granulation
Process water	kg	110	dilution of acid
Transport, sea ship, 60000 DWT, 100% F, short, default/GLO	tkm	1,665	transport of phosphate rock from western Sahara to port in Europe
Transport, freight train, electricity, bulk, 100%LF, flat terrain, empty return/GLO	tkm	135	transport of phosphate rock from port to phosphoric acid production plant
Emissions to air			
Water	kg	182	vapor released during drying

Table 8-18: Production of single super phosphate

	Unit	Quantity	Comment
Product			
Single superphosphate, as 35% $Ca(H_2PO_4)_2$ (NPK 0-21-0), at plant /RER	kg	1,000	remainder is $CaSO_4$
Inputs			
Phosphate rock (32% P_2O_5, 50%CaO) (NPK 0-32-0)	kg	656.25	-
Sulfuric acid (98% H_2SO_4), at plant /RER	kg	367.5	-
Process steam from natural gas	GJ	1.4	-
Transport, sea ship, 60000 DWT, 100%LF, short, default/GLO	tkm	2,428.12	Transport of phosphate rock from western Sahara to port in Europe
Transport, freight train, electricity, bulk, 100%LF, flat terrain, empty return/GLO	tkm	196.88	

Table 8-19: Production of potassium chloride

	Unit	Quantity	Comment
Product			
Potassium chloride (NPK 0-0-60), at mine /RER	kg	1,000	-
Inputs			
Potassium chloride	kg	1,000	-
Energy, from diesel burned in machinery /RER	GJ	3	-

Table 8-20: Production of potassium sulfate

	Unit	Quantity	Comment
Product			
Potassium sulfate (NPK 0-0-50), Mannheim process, at plant/RER	kg	1,000	92% SOP assume 420 E/t
Hydrochloric acid, 30% HCl, Mannheim process, at plant/RER	kg	1,266.667	assume 140 E/t
Inputs			
Potassium chloride (NPK 0-0-60), at mine /RER	kg	833	-
Sulfuric acid (98% H_2SO_4), at plant /RER	kg	570	-
Process steam from natural gas	GJ	2.883	-
Electricity mix	GJ	0.217	-
Process water	kg	887	used for HCl solution
Transport, freight train, diesel, bulk, 100%LF, flat terrain, default/GLO	tkm	1,666	Assumption: all potash is imported from Russia, via rail. 50% electric and 50% diesel
Transport, freight train, electricity, bulk, 100%LF, flat terrain, empty return/GLO	tkm	1,666	

Table 8-21: Production of NPK compound

	Unit	Quantity	Comment
Product			
NPK compound (NPK 15-15-15), at plant /RER	kg	1,000	-
Inputs			
Potassium chloride (NPK 0-0-60), at mine /RER	kg	250	-
Ammonium Nitrate, as 100% $(NH_4)(NO_3)$ (NPK 35-0-0), at plant /RER	kg	263	-
Di ammonium phosphate, as 100% $(NH_3)_2HPO_4$ (NPK 22-57-0), at plant /RER	kg	263	-
Limestone	kg	224	-

Table 8-22: Production of liquid Urea-ammonium nitrate solution

	Unit	Quantity	Comment
Product			
Liquid Urea-ammonium nitrate solution (NPK 30-0-0), at plant/RER	kg	1,000	Solution of Urea and ammonium nitrate in water assume equal ratios by mass
Inputs			
Urea, as 100% $CO(NH_2)_2$ (NPK 46.6-0-0), at plant /RER	kg	366	-
Ammonium Nitrate, as 100% $(NH_4)(NO_3)$ (NPK 35-0-0), at plant /RER	kg	366	-
Process water	kg	268	-

Table 8-23: Production of PK compound

	Unit	Quantity	Comment
Product			
PK compound (NPK 0-22-22), at plant /RER	kg	1,000	-
Inputs			
Triple superphosphate, as 80% $Ca(H_2PO_4)_2$ (NPK 0-48-0), at plant /RER	kg	458	-
Potassium chloride (NPK 0-0-60), at mine /RER	kg	366.7	-
Limestone	kg	175.3	Inert

Table 8-24: Production of ammonium sulfate

	Unit	Quantity	Comment
Product			
Ammonium sulfate, as 100% $(NH_4)_2SO_4$ (NPK 21-0-0), at plant /RER	kg	1,000	-
Inputs			
Ammonia, as 100% NH_3 (NPK 82-0-0), at plant /RER	kg	257.5	-
Sulfuric acid (98% H_2SO_4), at plant /RER	kg	742.5	-
Process steam from natural gas	GJ	0.8	-

8.4 Fertilizers market mix

Regionalization of the impact requires the modelling of trade statistic in order to derive the utilization mix in a certain region. We derived the consumption mix based on trades and production statistics from IFAstat, EUROstat and COMtrade.

Table 8-25 Fertilizers products import by different regions.

