# Statistical data

A two-stepped approach was used to collated preprocess statistical data for Portugal due to annual heterogeneity in data available and spatial resolution. Firstly, data was collated for the agricultural census’ years – 1989, 1999 and 2009 -, at the municipality scale. This includes key statistical data such as animal population, crop areas and yields and other specific parameters useful when calculating nutrient flows in Portugal (Table XX). For the remaining years – 1987 until 2017 -, data are only available at the regional level, particularly at the agrarian region level. Moreover, because data categories and subcategories are not the same for the agricultural census years and the remaining years, a harmonization preprocess treatment was applied.

### Local data - Municipality

Data from the agricultural census years is quite more detailed than in the other years, not only in terms of spatial resolution but also due to the existence of interesting data that can be inputted to the model. Table XXX summarizes the key data collated at the municipality level, which regards livestock population, crop areas and the irrigated areas of different crops using different irrigation methods.

Table 1. Main activity data collated from the agricultural census years – 1989, 1999 and 2009.

|  |  |  |
| --- | --- | --- |
| **Years** | **Parameter** | **Description** |
| **AG\_census** | **Animal population**  (heads yr-1) | Cattle:   * Male calves (<1 yr, 1-2 yr, > 2 yr); female calves (<1 yr, 1-2 yr, > 2 yr); beef calves (young); Dairy and non dairy cows   Equides:   * Horses, Other\_equidae   Goats:   * Goats (total)   Sheep:   * Ewes (total)   Rabbits:   * Rabbits (total)   Pigs:   * Sows (total); Pigs (< 20 kg, 20 – 50 kg, > 50 kg); Other swine   Poultry:   * Laying/reproductive hens (total); Broilers; Ducks, geese and turkeys |
| **Crop areas** (ha yr-1) | Cereals:   * Oat, barley, triticale, rice, maize, wheat, rye   Pulses:   * Beans, chickpea, other dried pulses   Potato:   * Potato   Industry:   * Other industry crops, sunflower   Fresh fruits:   * Apple, pears, peach, cherry, other fresh fruits   Citrus:   * Orange, tangerine, lemon   Dried nuts:   * Almond, nuts, chestnut   Olive grove:   * Olive grove   Vineyard:   * Vineyard   Forage:   * Forage maize, annual mixtures, forage oat, forage roots, forage sorghum, other forage   Horticulture:   * Intensive, extensive   Pastures:   * Intensive (temporary), extensive (permanent |
|  | **Irrigated areas** (ha yr-1) | Data are available for crops irrigated by 7 different irrigation methods: gravity (furrow, other gravity), localized (micro-sprinkler, drip) and sprinklers (sprinkler, gun and center pivot). |
|  | **Other params** | Manure:   * Fraction of manure applied to the soils, discharge to rivers, transported to other municipalities |

### Regional data – NUTS2, Agrarian Region

Data outside of the agricultural census years was mostly collated at the agrarian region level. This applies, for instance, to livestock population, crop areas and crop yields. Data for animal products such as milk was, however, only available at the NUTS2 level for the period 2003-2017. Furthermore, the availability of data for this period sometimes was limited to specific years (e.g., 1989,1993,1995,1999,2003,2005,2007,2009,2013,2015).

Table 2. Main activity data collated for the period 1987-2017 at the agrarian region scale or NUTS2 level

|  |  |  |
| --- | --- | --- |
| **Years** | **Parameter** | **Description** |
| **Outside\_**  **AG\_census** | **Animal population**  (heads yr-1) | Cattle:   * Male calves (<1 yr, 1-2 yr, > 2 yr); female calves (<1 yr, 1-2 yr, > 2 yr); beef calves (young); Dairy and non dairy cows   Equides:   * Horses, Other\_equidae   Goats:   * Goats (total)   Sheep:   * Ewes (total)   Rabbits:   * Rabbits (total)   Pigs:   * Pregnant and non-pregnant sows; Pigs (< 20 kg, 20 – 50 kg, > 50 kg); Other swine   Poultry:   * Laying and reproductive hens (total); Broilers; Ducks, geese and turkeys |
| **Crop areas** (ha yr-1)  **Crop yields** (kg dry-matter ha-1 yr-1) | Cereals:   * Oat, barley, triticale, rice, irrigated maize, rainfed maize, wheat, rye   Pulses:   * Beans, chickpea   Potato:   * Rainfed potato, irrigated potato   Industry:   * Tomato, sunflower   Fresh fruits:   * Apple, pears, peach, cherry, plum, fig   Citrus:   * Orange, tangerine, lemon   Dried nuts:   * Almond, nuts, chestnut   Olive grove:   * Olive grove   Vineyard:   * Vineyard   Forage:   * Forage maize, annual mixtures, forage oat, forage roots, forage sorghum   Horticulture:   * Intensive, extensive   Pastures:   * Intensive (temporary), extensive (permanent |
| **Animal products** | Milk:   * Dairy cow, dairy ewes and dairy goats (tonnes milk yr-1) |

### Data harmonization at the municipality scale over time

### Irrigated/irrigable areas – data processing

From the three years where agricultural census’ took place, only the year 2009 has data available for irrigated areas per crop and different irrigation methods at the municipality scale. It was thus necessary to estimate such data for the remaining years. The approach used was based on data on irrigable areas, irrigated:irrigable mainland ratio for 1987-2017 and data from 2009 to use as baseline.

