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Nutri2Cycle

D1.5 Mapping and characterization of CNP flows and their stoichiometry in main farming systems in Europe

Deliverable: Mapping and characterization of CNP flows and their stoichiometry in main farming systems in Europe

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Executive summary

This report constitutes the Deliverable 1.5 of the Nutri2Cycle project. The Nutri2Cycle project aims at testing and implementing innovative technologies to better close the gaps in nutrient cycling within European agriculture. This report presents studies carried out within work package 1 on the characterization of the CNP flows and their stoichiometry in main farming systems in Europe, and the determination of a baseline, against which new technologies and solutions for improving CNP cycling can be evaluated. This report is divided in four chapters:

1. **Chapter 1** introduces the Nutri2Cycle project, and the work related to this report. The objectives and general approaches applied during the study are presented.

2. In **Chapter 2**, mechanistic modelling tools, Daisy and SWAP/ANIMO, were used to simulate the CNP flows at field level. We first briefly reviewed the use of modelling tools in studying field-level N dynamics, and the coupling of field-level simulation to larger-scale analysis. On the basis of an overview of the environmental zones and main farming systems in the EU, ten baseline scenarios in six geoclimatic regions were selected to represent part of the farming typologies in the EU. The CNP flows at field-level, including emissions to the environment, N and P balances, and long-term changes in soil organic C and N, were simulated for the baseline scenarios using Daisy and SWAP/ANIMO. The simulated data were validated against field measurements, and compared between the two models. We conclude that the selected baseline scenarios represent a significant part of agricultural production in the EU, and Daisy and SWAP/ANIMO are suitable for simulating the CNP flows that will form the benchmark for evaluation of the environmental performances of appropriate shortlisted solutions at field-level.

3. **Chapter 3** presents the work on the integrated assessment of CNP flows in farming systems at regional and national levels. The aim of this chapter was to provide an overview of the current CNP flows and balances in EU agriculture, which will serve as baseline for the assessment of the Nutri2Cycle solutions at EU scale. The results of the baseline simulation clearly show that there is a large variability in environmental impacts within the EU, with high emission intensities in livestock dense regions, whereas in other regions negative nutrient and soil carbon balances occur. Targeted solutions should be applied to improve nutrient cycling and reduces losses to the environment. The results presented, provide the baseline to select relevant practices and techniques from the Nutri2Cycle solutions, which will be assessed on their environmental effectiveness against the baseline values at a regional level, as determined by the MITERRA-Europe model.

4. And finally, **Chapter 4** extends the discussion on the linkage of field-level modelling and life cycle assessment of the environmental impact, which is a highly relevant approach for the Nutri2Cycle project. We presented methods and data requirement on how a technology can be analysed in the context of field-level modelling. An assessment was performed to all shortlisted solutions to identify their feasibility for model simulation, based on the capabilities of the modelling tools, and prospect of data availability.

The baseline scenarios selected in this report, and the simulated CNP flows at field and regional/national levels, will contribute to subsequent tasks of the Nutri2Cycle project, especially work package 3, in which life cycle assessment will be applied to evaluate the environmental performances of selected shortlisted solutions.

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1. Introduction

1.1. Background and objectives

Intensive agriculture is the pillar of food security for Europe. However, agricultural practices often bring environmental challenges related to greenhouse gas (GHG) emissions and nutrient losses. Although agricultural intensification may reduce the environmental footprint on a per unit product basis as compared to small-scale production, the overall emission from intensive agriculture is substantial and needs mitigation. Meanwhile, concentrated production implies that targeted mitigation measures may be applied efficiently. To explore and enable a transition of agronomic practices from the current, suboptimal nutrient flows to an improved recycling system, the Nutri2Cycle project was launched within the Horizon 2020 framework of the European Union (EU). The Nutri2Cycle project aims at proposing, testing, and implementing innovative technologies to track and better close the gaps in carbon (C), nitrogen (N), and phosphorus (P) cycling, and ultimately improving nutrient cycling and reducing the environmental footprint of European agriculture. In this context, quantitative understanding of the C, N, and P (CNP) flows cross the soil-water-atmosphere interfaces, and within various agroecosystems across Europe, is essential for optimizing field management strategies within European agronomic systems.