		Partner								
Product	**Importer**	**EU**	**CIS**	**Latin America**	**Africa**	**Oceania**	**Middle East**	**East Asia**	**North America**	**South Asia**
Urea (NPK 46.6-0-0)	Europe	75%	11%	1%	8%	0%	3%	1%	1%	0%
	CIS	2%	92%	2%	1%	0%	2%	1%	0%	0%
	Latin America	5%	13%	51%	4%	1%	12%	10%	2%	2%
	Africa	10%	7%	3%	63%	0%	8%	4%	2%	2%
	Oceania	1%	1%	3%	3%	29%	35%	18%	4%	6%
	Middle East	2%	3%	3%	4%	1%	67%	7%	5%	8%
	East Asia	0%	0%	0%	0%	0%	1%	97%	0%	1%
	North America	2%	3%	3%	3%	1%	12%	4%	71%	2%
	South Asia	0%	1%	1%	1%	0%	8%	10%	1%	78%
Ammonium sulfate (NPK 21-0-0)	Europe	91%	5%	0%	1%	0%	0%	2%	0%	0%
	CIS	4%	89%	2%	1%	0%	1%	3%	1%	0%
	Latin America	24%	4%	36%	0%	1%	0%	24%	11%	0%
	Africa	17%	6%	0%	60%	0%	1%	13%	2%	0%
	Oceania	1%	0%	2%	0%	66%	0%	27%	3%	0%
	Middle East	16%	27%	1%	1%	0%	21%	30%	0%	1%

	East Asia	0%	0%	0%	0%	0%	0%	100%	0%	0%
	North America	3%	1%	2%	0%	0%	0%	2%	92%	0%
	South Asia	0%	0%	0%	0%	0%	0%	25%	0%	74%
Ammonium nitrate (NPK 35-0-0)	Europe	97%	3%	0%	0%	0%	0%	0%	0%	0%
	CIS	1%	96%	2%	1%	0%	0%	0%	0%	0%
	Latin America	6%	38%	52%	1%	0%	0%	1%	2%	0%
	Africa	3%	5%	0%	90%	0%	2%	0%	0%	0%
	Oceania	1%	2%	0%	0%	93%	0%	4%	0%	0%
	Middle East	8%	15%	0%	8%	0%	65%	2%	0%	2%
	East Asia	0%	0%	0%	0%	0%	0%	99%	0%	0%
	North America	0%	1%	0%	0%	0%	0%	0%	99%	0%
	South Asia	2%	15%	0%	1%	0%	2%	2%	0%	79%
Calcium ammonium nitrate (NPK 26.5-0-0)	Europe	96%	3%	0%	0%	0%	0%	0%	0%	0%
	CIS	9%	90%	0%	1%	0%	0%	0%	0%	0%
	Latin America	87%	10%	2%	0%	0%	0%	0%	0%	0%
	Africa	20%	5%	0%	65%	0%	7%	2%	0%	0%
	Oceania	78%	3%	0%	0%	3%	1%	15%	0%	0%
	Middle East	8%	2%	0%	4%	0%	86%	0%	0%	0%
	East Asia	0%	0%	0%	0%	0%	0%	100%	0%	0%
	North America	82%	6%	0%	0%	0%	1%	1%	10%	0%
	South Asia	0%	0%	0%	0%	0%	0%	0%	0%	100%
Liquid urea-ammonium nitrate solution	Europe	81%	8%	2%	2%	0%	0%	0%	6%	0%
	CIS	2%	94%	1%	0%	0%	0%	0%	3%	0%

(NPK 30-0-0)	Latin America	23%	12%	38%	1%	0%	0%	2%	25%	0%
	Africa	6%	1%	1%	83%	0%	8%	1%	1%	1%
	Oceania	3%	38%	1%	13%	20%	2%	18%	6%	0%
	Middle East	3%	3%	2%	1%	0%	77%	5%	5%	4%
	East Asia	1%	2%	1%	0%	1%	0%	92%	4%	0%
	North America	10%	13%	4%	1%	0%	0%	1%	71%	0%
	South Asia	0%	0%	0%	0%	1%	0%	22%	1%	76%
NPK compound (NPK 15-15-15)	Europe	65%	29%	1%	2%	0%	1%	2%	0%	0%
	CIS	7%	82%	2%	2%	0%	1%	4%	0%	0%
	Latin America	9%	11%	77%	1%	0%	1%	1%	0%	0%
	Africa	0%	0%	0%	100%	0%	0%	0%	0%	0%
	Oceania	24%	15%	0%	6%	40%	2%	13%	1%	0%
	Middle East	13%	12%	2%	12%	0%	55%	3%	1%	0%
	East Asia	3%	4%	0%	1%	0%	0%	91%	0%	0%
	North America	4%	3%	2%	1%	0%	1%	1%	88%	0%
	South Asia	14%	23%	1%	8%	0%	2%	11%	0%	43%
Di ammonium phosphate (NPK 22-57-0)	Europe	51%	9%	2%	25%	0%	7%	2%	2%	2%
	CIS	7%	63%	2%	8%	1%	3%	7%	5%	4%
	Latin America	4%	5%	31%	9%	1%	4%	12%	30%	3%
	Africa	5%	3%	1%	73%	1%	7%	4%	4%	2%
	Oceania	1%	1%	2%	3%	45%	7%	24%	7%	10%
	Middle East	3%	2%	1%	9%	1%	81%	2%	1%	1%
	East Asia	0%	0%	0%	0%	0%	1%	95%	1%	2%