Firstly, irrigable areas were collated from Statistics Portugal at the municipality scale for 1989, 1999 and 2009 and at the agrarian region scale for 1989, 1993, 1995, 1999, 2007, 2009, 2013 and 2016. Municipality data was interpolated following the same approach used to harmonize the statistical data, while data at the agrarian region scale was linearly interpolated. Municipality data over the period 1987-2017 was adjusted according to the total sum of each agrarian region level for the same period.

The irrigated:irrigable mainland ratio (IIratio) was used to estimate the irrigated areas at the municipality level for 1987-2017 as the product of IIratio and the irrigable areas of each municipality. The total irrigated areas of 2009 were compared to the statistical data available for the same year, attaining a very strong correspondence (R2 = 0.97).



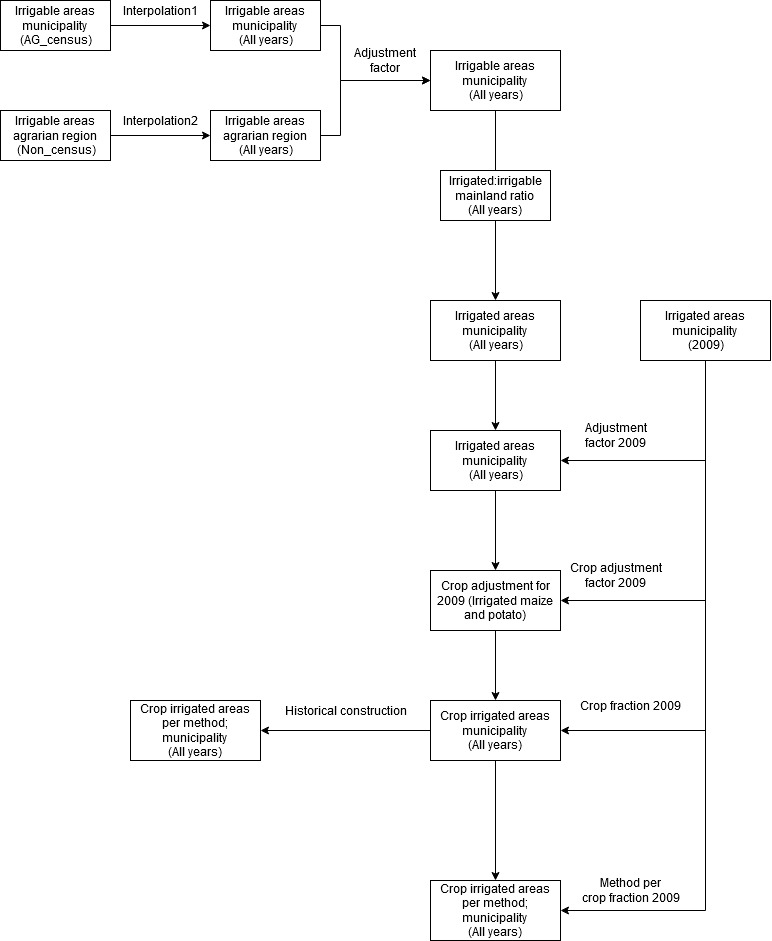
**Figure 1.** Comparison of the modelled total irrigated areas for 2009 and the statistical data for the same year (R2 = 0.97).

The total irrigated areas per crop for the *X*th year (TIAcrop, X; in ha) for the period 1987-2017 were derived according to the ratio of total irrigated areas per crop of 2009 (TIAcrop, 09; in ha) and the total sum of irrigated areas (TIA; in ha). In equation:

where TIAX is the sum of irrigated areas for the *X*th year. The irrigated areas concerning maize and potato were derived from the previous harmonization process. Furthermore, the total irrigated areas of a crop were corrected according to the total acreage of the said crop (rainfed plus irrigated). If the total irrigated area was higher than the total area of a crop, it was assumed that 100% of the crop is irrigated. For rice, all the acreage was assumed to be irrigated.

Lastly, the 2009 fraction of the different irrigation methods used for a crop were used to infer the acreage in the remaining years. For the *I*th irrigation method and for the *Y*th crop for the *X*th year, the acreage under an irrigation method (IAI, Y, X;in ha) was computed as:

where TIAY, X is the total irrigated area for the *Y*th crop in the *X*th year, TIAY, 09, I the total irrigated area for the *Y*th crop for the *I*th irrigation method in 2009 and TIAY, 09 the total irrigated area for the *Y*th crop in 2009.



**Figure 2.** General methodological approach to interpolate irrigated crop areas under different irrigation methods for the period 1987-2017 according to irrigable areas, irrigated:irrigable mainland ratios and data for 2009.