This report is the work of Nutri2Cycle work package (WP) 1. WP1 assesses the CNP flows and losses, their stoichiometry, and their drivers in main European farming systems during the last few decades, and derives a set of indicators for enhancing the efficiency of CNP flows. This report focuses on the characterization of the CNP flows and their stoichiometry in main farming systems in Europe for determination of a baseline, against which new technologies and solutions for improving CNP cycling can be evaluated. The specific objectives of this report are:

(i) To select modelling scenarios for different European farming systems, and simulate their CNP flows at field-level, establishing baselines for assessment of environmental performances of shortlisted solutions selected in Deliverable 2.2 of WP2.

(ii) To perform an integrated assessment of CNP flows in farming systems at regional levels, allowing quantification of spatial variations and changes over time in CNP flows.

1.2. General approaches for mapping baseline CNP flows

The following approaches were applied:

(i) Based on an overview of the main farming systems in the EU and several geographic regions, several scenarios representing some typical farming systems and geoclimatic regions will be selected. CNP flows will be simulated for these selected scenarios using mechanistic models Daisy and SWAP/ANIMO, which will allow quantitative assessment of environmental emissions and CNP balances at field level. These flow simulations will serve as a modelling framework which can be easily adapted to form the baseline against which innovations will be benchmarked in later tasks (WP3 Task 3.1).

(ii) A review and integrated assessment will be performed for CNP flows in farming systems at regional and national levels, using integrated CNP assessment tools (MITERRA-Europe) and EU-wide databases. These assessments allow quantification of spatial variations and changes over time in CNP balances, CNP losses to groundwater and surface waters as well as emissions of CO_2, CH_4, NH_3, and N_2O to the atmosphere.

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2. Field-level modelling of baseline CNP flows in different farming systems

2.1. Introduction

2.1.1. Model description

Daisy

Daisy is a mechanistic model that simulates the physicochemical processes of water, solutes, gases, and energy fluxes in the bioactive zone across the soil-vegetation-atmosphere interfaces (Abrahamsen & Hansen, 2000). Daisy consists of several submodules (Figure 2.1): a soil column module that emulates the processes of water and matter fluxes in the soil; a bioclimate module that keeps track of temperature, light distribution, water interception, etc.; and a vegetation module that simulates the growth and production of crops and associated nutrients uptake. Consequently, Daisy requires information concerning these submodules to properly simulate a system, including weather (hourly or daily values of solar radiation, air temperature, precipitation, etc.), soil (texture, organic matter, hydraulic properties, etc.), water (depth, drainage, etc.), field management activities (crop rotation, tillage, sowing, fertilisation, irrigation, harvesting, etc.), as well as organic matter turnover in the soil. Daisy simulations are performed at field scale, and can be in either one or two dimensions. Typical usage of Daisy includes simulation of water flows in soil, transport and transformation of N, changes in soil organic matter (SOM) pools, crop yields estimation, and emissions of C and N to the environment.

Daisy has been continuously developed since the early 1990s, and has been validated in numerous studies and peer-reviewed papers. By January 2021, the most recent version of Daisy is v5.93 (daisy.ku.dk).