	North America	1%	2%	3%	3%	1%	1%	4%	82%	2%
	South Asia	2%	2%	1%	4%	2%	12%	28%	3%	46%

8.5 Amino acids from Evonik

Evonik is the only company in the world that produces all five essential amino acids for animal feed. A comparative life cycle analysis of the production of amino acids by Evonik Nutrition & Care GmbH, based on ISO 14040:2006 and 14044:2006, was performed and externally reviewed in 2015 (Evonik Nutrition & Care GmbH, 2015). The GaBi model, used for this study, was converted to SimaPro formatin 2019 and the LCI's of the different amino acids are included into Agri-footprint as aggregated system process. As the LCI is a result of a conversion from a GaBi model (Kupfer, 2018), no background data of Agri-footprint was used. [13]

The data set covers all relevant process steps / technologies over the supply chain of the represented cradle to gate inventory with a very good overall data quality. The inventory is mainly based on primary industry data and is completed, where necessary, by secondary data.

MetAMINO® is synthesized from petrochemical raw materials using an environmentally friendly patented proprietary process by the feed additives business of Evonik Nutrition & Care GmbH, known as the carbonate process. This proven complex, system results in a high-quality product without the formation of waste salt, while largely avoiding pollution by waste air and water. The product MetAMINO® is produced in Belgium (it is also produced in Germany, the US, and Singapore but the data is based on the Belgium plant) and contains 99% DL-Methionine (feed grade).

Biolys®, ThreAMINO®, TrypAMINO® and ValAMINO® are produced by a fermentation process. The biotechnological production of these amino acids is predominantly based on sugar either derived from dextrose or saccharose and sucrose as well as corn steep liquor as an additional source for minerals and nutrients. Major parts of the production process are patented by the feed additives business of Evonik Nutrition & Care GmbH.

The product Biolys® is produced in the US and contains 54.6% L-Lysine (feed grade) with a digestibility of 100%, ThreAMINO® is produced in Hungary and contains 98.5% L-Threonine (feed grade) with a digestibility of 100%. TrypAMINO® is produced in Slovakia and contains 98.0% L-Tryptophan (feed grade) with a digestibility of 100%. ValAMINO® is produced in Slovakia and contains 98.0% L-Valine (feed grade) with a digestibility of 100%.

Table 8-26: Naming of amino acid products in Agri-footprint.

Product	Name of process in Agri-footprint
Biolys®	Biolys®, 54.6% L-Lysine, at Evonik plant/US
MetAMINO®	MetAMINO®, 99% DL-Methionine, at Evonik plant/BE
ThreAMINO®	ThreAMINO®, 98.5% L-Threonine, at Evonik plant/HU
TrypAMINO®	TrypAMINO®, 98.0% L-Tryptophan, at Evonik plant/SK
ValAMINO®	ValAMINO®, 98.0% L-Valine, at Evonik plant/SK

Note that although the amino acids are available to in all AFP libraries, the original data is generated using economic allocation.

[13] Also please be aware that SimaPro and GaBi did not align implementation of impact assessment methods in their software. A process with same substance flows and same impact assessment method applied, could therefore result in different environmental impacts on several impact categories.

9. Data quality ratings

New data quality rating system for Agri-footprint will be implemented in the next versions, based on the new EF Data Quality Rating rules for datasets that have been developed by the JRC for Environmental Footprint compliant datasets. The rules are expected to be finalized in summer 2025.

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11. List of tables and figures

11.1 List of tables

11.2 List of figures

Appendix I NPK Model

To estimate the Nitrogen, Phosphorus and Potassium (NPK) application for specific country-crop combinations, a top-down model has been designed (Figure 18). Nitrogen application are here expressed under the form of N, phosphorus as P2O5 and potassium as K2O.