# Atmospheric deposition

Atmospheric deposition was only calculated for nitrogen, while phosphorus dust deposition was assumed negligible. Data for wet and dry deposition was collated from EMEP for the period 2000-2017. For the remaining years (i.e., 1987-1999), atmospheric N deposition was scaled according to total annual ammonia emissions and using the year 2000 as baseline. For the *i*th cell grid and respective municipality, N deposition was computed as:

Atmospheric N deposition was calculated separately for the different fertiliser allocation mechanisms implemented (i.e., with or without manure surplus and the two different approaches employed; **currently only method 1 is implemented**), as these heavily influence total ammonia emissions. See “Gaseous Emissions – Ammonia (NH3) section” for detailed explanation of the methods behind the different approaches used.

# Biological N fixation

Biological N fixation (BNF) was computed separately for forage (Intensive and Extensive\_pasture) and grain legumes (pulses) following the methodology described in (Baddeley et al., 2014). Evidently, BNF was calculated only for nitrogen. For forage legumes, BNF was calculated as:

where BNF is the N fixed by a crop (kg N yr-1) , Nretention is the N retained within the biomass of a given crop (kg N ha-1 yr-1) and N fixation coefficient a fixed parameter (Table XX).

Table 3. Parameters used to calculate the N fixed in forage legumes in Pastures

|  |  |  |  |
| --- | --- | --- | --- |
| Crop | N\_retention | N\_fixation | N\_fixed |
| Intensive\_pasture | 92 | 0.05 | 4.6 |
| Extensive\_pasture | 54 | 0.05 | 2.7 |

For grain legumes, the total N fixed by a crop was calculated by applying a crop-specific fraction of total N in crop biomass that was fixed from atmospheric N2 (Ndfa; %Nbiomass) to the total N in crop biomass. All the parameters collated from (Baddeley et al., 2014) are displayed in Table XX.

The total N in crop biomass (Nbiomass; kg N yr-1) was computed as:

Thus, the N fixed by grain legumes (BNF; kg N yr-1) could be estimated:

Table 4. Parameters used to calculate the biological N fixation of grain pulses

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Crop | DM | Grain protein content | Protein to N | Harvest index | Harvest N index | Root shoot ratio | Root N content | Rhizodeposition | Ndfa |
| % | | | | | | | | |
| Beans | 0.89 | 0.25 | 6.25 | 0.48 | 0.83 | 0.265 | 0.022 | 0.15 | 0.442 |
| faba\_bean | 0.91 | 0.29 | 6.25 | 0.49 | 0.675 | 0.23 | 0.022 | 0.185 | 0.77 |
| Chickpea | 0.91 | 0.22 | 6.25 | 0.31 | 0.805 | 0.44 | 0.014 | 0.54 | 0.5 |
| Other\_dried\_pulses | 0.91 | 0.29 | 6.25 | 0.415 | 0.65 | 0.37 | 0.014 | 0.15 | 0.7 |

The total N fixed for a given municipality (or alternatively, a cell grid) was calculated as the sum of the N fixed from grain and forage legumes. Furthermore, the total N fixed was calculated for two reference areas: cropland and grassland. For grassland, only extensive pastures were considered.

# Manure

The manure module calculates nutrient flows, from the moment nutrients are excreted until manure is applied to the soil or used elsewhere. Nutrient flows were calculated separately for N, P and C. The nutrient content of livestock excretions for P and P (Grossman; kg N-P yr-1) were calculated using the same approach. For a given animal subclass (e.g., dairy cows), Grossman can be computed as:

where Populationanimal is the population of the animal subclass (heads yr-1) and Nutexc,coeff the nutrient excretion coefficient (kg N-P head-1 yr-1). Animal population data was collected and preprocessed according to the methodologies and sources described in “Statistical data”. Country-specific for non-dairy excretion coefficients were derived from CdPBA (2018) – Table XX.

|  |  |  |  |
| --- | --- | --- | --- |
| Main\_animals | Animals | Nex | Pex |
| kg N-P head-1 yr-1 | |
| Bovine | Non\_dairy | 80 | 13.09 |
| Bovine | Female\_calf-1 | 25 | 3.27 |
| Bovine | Beef\_calf | 25 | 3.27 |
| Bovine | Male\_calf\_1-2 | 40 | 5.67 |
| Bovine | Female\_calf\_1-2 | 40 | 5.67 |
| Bovine | Male\_calf\_2 | 65 | 7.86 |
| Bovine | Female\_calf\_2 | 55 | 8.73 |
| Bovine | Other\_calf | 55 | 8.73 |
| Goats | Goats | 6.52 | 1.96 |
| Poultry | Broilers | 0.45 | 0.07 |
| Poultry | Laying\_hens | 0.8 | 0.20 |
| Poultry | Rep\_hens | 0.34 | 0.09 |
| Poultry | Turkeys | 1.4 | 0.31 |
| Poultry | Ducks | 0.45 | 0.07 |
| Poultry | Geese | 0.45 | 0.07 |
| Equides | Horses | 44 | 10.04 |
| Equides | Other\_equidae | 22 | 5.02 |
| Rabbits | Rabbits | 9 | 2.62 |
| Swine | Pregnant\_sows | 6.5 | 1.53 |
| Swine | Non\_pregnant\_sows | 5.1 | 1.22 |
| Swine | Boars | 18 | 4.36 |
| Swine | Pigs\_20 | 4 | 0.87 |
| Swine | Pigs\_50 | 4 | 0.87 |
| Swine | Other\_swine | 4 | 0.87 |
| Sheep | Ewes | 12 | 1.96 |

# Crop production

The nutrient (phosphorus, nitrogen and carbon) removal through crop harvest was calculated for 33 individual crops, included Cereals (barley, rye, irrigated and rainfed maize, rice, wheat, oat and triticale), Citrus (lemon, orange and other citrus), Dried nuts (almonds, chestnut, nuts and other dried nuts), Fresh fruits (apple, pears, cherry, peach and other fresh fruits), Horticulture (extensive and intensive horticultural crops), Industry (tomato and sunflower), Potato (rainfed and irrigated potato), Pulses (beans, chickpea and other pulses), Olive groves and Vineyards. Fodder crops (Forage, Pastures) were excluded from this module (see **Fodder production**).