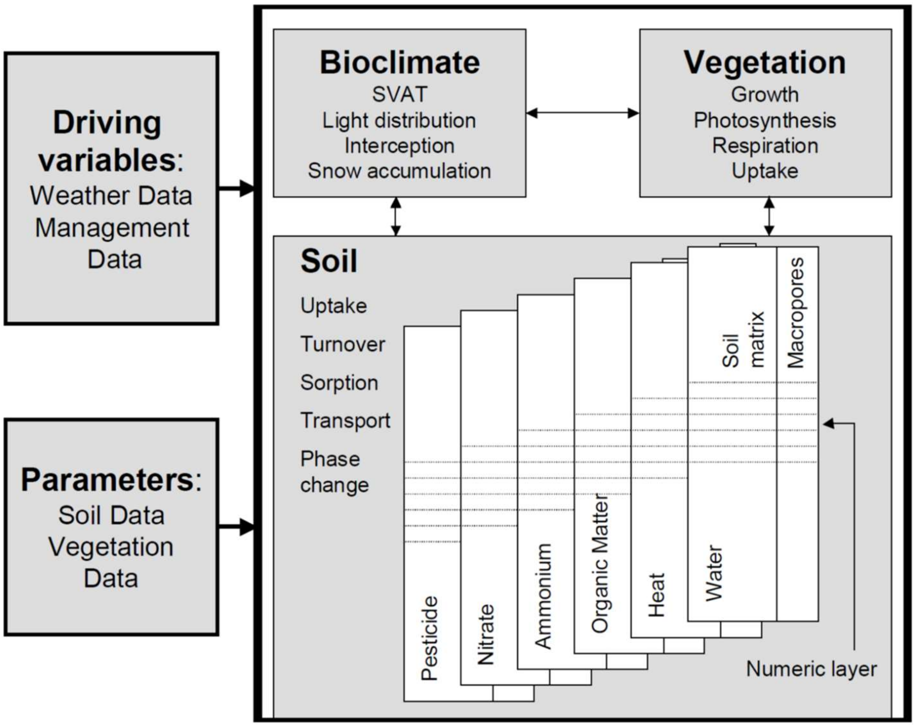

Figure 2.1: Schematic illustration of the Daisy model.

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SWAP/ANIMO

SWAP/ANIMO has been developed since the 1980s to evaluate and predict the effect of fertilization, land use and land management on the soil-emissions of carbon, nitrogen and phosphorus to the air, groundwater and surface water (Figure 2.2). SWAP-ANIMO consists of two coupled process-based models. The SWAP model simulates temperature and water flow in the soil-plant-atmosphere domain in an integrated manner (Kroes et al., 2017). The ANIMO model uses this hydrological information in combination with fertilizer application rate and soil management to simulate the fate of N, P and C in the soil (Groenendijk et al., 2014; Groenendijk et al., 2005). The upper boundary of the ANIMO model is the agricultural land surface, where nutrients are applied, the side boundary is the edge of the field, where N and P leach from soil to surface water. The lower boundary is defined at a hydrological boundary in the groundwater. ANIMO includes complete descriptions of the organic matter, nitrogen and phosphors cycle since these cycles are interrelated in farming systems and in soil biochemistry.

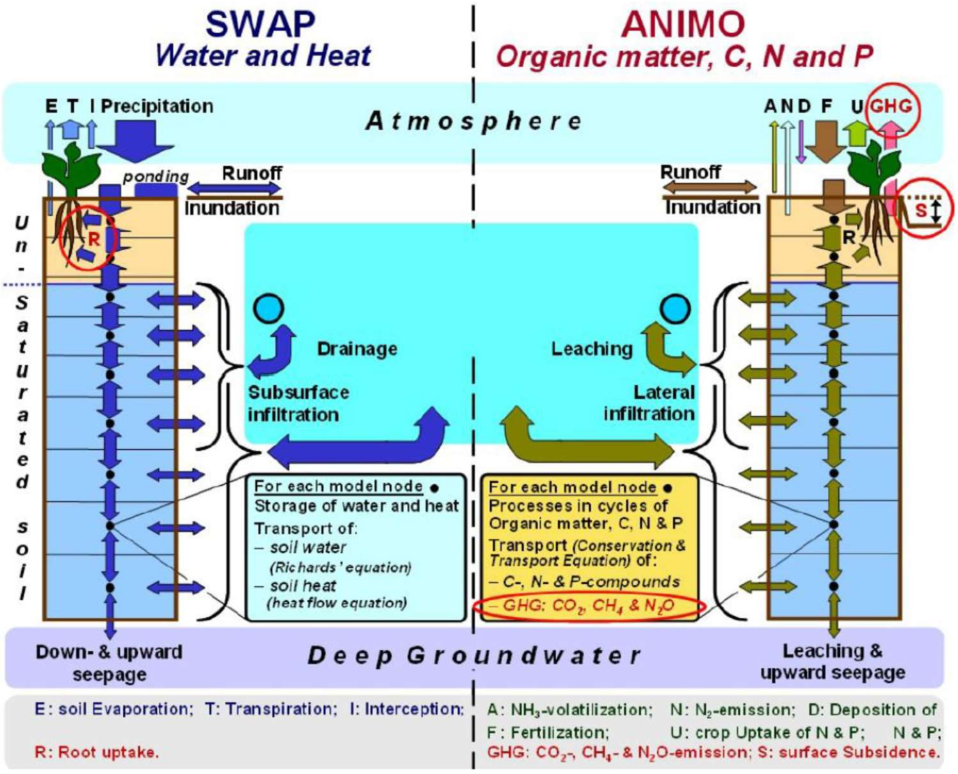

Figure 2.2: Schematic illustration of the SWAP/ANIMO models.