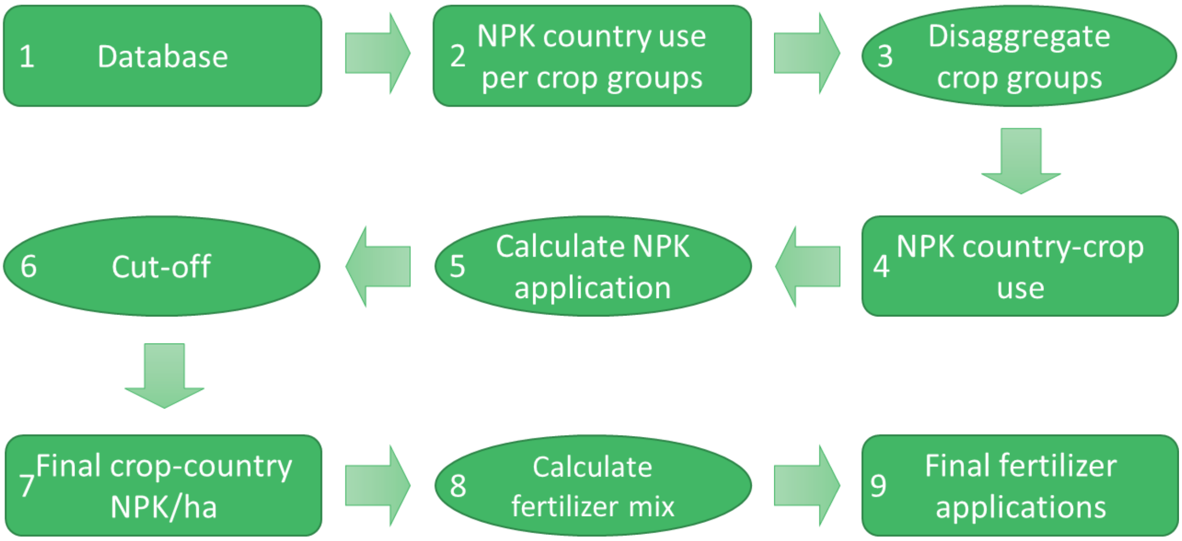

Figure 18: Top-down model conceptualization. The number indicated inside the boxes will be used throughout the text to help the reader identifying the specific step in the model.

The model database (1) is based on national statistics available on NPK land application per country (IFA, 2025), production and harvested area of country-crop combinations (FAO, 2025a) and estimates of fertilizer use by crop category per country (IFA, 2022). In particular, the last cited study allowed to derive from the overall NPK use in a specific country (IFA, 2022), average 2028-2022), how much was used for cultivation of crops (4) (wheat, rice, maize, soybean and oil palm) and crop groups (2) (other cereal, other oil seed, fibre crops, sugar crops, roots & tuber, fruits and vegetables). For the fertilizer use by crop group in a specific country a model was developed (3). For each country/crop group combination three (for N, P2O5 and K2O) parameter R (kg/kg) requirement are calculated:

$$R_{NPK} = \frac{kg_{NPK}}{\sum(kg_{prod,c} * DM_c)}$$

where kg_{NPK} is the kg of N, P_2O_5 or K_2O used for a certain country/crop group combination, $kg_{prod.c}$ is the production in kg of the specific crop c and DM_c is the dry matter content (kg/kg) of the specific crop c.

The dry matter content was retrieved from (USDA, 2019), (RIVM, 2016) and in the few cases from literature.

The parameter R represent how much NPK is required to have 1 kg of solids as output. It is then multiplied by the dry matter yield (FAOSTAT data * DM content) to calculate the NPK application per hectare (5). For the one-crop groups was possible derive the NPK application directly (5), by dividing the fertilizer use by crop in a specific country by the production area reported by FAOstat for the specific country-crop combination (average 2013-2017).

Other options were investigated, such as express the NPK use per kg as is. The chosen option avoids allocating NPK to a crop just because contain high water contents, this is relevant for oilseed (specifically coconuts and olives) and for fruit and vegetables, that show a large variability in water content. Another discarded option was calculating NPK use per kg of specific nutrient (NPK). Calculating the NPK application based on the NPK extraction from field is a common agricultural practice. The option of further considering NPK content was discarded due to the high uncertainty and variability in NPK content, even between the same crop in different countries or cultivation practices.

The source IFA provides data for specific crops and for crop groups, making the accuracy on the statistical results more complex for fruits and vegetables, due to the high variation of NPK doses between crops of the same crop-group.

Since the estimation are based on global statistics from two different source, we considered the possibility of inconsistent or unrealistic estimates. This is more relevant for low produced crops (inconsistency between IFA percentages per crop and FAO harvested areas), rare for largely produced crop. Cut off criteria (Table I-1) were therefore selected based on previous literature search performed by Blonk Consultants (6).

Example:
-Synthetic fertilizer use is: ***12.13*** *kg N, 11.26 kg P205 and* ***2.02*** *kg K2O equivalents, based on NPK model.*

-Synthetic fertilizer use is: ***270.00*** *kg N, 0.00 kg P205 and* ***160.00*** *kg K2O equivalents, based on KWIN 2015 table 6.3.7.*

Table I-1: Cut-off values for N, P2O5 and K2O applications. When an estimation resulted higher than the selected cut-off the values was considered unreliable and not used for the LCI.