For the *n*th nutrient and the *i*th crop, the total amount of nutrient removed through the harvest of main crop products was calculated as:

where Nutofftake is the amount of nutrient removed (kg nutrient yr-1), Areacrop is the area of a given crop (ha yr-1), Yieldcrop is the fresh-matter crop yield (kg FM ha-1 yr-1), FRACDM is the dry-matter fraction (%FM) and Nutofftake, coeff is the average nutrient offtake parameter (kg nutrient N tonnes DM-1 yr-1). The nitrogen and phosphorus coefficients were collated from the Code of Good Agricultural Practices of Portugal (CdBPA, 2018), while C coefficients were taken from (Le Noë et al., 2017). Phosphorus coefficients were converted from kg P2O5 ha-1 yr-1 to kg P ha-1 yr-1 using a unit conversion factor of 0.4364.

Table 5. Crop-specific offtake coefficients used to calculate crop nutrient harvest

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| main\_crop | crop | P2O5\_offtake | C\_offtake | N\_offtake |
| kg P2O5-C-N tonnes DM-1 yr-1 | | |
| Cereals | Barley | 10.8 | 340 | 18 |
| Cereals | Rainfed\_maize | 10.3 | 340 | 27.68 |
| Cereals | Irrigated\_maize | 10.3 | 340 | 27.68 |
| Cereals | Oat | 10 | 340 | 23 |
| Cereals | Rice | 6 | 340 | 12.25 |
| Cereals | Rye | 10 | 340 | 33 |
| Cereals | Triticale | 10 | 340 | 19.25 |
| Cereals | Wheat | 8.6 | 340 | 20.64 |
| Citrus | Lemon | 0.4 | 60 | 1.9 |
| Citrus | Orange | 0.4 | 60 | 1.9 |
| Citrus | Other\_citrus | 0.4 | 60 | 1.9 |
| Citrus | Tangerine | 0.4 | 60 | 1.9 |
| Dried\_nuts | Almond | 12 | 400 | 32 |
| Dried\_nuts | Chestnut | 1.7 | 400 | 5 |
| Dried\_nuts | Locust | 12 | 400 | 32 |
| Dried\_nuts | Nuuts | 7.2 | 400 | 22.75 |
| Dried\_nuts | Other\_dried\_nuts | 32 | 400 | 32 |
| Fresh\_fruits | Apple | 0.2 | 60 | 0.4 |
| Fresh\_fruits | Cherry | 0.4 | 60 | 2 |
| Fresh\_fruits | other\_fresh | 0.6 | 60 | 1 |
| Fresh\_fruits | Peach | 0.6 | 60 | 1 |
| Fresh\_fruits | Pear | 0.2 | 60 | 0.5 |
| Horticulture | Horticulture\_extensive | 1 | 32 | 3 |
| Horticulture | Horticulture\_intensive | 1 | 32 | 3 |
| Industry\_crops | Sunflower | 17 | 420 | 27 |
| Industry\_crops | Tomato | 0.9 | 32 | 3.14 |
| Olive\_grove | Olive\_grove | 1 | 60 | 3.5 |
| Potato | Rainfed\_potato | 2.4 | 88.8 | 5 |
| Potato | Irrigated\_potato | 2.4 | 88.8 | 5 |
| Vineyard | Vineyard | 0.6 | 60 | 1 |
| Pulses | Beans | 7.6 | 36 | 30 |
| Pulses | Chickpea | 7.6 | 36 | 30 |
| Pulses | Other\_dried\_pulses | 7.6 | 36 | 30 |
| Pastures | Intensive\_pasture | 1.06 | 400 | 4.38 |
| Pastures | Extensive\_pasture | 6.67 | 200 |  |
| Forage | forage\_roots | 6.67 | 32 | 16.3 |
| Forage | Annual\_mixtures | 6.67 | 340 | 16.3 |
| Forage | forage\_sorghum | 6.67 | 340 | 16.3 |
| Forage | forage\_oat | 2.35 | 340 | 9 |
| Forage | forage\_maize | 1 | 430 | 2.45 |
| Forage | other\_forage | 6.67 | 340 | 16.3 |

# Irrigation

### Irrigation water requirements

Irrigation water requirements, already accounting for irrigation field efficiency of the different irrigation methods, was calculated for each crop at the municipality level for the period 1987-2017. The acreage of the different irrigated areas and irrigation methods was collated as described in the topic “Irrigated/irrigable areas – data processing”. Historical crop water requirements for the different irrigation methods were collated from three main regions in mainland Portugal from SNIRH. Therefore, crop water requirements (CWR; m3 yr-1) were estimated as:

where IAcrop is the acreage of a crop under a given irrigation method (in ha) and IVcrop the irrigation water requirements for a crop under a given irrigation method (in m3 ha-1 yr-1).