2.1.2. Use of field-scale modelling tools to simulate C, N, and P flows

Field-scale modelling tools have been used to simulate C, N, and P flows in soil for decades. The SWAP/ANIMO model has been used for that purpose since the 1980s, in many international studies. On the field-scale level, SWAP/ANIMO has been applied to different European sites and has been reviewed and compared with other European models for several aspects, such as the organic matter and N cycle (Wu and McGechan, 1998), the P cycle (Lewis and McGechan, 2002) and the simulation of nitrate leaching to the groundwater in different farming systems (Groenendijk et al., 2014).

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Daisy was first developed in the 1990s, with the purpose to simulate N leaching. Since then, Daisy has been applied in many studies to simulate N dynamics in soil and emissions to the environment, as well as uptake by plants. Nitrogen dynamics can be simulated with different N fertilisation levels (Kersebaum et al., 2018), a variety of conventional or novel fertilisers (Yoshida et al., 2016), or different cropping systems (Manevski et al., 2015). It is generally concluded that Daisy was a useful tool for analyses of soil N dynamics in complex systems and crop growth processes. However, it was also noted that differences may occur between measured and Daisy simulated data, and the cause of discrepancies was often attributed to the lacking of proper crop model parameterisation, limited information on organic matter pools, etc. (Manevski et al., 2015).

Soil organic matter content is an important index for soil fertility. Daisy divides SOM into a number of pools characterised by their C:N ratios and decomposition rates (Hansen et al., 2012), and simulates the changes in pool sizes over time. The model has been calibrated using results from long-term field experiments with a range of different treatments of manure application and crop residues (Bruun et al., 2003). Daisy is able to simulate field management activities that lead to changes in SOM, such as organic waste or crop residue incorporation. For example, Peltre et al. (2016) simulated the decline in soil C stocks due to removal of winter wheat straw, and effect of catch crops to offset soil C and N losses.

While Daisy and SWAP/ANIMO simulates nutrient flows at field scale, the simulation results can be used as input to feed other models and tools, facilitating larger-scale analyses beyond the border of the field. Olesen et al. (2019) investigated nitrate leaching from two Baltic Sea catchments using the NLES model, in which Daisy was used to calculate the monthly percolation from the root zone, and to correct the bias in NLES predicted N-leaching. In a study by ten Hoeve et al. (2016), life cycle impact assessment was adopted to evaluate the environmental performances of acidification of pig slurry, and Daisy was applied to simulate crop yields and N emissions during field application of slurries. On the catchment level, SWAP/ANIMO has been used in different European countries to predict the losses of nitrogen and phosphorus from agricultural land to surface freshwater systems (Schoumans et al., 2009). Furthermore, SWAP/ANIMO makes part of the STONE model, which is used on a nation-wide level to evaluate fertiliser policy measures in the Netherlands (Wolf et al. 2003). The approach coupling field-scale modelling tools with regional or national level models, as well as life cycle assessment, is highly relevant to the Nutri2Cycle project, in which a group of shortlisted solutions must be evaluated for their environmental performances. This will be further discussed in section 4.1.

2.2. Selection of baseline scenarios for field-level modelling

One major task of the Nutri2Cycle project is to assess the environmental impact of the shortlisted innovative solutions. To establish a benchmark for evaluating these solutions, a baseline scenario that represents the emission levels of current agricultural practices must be set up.

A baseline scenario is the combination of regional geoclimatic conditions and current agricultural management practices of a specific farming system (e.g., cattle/dairy, pig, or arable production system). Using a field-level modelling approach, the current C, N, and P flows of the scenario will be simulated, and several indicators will be calculated to be used as the benchmarks. Later, the environmental performances of shortlisted solutions will be assessed against these baselines (WP3 tasks).