Table I-1: Cut-off values for N, P2O5 and K2O applications.

Cultivation type	kg N/ha	kg P2O5/ha	kg K2O/ha
Arable/Paddy	550	500	700
Orchard/Greenhouse	750	250	1500

Other countries excluded from the scope of the model are the one included by (IFA, 2022) in Rest of the World (ROW). Pulses, tree nuts, coffee, cocoa and tea are included in the group “residual” in the cited report, together with other non-agricultural uses. It was therefore not possible to disaggregate these fertilizer uses. Even though grass is a disaggregated NPK use in the cited report, FAO surface data on how much grass surface is naturally growing, and how much is cultivated are incomplete. Pulses, tree nuts, coffee, cocoa, tea and grass are therefore out of the scope of the model. NPK application for out of scope country-crop combinations are based on literature (Pallière, 2011; Rosas, 2011).

Another limitation of the model is related to legumes. Three crops included in the vegetable crop group are indeed legumes (green peas and green beans). But since the N application is based on solids extraction from field, it does not account for the fact that nitrogen is fixated by the plants. This usually results in lower N application on field. The option of including a N fixation rate of the specific legume was investigated but discarded due to low data reliability.

To match these total N, P and K application rates (7), to specific fertilizer types (e.g. Urea, NPK compounds, super triple phosphate etc.), data on regional fertilizer consumption rates from (IFA, 2025) were used (8).

Some fertilizers supply multiple nutrient types (for example ammonium phosphate application supplies both N and P to agricultural soil). In IFA statistics (IFA, 2025), the share of ammonium phosphate is given as part of total N and also as part of total P supplied in a region. To avoid double counting, this dual function was taken into account.

Therefore, the following calculation approach was taken:

1. A fertilizer type is considered in isolation (e.g. only Potassium supplying fertilizers, or only Nitrogen). The relative shares of the specific fertilizers were calculated for a crop (e.g. if a crop A in Belgium requires 10 kg K/ha, 35% is supplied from NPK, 52% from Potassium Chloride and 11% from Potassium Sulfate). However, some fertilizers supply nutrients of different types (e.g. both N and P or N, P and K). The amounts of other nutrients supplied are subtracted from the total nutrient requirements.
2. Next, the share of the second fertilizer type is calculated, taking into account the amount of nutrient supplied by multi-nutrient fertilizers from the previous step. Again, other nutrients supplied are subtracted from the requirements for the last fertilizer type.
3. For the remaining nutrient, the single nutrient supplying fertilizers are used (as NPK and ammonium phosphate etc. are already considered during previous calculation steps).

In this approach, there are 6 different calculation routes (K then P then N, K then N then P and so forth). For most cases, these routes all yield similar answers. However, in some extreme cases (e.g. no K supplied, and high amount of N supplied), there is a risk of calculation negative application rates when the calculation starts with the nutrient with the highest quantity supplied (i.e. for most crops this would be N). For example, if an overall crop requirement is 100 kg N, 10 kg P and 0 kg K and the calculation is started with calculation the specific shares of N fertilizers first, the calculation results in a certain amount of NPK fertilizer being applied. However, as K requirement is zero, this cannot be true. However, if one starts with the smallest nutrient type being applied (in this case 0 kg K), no NPK will be applied, and the other nutrient requirements can be supplied by pure N and P or NP fertilizers.

For consistency, the approach used for Agri-footprint is therefore to determine the order of N, P and K from smallest to largest for each specific crop/country combination and use that order for the calculation (9). E.g. for a crop requiring N:60 kg, P:20 kg, K: 30 kg, the calculation starts with calculating the shares of specific fertilizers for P then K and finally N.

Appendix II Pesticide Model

Scope / limitations of the inventory

The scope / limitations of this inventory are:

- The inventory provides is on a crop-country level (e.g. soybean cultivation in Brazil).
- The focus is on pesticides use in crop cultivation so seed treatment, pesticides used for crop storage / transport and soil disinfection were not included.
- The location, technique of application and timing of application is not taken into account. These factors can be highly significant for emissions to various environmental compartments and are hence important for ecotoxicity impact scores. However, due to the complexity (and uncertainties) involved in modelling these impacts, average conditions are taken into account in standard impact assessment methods such as ReCiPe.

- Only the categories of “herbicide”, “insecticide” and “fungicides and bactericides” applications were considered. Other phytosanitary measures, as rodenticides or mineral oil applications are outside the scope of this inventory.
- Basic active ingredient mixes were defined for herbicide, insecticide and fungicide (H/I/F) respectively based on top 80% active ingredient use per H/I/F group in Netherlands, France and United States of America.
- The same active ingredient mix of each pesticide type is used for all crops and countries considering only differences for the EU region, where certain active ingredients are not allowed.

Inventory development process

Agri-footprint 7 modelling of pesticide use per crop/country (kg a.i/ ha) follows the steps described below.