### Spatial prediction of nitrate in surface- and groundwater

The SNIRH database (SNIRH, 2020) was used to collate monitoring stations data concerning nitrate in surface- and groundwater. For surface water,

# Crop residues

### Fodder production allocated products

By developing standard and typical rations for the whole country, some distortions are to be expected where roughage feed is over-estimated. That is, in intensive livestock regions where grazing animals still have a considerably higher intake of concentrate feeding than the values defined in the rations. To deal with these abnormally we set a threshold for both fresh grass and hay of 210 kg N ha-1 yr-1 as according to parameters from (Velthof et al., 2009). The partition between intensive and extensive grassland was proceeded according to the area fractions compared to the total pasture land (intensive plus extensive) and it was also assumed that the productivity of intensive grassland are two times higher than extensive grasslands (Velthof et al., 2009).

# Fertilization

Fertiliser data is often only available at the national level for most countries in Europe, which is the case for Portugal. (Serra et al., 2019) developed a downscaling mechanism to calculate fertiliser N at the municipality scale for 1989, 1999 and 2009. The underlying assumption used by these authors was balanced fertilization practices which imply that farmers first use the available farm resources to supply crops with nitrogen in order to fulfill their requirements; synthetic fertilisers are applied only if these are unable to meet crop nutrient requirements. That is, it is assumed that farmers apply manure first, sewage sludge secondly and lastly synthetic fertilisers. The approach used here was an adapted version of this approach, described below. Only P and N were considered.

### Sewage sludge

Data on the total sewage sludge used for agricultural purposes was collected from the Portuguese Environmental Agency for the years 2006-2017 (SludgeDM; tonnes DM yr-1). The remaining years (1987-2005) were interpolated using a linear regression. Firstly, SludgeDM was converted to N using a sludge N content of 0.0363 kg N kg DM-1 from (APA, 2017) (SludgeN; tonnes N yr-1). These values were further calibrated at the mainland level using the data presented in APA (2017) for the period 1990-2017; municipality values were corrected accordingly. For P and C, we derived the N:P and N:C ratios for France from (Le Noë et al., 2017).

We distributed the sewage sludge produced in the municipalities of the two most densely populated urban areas in Portugal – Lisbon’s and Porto’s metropolitan areas – according to the distribution of agricultural areas in the municipalities within. This was done under the assumption that it is not economically feasible to transport sewage sludge to distant locations.

### Crop nutrient requirements

Crop nutrient requirements (Nutreq; kg N-P yr-1) for a given crop was calculated according to the country-specific recommended fertiliser rates (Nutrec,fert ; kg N-P ha-1 yr-1), which are updated according to difference of annual crop yields (Yieldcrop; kg FM ha-1 yr-1) and standard crop yields (Yieldscrop, standard; kg FM ha-1 yr-1), and crop-specific fertiliser modifiers (Nutfert, mod; kg N-P ha-1 yr-1. The updated crop fertiliser rates (Nutupdated,fert ; kg N-P ha-1 yr-1) were calculated at the agrarian region level, for which crop yield data was available:

Examples of crop-specific standard yields and fertiliser modifiers are given below for cereal crops. Fertiliser modifiers are indicative of the difference of fertiliser that is required per difference in crop yields.

Table 6. Crop-specific fertiliser modifiers for nitrogen used to update crop fertiliser rates

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Agrarian  region id | Agrarian  region | Wheat | Rye | Oat | Barley | Triticale | Rainfed maize | Irrigated  maize | Rice |
| *kg N ha-1 yr-1* | | | | | | | |
| Entre Douro e Minho | 1 | 30 | 30 | 30 | 30 | 30 | 10 | 10 | 20 |
| Trás-os-Montes | 2 | 30 | 30 | 30 | 30 | 30 | 10 | 10 | 20 |
| Beira Litoral | 3 | 30 | 30 | 30 | 30 | 30 | 10 | 10 | 20 |
| Beira Interior | 4 | 30 | 30 | 30 | 30 | 30 | 10 | 10 | 20 |
| Ribatejo e Oeste | 5 | 30 | 30 | 30 | 30 | 30 | 10 | 10 | 20 |
| Alentejo | 6 | 30 | 30 | 30 | 30 | 30 | 10 | 10 | 20 |
| Algarve | 7 | 30 | 30 | 30 | 30 | 30 | 10 | 10 | 20 |

Table 7. Crop-specific standard yields (CdBPA, 2018)