The Nutri2Cycle project involves partner countries from the Nordic to the Mediterranean regions, and together they represent a wide variety of geoclimatic conditions in Europe. Farming typology and field management practices also vary greatly across these regions. For evaluation of environmental performances at field-level, one single baseline would be insufficient to capture the variations across Europe, and different baseline scenarios are required for different regions and farming types. However, due to the limitation on resources and capacity

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of the modelling tools, it would be impossible to build one baseline scenario for each shortlisted solution, or to build a set of scenarios that cover all shortlisted solutions. Therefore, we aim to create general baselines that are most relevant to manure/slurry recycling and processing, where the processed manure or fertiliser products are field applied. These baselines cover the majority of the shortlisted solutions. If needed, these baselines can also be adapted to evaluate a specific technology in WP3.

2.2.1. Selection principles and methods

During the development of baseline scenarios, the following principles were considered:

- The baselines must reflect the current agricultural practices in different regions in Europe. These practices should include current techniques and management systems to improve nutrient use efficiency, such as replacing mineral N fertilisers with livestock manure, crop rotations, cover crops, etc., as discussed in Deliverable 1.4.
- The baselines should focus on intensive farming systems, where the environmental emissions are high, and there is significant potential for improving nutrient recycling by applying the shortlisted solutions.
- To produce reliable simulation results, the baselines must be based on well-characterised farming systems where detailed data for field-level modelling are available. Baseline scenarios will be based on either characterisation of actual field trials, or theoretical cases that have been well modelled previously.
- While field-level modelling is site-specific in nature, the baselines should be easily modifiable to represent farming systems with similar environmental conditions and agricultural practices elsewhere in Europe.

The baseline scenarios for field-level modelling were chosen following these methods:

1. The Nutri2Cycle partner countries were classified into several geoclimatic regions based on the environmental stratification of Europe.
2. In each of the geoclimatic region, several predominant farming systems were identified, and associated environmental and agricultural data were collected for baseline modelling of environmental emissions.
3. For each geoclimatic region, the baseline simulations included variation in topsoil texture and/or topsoil organic carbon content, allowing the results to reflect a wider range of variation in that region.

2.2.2. Overview of environmental zones in Europe

The environmental stratification of Europe was constructed in 2003 which identifies relatively homogeneous regions in climate, terrain forms, soil, vegetation, and land cover (Metzger et al., 2012). In total, 84 strata were identified, and aggregated into 13 environmental zones (EnZs, Figure 2.3). While environmental variation can still be found internally, each EnZ represents a region with a set of environmental conditions that are statistically homogeneous, and can be a useful tool to facilitate the generalization and selection of sites for modelling exercises across the continent.