Step 1: FAOstat country use data per supergroup

Herbicides, insecticides and fungicides are the three large pesticide supergroups covered in Agri-footprint 7. In section we refer generally as pesticide supergroup to these three pesticide categories.

The first step on the inventory development was to obtain country specific data for total pesticide supergroup active ingredient use per year. FAOstat compiles national statistics on total herbicide, total insecticide and total fungicide use in tonnes of active ingredient per year (FAO, 2025c). FAO pesticide use statistics were implemented considering a five-year average from 2018 to 2022.

Step 2: Pesticide application per supergroup per crop

FAO statistics do not provide details on the amount of active ingredient of each pesticide supergroup used per hectare of cultivated crop. This was defined using a two-step approach.

First, the total active ingredient used per supergroup (tonne/year) was distributed per crop based on the share of the annual harvested area of each crop to the total national harvested area. This was done using FAOstat data on ha crop/year considering a five-year average from 2018 to 2022.

This first step results on the same use of active ingredient of supergroup per hectare for all crops in a given country. This is logically not the case. Different crops have different pesticide use needs, some being high, as for example soft fruits, or others low as cereals. We had to define a way to reflect this "pesticide use intensity" for each crop, needing to include a weighing factor to the distribution of the national pesticide use among crops, considering more than the harvested area per crop.

The best way to estimate this weighing factors per crop was to look at the limited number of available national statistics on active ingredient application per crop and observe the real active ingredient annual dosage (kg a.i./ha) for different cultivation systems.

We looked at national statistics of pesticide application from France (AGRESTE, 2018), The Netherlands (CBS, 2018) and the United States (USDA-NASS, 2019a). These three countries were chosen because their data was readily available, had relatively large crop coverage and detail on specific active ingredient use per crop (at a.i. per supergroup and a.i. per active chemical substance level). Other available country statistics did not meet one or several of these criteria, so were not able to be used for our model.

For each crop, the active ingredient dosage per super group was averaged for the three countries and then used as a weight to define the pesticide use intensity of each pesticide supergroup for each crop. This was done by indexing the supergroup dosage of all crops to the crop with the highest average dosage from our three sample countries. This means that the indexed weight value of the crop with the largest a.i. per supergroup/ha would be the largest and would reduce for all other crops relative to their standing to the crop with the largest pesticide dosage.

These weights ere integrated to the harvested area to calculate the weighted share of pesticide use per super group per crop (kg a.i. supergroup/ha).

Step 3: Definition of active ingredient "cocktail" per super group.

Having defined the amount of active ingredient per super group per hectare of crop, next step was to spread the amount used per super group into specific active chemical ingredients. The number of possible chemical ingredients per pesticide supergroup is enormous, but in practice there are only a few in each supergroup which are regularly and widely used. These regularly and widely used chemical substances are the best estimate when modeling pesticide use. We decided to follow an 80/20 approach, identifying the chemical active substances covering the 80% of the substances most used per pesticide supergroup and define them as our "base cocktail".

To establish the active substance base cocktail for each super group, we turned again to France (AGRESTE, 2018), The Netherlands (CBS, 2018) and the United States (USDA-NASS, 2019b) national inventory statistics.

These countries report on the total amount of different active substances used (kg) annually for the three major pesticide super groups. Within each country, the top 80% most used active substances were chosen for each supergroup, and then the top 80% ranking substances for each country were grouped and adjusted for country size and pesticide use to obtain the top 80% most used active substances per supergroup.

Once a preliminary cocktail for each super group was defined, the active substances have to be matched with substances and characterization factors in SimaPro. For all herbicide active substances a SimaPro equivalent name with a characterization factor was found, for Fungicide active substances, only sulfur had no characterized equivalent and was taken from the final mix, for insecticides, spinosad, flonicamid, spirotetramat, sulfur, tefluthrin and chlorantraniliprole, were not fond appropriate SimaPro equivalents with a characterization factor. Small percentages of each active substance were used, so it was decided not to make any replacement or use other substances as proxies.

Once the final substances per supergroup were identified, the share of each active substance was re-calculated to 100% to define our base active chemical substance per super group.

The resulting default cocktails are shown in Table 11-1 for each pesticide supergroup.

Table 11-1 Share of active ingredients per pesticide super group [%]. I Herbicide basic cocktail, II Insecticide basic cocktail, III Fungicide basic cocktail.