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Agrarian  region id | Agrarian  region | Wheat | Rye | Oat | Barley | Triticale | Rainfed maize | Irrigated  maize | Rice |
| kg FM ha-1 yr-1 | | | | | | | |
| Entre Douro e Minho | 1 | 4,000 | 2,500 | 2,500 | 4,000 | 4,000 | 7,500 | 1,0000 | 7,000 |
| Trás-os-Montes | 2 | 4,000 | 2,500 | 2,500 | 4,000 | 4,000 | 7,500 | 1,0000 | 7,000 |
| Beira Litoral | 3 | 4,000 | 2,500 | 2,500 | 4,000 | 4,000 | 7,500 | 1,0000 | 7,000 |
| Beira Interior | 4 | 4,000 | 2,500 | 2,500 | 4,000 | 4,000 | 7,500 | 1,0000 | 7,000 |
| Ribatejo e Oeste | 5 | 4,000 | 2,500 | 2,500 | 4,000 | 4,000 | 7,500 | 1,0000 | 7,000 |
| Alentejo | 6 | 4,000 | 2,500 | 2,500 | 4,000 | 4,000 | 7,500 | 1,0000 | 7,000 |
| Algarve | 7 | 4000 | 2,500 | 2,500 | 4,000 | 4,000 | 7,500 | 1,0000 | 7,000 |

The updated crop fertiliser rates (Nutupdated,fert) correspond to the crop nutrient requirements on an area basis. Total nutrient requirements for a given crop were calculated as the product of its area and Nutupdated,fert.

# Fodder production

### Getting other animal population for sheep and goat

The remaining sub-modules calculate sheep and goat nutrient flows based on the total population as the N excretion already includes for younglings and the N excretion rate is the same for these categories. In order to properly calculate the energy requirement for growth and lactation, these populations were disaggregated according to Statistics Portugal data. Data was collected at the agrarian region level. Fractions of these subclasses’ populations were calculated at this spatial resolution and “downscaled” to the municipality scale, followed by its computation based on downscaled-and-interpolated total animal populations at the municipality scale.

Similarly, sheep and goat milk production were collated from Statistics Portugal. The same procedure was used as in dairy cows’.

Because goat population data does not account for milking goats, it was assumed that 10% of the goats (var\_id = ‘11’) are lactating. When interpolating milk produced per head, a minimum of 500 milk head-1 was assumed. Furthermore, for wool production, it was assumed that 5% of each Sheep subclass are younglings and do not produce wool.

### Nitrogen feed intake

Nitrogen feed intake here is estimated as the sum of the N retention and N excretion. Total N excreted per the different animals was calculated in the manure module; the N retained in the body was estimated according to the GLEAMS model for the three different main classes: ruminants (large and small; dairy and non-dairy), pigs and poultry.

For large ruminants, GLEAMS distinguishes three different cohorts: adult females (dairy cows), adult males (>2 years and Non\_dairy) and the remaining. For dairy animals, N retention (kg N head-1 yr-1) was calculated as follows:

where:

Milk – Daily milk production (kg milk head-1 day-1)

Milkprot – the protein content of the milk ( protein/100)

Ckg – younglings’ weight (calves, goat and lamb kids) (kg head-1 day-1)

NEgro – the net energy for growth of replacement animals (i.e., calves , goat and lamb kids) (Mj head-1 day-1)

DWGrf – daily weight gain (kg head-1 day-1)

For dairy cows, the protein content was collated from Statistics Portugal for the period 2003-2017 and linearly interpolated to the remaining years; for sheep and goat it was set to 5.4 and 3.1%, respectively. The same procedure was applied to annual milk production for sheep and goats, though a minimum threshold of 50 and 500 kg head-1 year-1 was applied. The remaining parameters were collated from the national inventory reports and GLEAMS. Furthermore, NEgro was computed also according to GLEAMS for large and small ruminants.

For large ruminants:

,

Where LW is the live weight of growing animals (kg head-1), Cgro a GLEAMS parameter (Table 3.27 in GLEAMS documentation) and AFkg is the live weight of an adult animal (>2 years) (kg head-1).

For small ruminants:

,

Where a, b and c are GLEAMS parameters (Tablel 3.28 in GLEAMS documentation) and Ckg is the weight of lambs/kids at birth (kg head-1).

### Concentrate feeding

Because no reliable data concerning the use of concentrate feeding is available for Portugal, we estimated using external models and expert judgement. Following the assumptions made by (Serra et al., 2019) for the agricultural census years (1989, 1999 and 2009) for Portugal, 10% of the total nitrogen intake was assumed to be from concentrate feeding. For poultry, rabbits and pigs in industrial systems (i.e., housed), 100% of nutrient intake is fulfilled by concentrate feeding. Similar to Serra et al. (2019), concentrate feeding used for dairy cows was estimated based on milk yields and used the Nordic methodology (NorFor; (NorFor, 2011)).

* Dairy cow explanation

### Roughage feeding

The remaining nutrient intake was assumed to come from roughages (e.g., fresh grass, hay, crop residues). That is, the total nutrient intake from roughage (Nutroughage; kg P-N yr-1) was calculated as the difference of the nutrient intake and the nutrients from concentrate feedstuff. The methodology here employed enables an estimation of the nutrient flows from the main crop products and residues removed for animal feeding of Forage crops and Pastures (see below).

Typical roughage feed rations were created for sheep, goats, pigs in backyard production systems (i.e., grazing), horses and cattle (dairy cows, non-dairy cows and other cattle) based on the rations from GLEAMS. Table XX illustrates the design of a feed ration for non-dairy cows.