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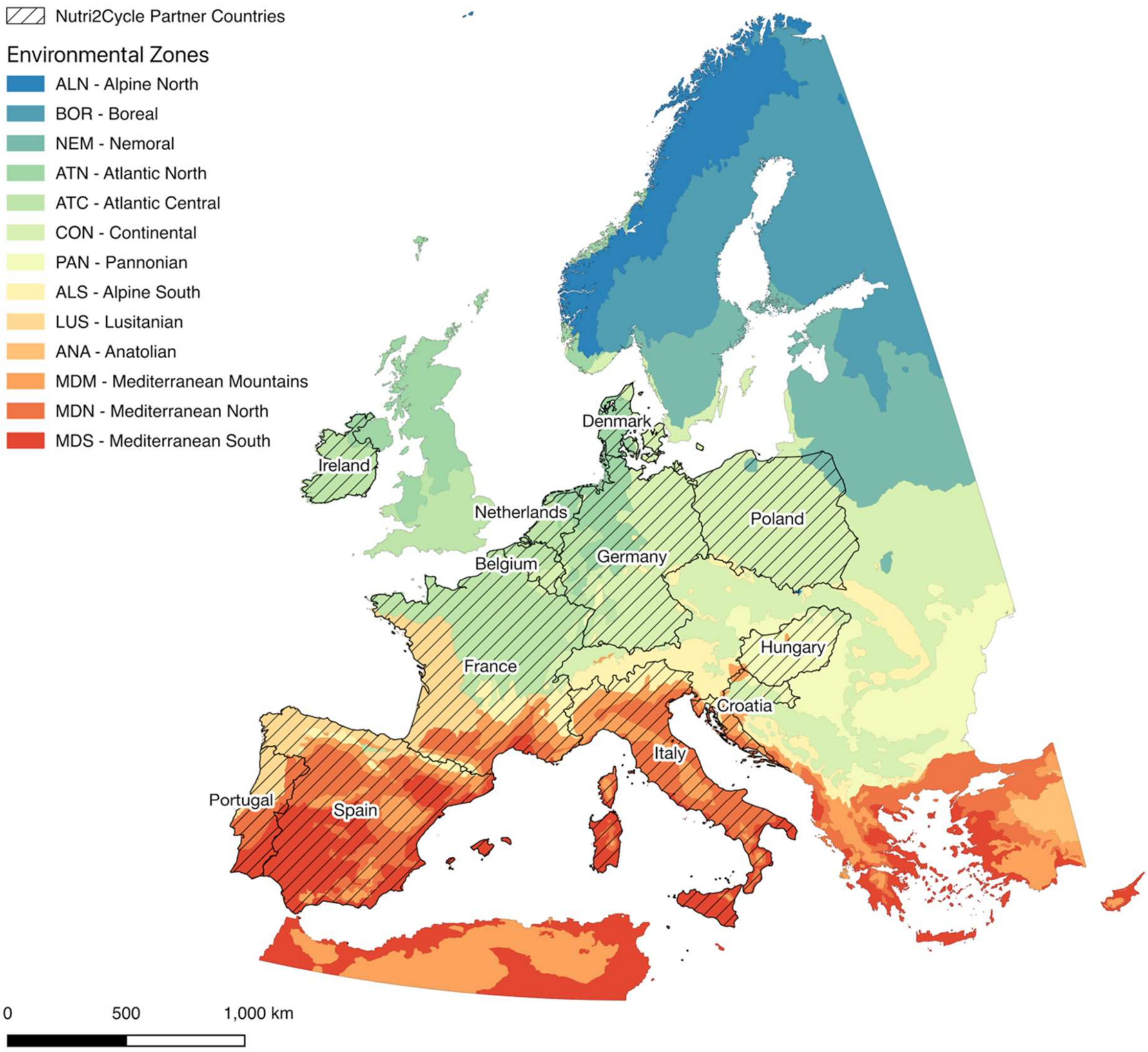

Figure 2.3: Environmental zones (EnZs) in Europe (reproduced from Metzger et al., 2012).

Climate

Between the EnZs, there is a clear latitudinal temperature gradient, in terms of both the number of growing days and temperature sums (Figure 2.4). The warmer Mediterranean region is characteristic of hot, dry summers, followed by temperate, wet winters. In the temperate Atlantic and Continental EnZs, precipitation usually concentrates in the summer, or is evenly distributed over the year. The co-occurrence of water and heat makes these EnZs important agricultural production regions.

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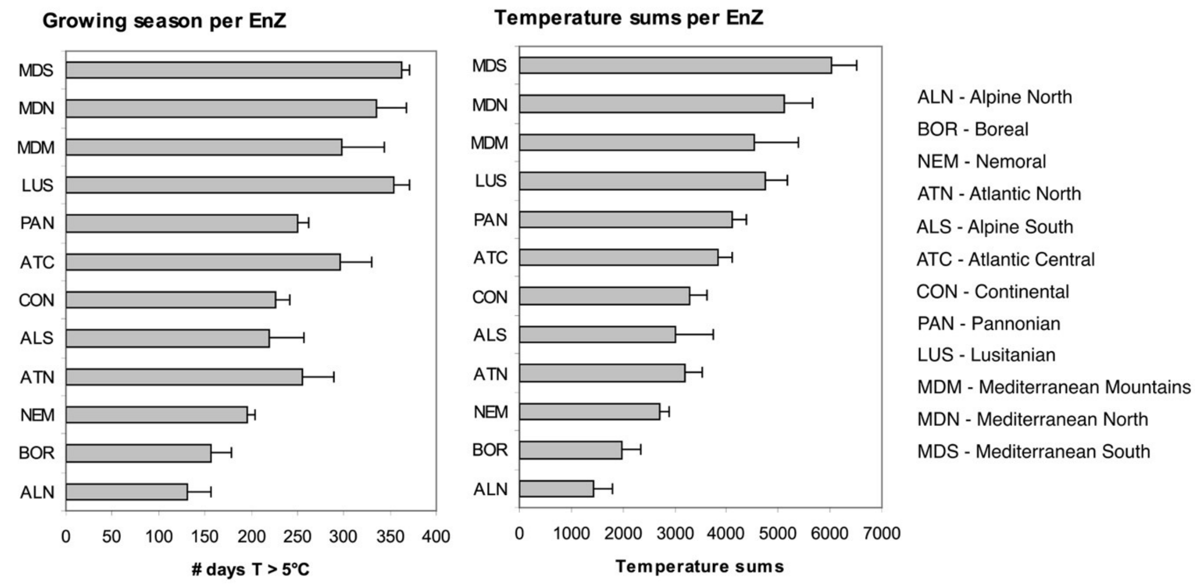