Active ingredients	Share for Herbicides I
Glyphosate	43%
Metolachlor, (S)	15%
Prosulfocarb	7%
Metamitron	6%
Pendimethalin	5%
Aclonifen	4%
Diquat dibromide	3%
Atrazine	3%
Chloridazon	2%
Isoproturon	2%
Terbuthylazin	1%
Ethofumesate	1%
Metribuzin	1%
2,4-D	1%
Linuron	1%
Metazachlor	1%
Napropamide	1%
Chlorpropham	1%
2-Methyl-4-chlorophenoxyacetic acid	1%

Active ingredients	Share for Insecticides II
Chlorpyrifos	26%
Pirimicarb	14%

Ethoprop	9%
Acephate	8%
Bifenthrin	7%
Methiocarb	7%
Lambda-cyhalothrin	5%
Oxamyl	5%
Indoxacarb	3%
Cypermethrin	3%
Pyriproxyfen	2%
Methomyl	2%
Imidacloprid	2%
Propargite	2%
Carbaryl	2%

Active ingredients	Share for Fungicides III
Mancozeb	55%
Chlorothalonil	15%
Captan	9%
Propamocarb	7%
Copper, ion	5%
Tebuconazole	2%
Maneb	2%
Azoxystrobin	2%
Folpet	2%
Propiconazole	1%
Epoxiconazole	1%

For European countries, EU restrictions are considered (European Commission, 2025), and the following chemical active substances were excluded, re-adjusting the rest of the mix per supergroup to 100%.

Table 11-2 List of “Not Approved” substances in EU. Status under Status under Reg. (EC) No 1107/2009.

Region	Super group	Restricted active ingredients
EU	Fungicide	Mancozeb
EU	Fungicide	Chlorothalonil
EU	Fungicide	Maneb
EU	Fungicide	Propiconazole
EU	Fungicide	Epoxiconazole
EU	Herbicide	Metolachlor, (S)
EU	Herbicide	Diquat dibromide
EU	Herbicide	Atrazine
EU	Herbicide	Chloridazon
EU	Herbicide	Isoproturon
EU	Herbicide	Metribuzin

EU	Herbicide	Linuron
EU	Herbicide	Chlorpropham
EU	Insecticide	Chlorpyrifos
EU	Insecticide	Ethoprop
EU	Insecticide	Acephate
EU	Insecticide	Bifenthrin
EU	Insecticide	Methiocarb
EU	Insecticide	Oxamyl
EU	Insecticide	Indoxacarb
EU	Insecticide	Methomyl
EU	Insecticide	Imidacloprid
EU	Insecticide	Propargite
EU	Insecticide	Carbaryl

Emission compartments

During the Product Environmental Footprint project, a consensus was reached on an appropriate division of pesticides emissions to different compartments. The paper of (Van Zelm et al., 2014) gives a good overview of the emission routes of pesticides and how they enter the fate modelling applied in the impact assessment method. The following division of emissions was proposed in the PEF guidance document, and this is adopted also in Agri-footprint:

- 90% to agricultural top soil
- 1% to fresh water
- 9% to air

It should be realized that both the 1% to water and the 9% to air can be considered as a first default estimate but actual emissions may differ greatly per type of active ingredient, environmental conditions at application, application technology, climate conditions, (existing) drainage system, crop height, local regulations on applications to reduce emissions.

Table 11-3 Example of pesticide inventory; Soy bean cultivation in Argentina, based on Agri-footprint 7.0 pesticide modelling.

Type of pesticide	Name	Application rate (kg a.i. per ha)
Fungicide	Mancozeb	0.284
Fungicide	Chlorothalonil	0.077
Fungicide	Captan	0.046
Fungicide	Propamocarb	0.036
Fungicide	Copper, ion	0.026
Fungicide	Tebuconazole	0.010
Fungicide	Maneb	0.010
Fungicide	Azoxystrobin	0.010
Fungicide	Folpet	0.010
Fungicide	Propiconazole	0.005
Fungicide	Epoxiconazole	0.005

Insecticide	Chlorpyrifos	0.116
Insecticide	Pirimicarb	0.063
Insecticide	Ethoprop	0.040
Insecticide	Acephate	0.036
Insecticide	Bifenthrin	0.031
Insecticide	Methiocarb	0.031
Insecticide	Lambda-cyhalothrin	0.022
Insecticide	Oxamyl	0.022
Insecticide	Indoxacarb	0.013
Insecticide	Cypermethrin	0.013
Insecticide	Pyriproxyfen	0.009
Insecticide	Methomyl	0.009
Insecticide	Imidacloprid	0.009
Insecticide	Propargite	0.009
Insecticide	Carbaryl	0.009
Herbicide	Glyphosate	0.597
Herbicide	Metolachlor, (S)	0.208
Herbicide	Prosulfocarb	0.097
Herbicide	Metamitron	0.083
Herbicide	Pendimethalin	0.069
Herbicide	Aclonifen	0.056
Herbicide	Diquat dibromide	0.042
Herbicide	Atrazine	0.042
Herbicide	Chloridazon	0.028
Herbicide	Isoproturon	0.028
Herbicide	Terbuthylazin	0.014
Herbicide	Ethofumesate	0.014
Herbicide	Metribuzin	0.014
Herbicide	2,4-D	0.014
Herbicide	Linuron	0.014
Herbicide	Metazachlor	0.014
Herbicide	Napropamide	0.014
Herbicide	Chlorpropham	0.014
Herbicide	2-Methyl-4-chlorophenoxyacetic acid	0.014