Table 8. Roughage feed ration created for non-dairy cattle

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Main\_crop | Crop | Crop\_product | Roughage | FRAC | Source |
| Pastures | Extensive\_pasture | Harvest | Fresh\_grass | 0.5 | GLEAMS |
| Pastures | Extensive\_pasture | Residues | Hay | 0.2 | GLEAMS |
| Cereals | Cereals | Residues | Cereals | 0.1 | GLEAMS |
| Forage | Annual\_mixtures | Harvest | Annual\_mixtures | 0.03 | GLEAMS |
| Forage | forage\_maize | Harvest | forage\_maize | 0.05 | GLEAMS |
| Forage | forage\_maize | Residues | forage\_maize | 0.02 | GLEAMS |
| Forage | forage\_maize | Residues | forage\_maize | 0.03 | GLEAMS |
| Forage | forage\_oat | Harvest | forage\_oat | 0.05 | GLEAMS |
| Forage | other\_forage | Harvest | other\_forage | 0.02 | GLEAMS |

For dairy cows, we adjusted the roughage intake according to the proportion of concentrates for the *i*th municipality.

where FRACconcentrate is the fraction of concentrate feed in the *i*th municipality (in %Nutintake), FRACroughage is the fraction of a roughage feed in the ration created (in %Nutintake) and SUM\_FRACroughage is the sum of the fraction of all roughage feedstuff in the ration created (in %Nutintake).

Roughage was then allocated according to the rations specified for the different animals and based on total nutrient intake. The nutrient flows for the *z*th roughage feedstuff (Nutroughage, z; kg N-P yr-1)was calculated for the different livestock subclasses as:

where FRACroughage, j is the fraction of the *j*th roughage feedstuff in the ration created for a given livestock subclass (%) and Nutintakeis the total nutrient intake for a given livestock subclass (kg N-P yr-1). The nutrient flows were separated into main crop products (“Main\_crop”) and residues (“Residues”), which will be subsequently fed to crop production regarding fodder production and associated crop residues removed from the field.

To convert roughage intake to fodder production (and residues), it was assumed that the fodder yield for the different fodder crops equals to the intake by livestock. Crop N-P yields were calculated as (NYcrop; kg N-P ha-1 yr-1) for the *i*th crop as:

where Nutroughage is the livestock roughage intake for the *i*th crop and Areacrop the area of the *i*th crop.

### Reality check of the estimates – Conversion from nutrient flows to DMI

In order to gain insight regarding the “truthfulness” of the results, NYcrop flows of N-P were converted to DMI. This was done using standard N-P crop contents from the GLEAMS model (FRACnut; g N-P kg-1) and a standard dry-matter conversion rate of 80%. Fodder yields were computed as (Fodderyield; kg ha-1 yr-1) for *i*th crop:

# Gaseous emissions

### Ammonia (NH3)

Ammonia emissions were calculated for manure management systems (housing including yards, storage), the field application of organic and inorganic fertilisers (biosolids, manure, synthetic fertilisers and grazing) and crop residues burnt *in situ*. Emissions from manure spreading were calculated for slurry and solid manure. The methodology used follows **EMEP (2016)**.

### Nitrous oxide (N2O)

### Nitrogen oxides (NOx)

Nitrogen oxides emission were calculated

# Runoff module

Runoff losses are calculated for the **recent application of nutrients to the soil from grazing and the field application of fertilisers** (sludge, manure and synthetic fertilisers) and for the “**memory effect**” over time (Beusen et al., 2015). The former applies the MITERRA-EUROPE approach to first estimate the runoff fraction (frunoff; %N-input) based on environmental parameters (G.L. Velthof et al., 2009). Runoff parameters receive as input static data (slope, soil texture and depth to rock) and dynamic data calculated on a yearly basis (land use, precipitation surplus). Land use classes were derived from the land use module.

Two different methodologies were applied to calculate frunoff: one based on **the potential land use allocation to different crops and management practices**, the other calculated by accounting **for spatial explicit crop areas** (*to be implemented*). The first approach was implemented by firstly separating management practices (fertilisers and grazing) and by defining allowed land use classes to allocate different crop nutrient flows. Land use classes were crop nutrient flows are not allowed were masked out and set to NA, while the authorized land uses were set to 1 and multiplied by the annual runoff fraction. The following crop classes were aggregated and further allocated: AnnualCrops (cereals, vegetables, potatoes, pulses), FruitTrees (citrus, fresh fruits, dried nuts), IntensivePasture, OliveGrove, Vineyards and Rice. For grazing, it was assumed that this practice only occurs in certain LU classes.

The second approach was calculated by masking spatially explicit crop areas from the runoff fraction mask.