Figure 2.4: Mean length of the growing season (number of days where average temperature is > 5°C) and mean temperature sums for the twelve European EnZs (Metzger et al., 2012).

Soils

The productivity of agricultural soils is mainly influenced by nutrient and soil water dynamics which are largely dependent on soil texture (McLauchlan, 2006). Figure 2.5 illustrates the distribution of topsoil textures and organic carbon content in Europe.

While the formation of soil is closely related to historic climate, it is still obvious to see a moderate correlation in topsoil texture with the EnZs (Ballabio et al., 2016; Metzger et al., 2005). The majority of the area in ATN, and the northern parts of the ATC and CON zones are covered by loamy sand and sandy loam soils. In the southern Mediterranean zones, loam and silt loam soils are predominant (Figure 2.5a).

Generally, there is a trend of decreasing topsoil organic carbon (SOC) content from north to south in Europe. SOC contents as high as over 20% is common in the Boreal (BOR) zone, whereas in some part of the Mediterranean zones, SOC can be less than 1%. In most part of the ATN, ATC, and CON zones, SOC content varies between 1–12% (Figure 2.5b).

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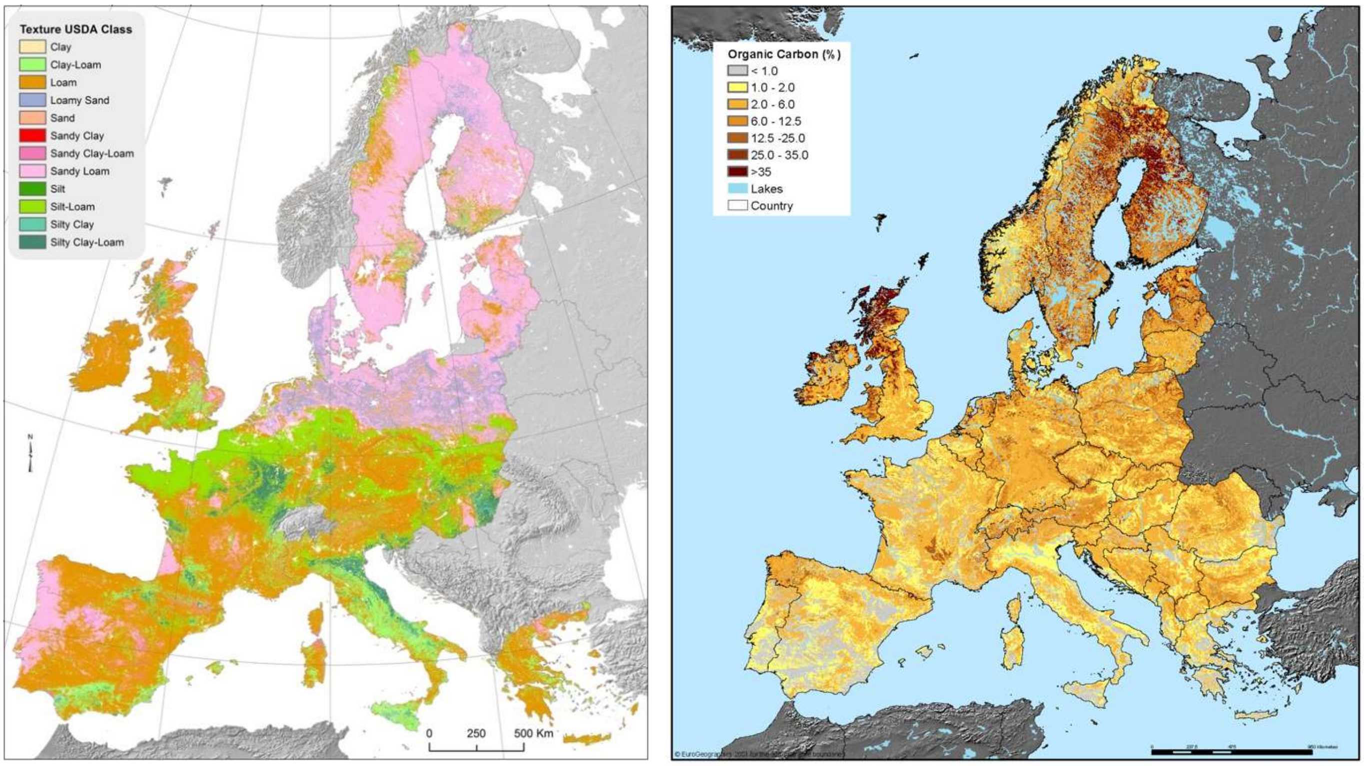