Appendix III List of crop and country combinations

Table III-1:List of crops and countries combinations in Agri-footprint

Almonds, with shell	US
Barley grain	AR, AT, AU, BE, BG, BR, CA, CH, CN, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, JP, LT, LV, NL, NO, NZ, PL, PT, RO, RU, SE, SI, SK, TH, UA, US
Beans, dry	AR, CA, CN, ET, FR, GR, IE, IT, NL, PL, RO, US, ZA
Beans, green	DE, EG, ES, FR, KE, MA, NL
Broad beans	AU, DE, FR, GB, IT
Cabbages	ES, NL
Carrots and turnips	BE, NL
Cassava	BR, CR, IN, TH, VN
Cauliflowers and broccoli	ES, FR, NL
Chick peas	AR, AU, IN, RU, TR, US
Chicory roots	BE, NL
Coconuts	ID, IN, PH
Fodder beet	NL
Grass	BE, BR, DE, DK, ES, FR, GB, IE, IT, NL, NZ, PL, US
Groundnuts, with shell	AR, AU, BR, CN, EG, ID, IN, MX, SD, SN, TH, TR, UG, US, VN, ZA
Lentils	AU, CA
Linseed	AR, AT, BE, BG, BY, CA, CN, CZ, DE, DK, ES, FR, GB, HU, IN, IT, LT, LV, PL, RO, RU, SE, SK, UA, US
Lucerne	ES, IT, US
Lupins	AU, DE, ES, FR, IT, PL
Maize silage	BE, BR, DE, DK, FR, IT, NL, NZ, PL, US
Maize	AR, AT, BE, BG, BR, BY, CA, CH, CN, CZ, DE, ES, FR, GR, HU, ID, IN, IT, JP, LT, MX, NL, PH, PK, PL, PT, RO, RU, SI, SK, TH, TR, UA, US, VN, ZA
Mustard seed	CA, CZ, DE, RU, UA, US

Oat grain	AT, AU, BE, BG, BR, CA, CH, CL, CN, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, JP, LT, LV, NL, NO, PL, PT, RO, RU, SE, SI, SK, UA, US
Oil palm fruit	BR, ID, MY, TH
Onions, dry	FR
Peas, dry	AT, AU, BE, BG, BR, CA, CH, CN, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LT, LV, NL, PL, RO, RU, SE, SI, SK, UA, US
Peas, green	AT, BE, DE, EG, ES, FR, GB, MA, NL, ZA
Pigeon peas	IN
Potatoes	AT, BE, BG, CA, CH, CN, CY, CZ, DE, DK, EE, EG, ES, FI, FR, GB, GR, HU, IE, IN, IT, LT, LV, NL, NO, PL, PT, RO, RU, SE, SI, SK, TR, US
Rapeseed	AR, AT, AU, BE, BG, BR, CA, CH, CN, CZ, DE, DK, EE, ES, FI, FR, GB, HU, IE, IN, IT, JP, LT, LV, NL, NO, PL, RO, RU, SE, SI, SK, UA, US
Rice	AR, BG, BR, CN, EG, ES, FR, GR, HU, IN, IT, KH, MM, PK, PT, RO, RU, TH, TR, UA, US, UY, VN
Rye grain	AT, BE, BG, BY, CA, CH, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LT, LV, NL, NO, PL, PT, RO, RU, SE, SK, UA, US
Seed cotton	US
Sesame seed	IN, MX, PK, TR
Sorghum grain	AR, AU, BR, CN, EG, FR, IN, IT, MX, RU, UA, US, ZA
Soybeans	AR, AT, BG, BR, CA, CH, CN, CZ, DE, EG, ES, FR, GR, HU, IN, IT, JP, MX, PL, PY, RO, RU, SI, SK, TH, TR, UA, US, VN
Spinach	BE, NL
Sugar beet	AT, BE, CH, CL, CZ, DE, DK, ES, FI, FR, GB, HU, IT, LT, NL, PL, RO, RU, SE, SK, UA, US
Sugar cane	AR, AU, BR, CN, CO, EG, ID, IN, MX, PK, SD, TH, US, VE
Sunflower seed	AR, AT, AU, BG, BR, CA, CH, CL, CN, CZ, DE, EG, ES, FR, GR, HU, IN, IT, PL, RO, RU, SK, TH, TR, UA, US
Triticale grain	AT, BE, BG, CH, CZ, DE, DK, EE, ES, FR, GB, HU, LT, LV, NL, PL, PT, RO, SE, SI, SK
Wheat grain	AR, AT, AU, BE, BG, BR, CA, CH, CN, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IN, IT, JP, LT, LV, MX, NL, NO, PK, PL, PT, RO, RU, SE, SI, SK, TH, TR, UA, US

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