Table 9. Allowed land use (allocation) classes for AnnualCrops (Activity\_data/General\_params/LULCC/Runoff/LU\_allocation)

|  |  |  |  |
| --- | --- | --- | --- |
| clc\_id | label | LULCC\_label | allow\_runoff |
| 1 | urban | urban | 0 |
| 2 | forest | forest | 0 |
| 3 | wetlands | wetlands | 0 |
| 211 | Non-irrigated arable land | Non\_irrigated | 1 |
| 212 | Permanently irrigated land | Permanently\_irrigated | 1 |
| 213 | Rice fields | Rice | 0 |
| 221 | Vineyards | Vineyards | 0 |
| 222 | Fruit trees and berry plantations | Fruit\_trees | 0 |
| 223 | Olive groves | Olive\_groves | 0 |
| 231 | Pastures | Pastures | 0 |
| 241 | Annual crops associated with permanent crops | Annuals\_permanents | 1 |
| 242 | Complex cultivation patterns | Complex\_patterns | 1 |
| 243 | Land principally occupied by agriculture with significant areas of natural vegetation | Agriculture\_naturalVeg | 0 |
| 244 | Agro-forestry areas | AgroForestry | 0 |
| 321 | Natural grasslands | Natural\_grasslands | 0 |
| 512 | Water bodies | Water\_bodies | 0 |

Nutrient runoff losses from recent application (NutRes, rf) were calculated as the product of runoff fractions and the net nutrient returned to the soil (NutRes, net). For nitrogen, ammonia (NH3) emissions were subtracted from the field application of fertilisers and grazing.It is implied that that the total Nutres, rf is the sum of the runoff losses from all crop classes **and** for grazing and field application.

For instance, for the nitrogen losses of Irrigated\_maize (an annual crop) from manure application, frunoff was calculated by allocating the net nutrient losses to the allowed land use classes (i.e., gross manure spreading minus the NH3 emissions following application (Table 1).

## Summary of operations

|  |  |
| --- | --- |
| **Implemented** | * NITROGEN: Runoff losses from recent application of fertilisers (biosolids, manure, synthetic fertilisers) for all crops and for grazing * frunoff calculated using the first approach (land use allocation approach) |
| **Not implemented yet** | * NITROGEN, PHOSPHORUS: “Memory effect” of runoff losses * NITROGEN, PHOSPHORUS: frunoff using spatially explicit crop areas * PHOSPHORUS: runoff losses |

# Nutrient balances

Depending on the system boundaries established, it is possible to compute different typologies of nutrient balances (Leip et al., 2011). The definition of the system boundaries depends on the model’s main goal. For instance, the land nutrient balance (gross nutrient balance) is useful to roughly estimate where the potential of environmental nutrient losses are greater (Serra et al., 2019). Conversely, the soil surface nutrient balances (Van Grinsven et al., 2012) can be used to assess N exports to surface- and groundwater. These two nutrient balance approaches were calculated here for different agricultural reference areas – for cropland and grassland (extensive pastures).

### Land nutrient balance

The land nutrient balance (Nutland; kg N-P ha-1 yr-1 was computed for (i) phosphorus and nitrogen, and (ii) cropland and grassland (permanent pastures).

Nitrogen and phosphorus land balances, Nland,crop and Pland, crop , respectively, for **cropland** were calculated as:

where NBNF is the biological N fixed by pulses and intensive pastures, Nman is the gross manure excretion minus the N excreted onto permanent pastures, Nfert and Nsludge the N applied in inorganic and organic fertilisers, Ndep the atmospheric N deposited in cropland and Nirrig the N input from irrigation water. The output side includes the N contained in fodder main product and residues (Nfodder, offtake and Nfodder, residues) which include hay and fresh grass production of intensive pastures; similarly, crop offtake and respective residues were also included.

For grassland, specifically permanent grassland, the nutrient land balances were calculated as:

### Soil surface nutrient balance

The soil surface nutrient balance (SSNB), or soil balance, is a proxy for nutrient exports to surface- and groundwater. Similar to the land balance, the SSNB was calculated for cropland and grassland, for nitrogen and phosphorus. The SSNB includes all nutrient losses, calculated in a cascading effect, such as gaseous N losses in storage, housing, field application and runoff nutrient losses. For **nitrogen**, the SSNB equals to the nitrogen leaching and denitrification to N2 while for **phosphorus** the SSNB represents only leaching losses.

For **cropland** and **nitrogen**, the following N losses were included:

Most parameters are self-explanatory and were already mentioned in the “Gaseous emissions” and “Runoff module”. Care should be taken regarding Grazingloss which refers to the gaseous N losses from N excreted onto intensive pastures, to Runoffman which refers to the runoff N losses from manure field application (different from gross manure N excreted).

Therefore, the SSNBcropland was calculated as:

For **cropland** and **phosphorus**, the SSPB was differently calculated since there is no gaseous emissions from phosphorus, only runoff losses which were calculated similarly to nitrogen runoff losses:

For **grassland** and **nitrogen**, the SSNB was estimated as:

While for **grassland** and **phosphorus**, SSPBgrassland was calculated analogously to the SSPBcropland but only for permanent grassland.

# Leaching module

Nitrogen losses derived from leaching from below the root zone were computed using an empirical approach based on the leaching fractions, expressed as a fraction of the SSNB (Velthof et al., 2009). For phosphorus, leaching losses equal to the SSPB. Aiming to better represent the contrast between the often intensive-managed arable land to the extensive permanent pastures, leaching was calculated separately for cropland and grassland.

For **phosphorus**:

For **nitrogen**, the leaching fractions were calculated separately and using a spatially explicit approach for grassland and cropland.

The total nutrient leaching, for either P or N, from below the root zone was thus the sum of leaching in cropland and grassland.