Figure 2.5: Topsoil texture (left, a) and organic carbon content (right, b) in Europe (European Soil Data Centre; Jones et al., 2005.).

2.2.3. Overview of farming types in Europe

France, Spain, United Kingdom, Germany, and Poland are the top five countries with the largest utilized agricultural area in the EU. More than half (52.5%) of the total farms in the EU specialise in crop production, predominantly in field crops, followed by permanent crops and horticulture. Animal production and mixed farms account for 25.1 and 21.1% of the number of farms, respectively.

The majority of the Mediterranean countries (Spain, Italy, Greece, and Cyprus) specialise in crop production. In parts of North-western Europe (e.g., Brittany region of France, Benelux, the United Kingdom, and Ireland), a high proportion of farms focuses on livestock production. Mixed farms are common in Portugal, Romania, Bulgaria, Lithuania, and Croatia, where more than 30% of farms have mixed production.

Cereals are the main crops grown in the EU, accounting for 11.9% of global production in 2017. The dominant species are wheat (142.6 million tonnes), grain maize and corn-cob-mix (64.7 million tonnes), and barley (58.7 million tonnes) (Eurostat, 2018). The production of oilseed crops is also significant, with a yield of 35.1 million tonnes in 2017. Oilseed rape, sunflower, and soya are the three main oilseed crops cultivated in the EU.

The two main root crops grown in the EU are sugar beet, cultivated on 1.8 million hectares across the EU in 2017 representing one half of the global production, and potatoes, cultivated on 1.7 million hectares. Other common root crops include fodder beet, fodder kale, fodder carrot, and turnips.

Cattle production is mostly located in Western Europe, where France and Germany have the largest production. Ireland, the United Kingdom, the Netherlands, and Denmark also have intensified production. In terms of

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hectares of forage area, farms in Eastern Europe, especially in Slovakia and the Czech Republic, have the largest areas (European Commission, 2018).

Pig production in the EU is concentrated in several regions, predominantly in Western Europe (the Netherlands, Denmark, Germany, and France), the Mediterranean region (Spain), and Eastern Europe (Poland). The average share of pig production in agricultural output is highest in Denmark (29 %), followed by Belgium (20 %), Spain (14.7 %), and Germany (14.5 %) (Marquer et al., 2014).

In WP1, Nutri2Cycle project partners were asked to identify the main farming systems in their country and the common crops (reported in Deliverable 1.4). Based on this limited survey, arable, pig, and beef/dairy farms are the most common farming typologies found in these countries, and cereal crops and maize are cultivated in almost all countries. These responses are consistent with the major farming types in respective regions.

2.2.4. Selection of baseline scenarios

Baseline scenarios for field-level modelling were selected following the steps laid out in section 2.2.1.

Firstly, several geoclimatic regions were selected based on the distribution of EnZs in Nutri2Cycle partner countries (Figure 2.3). The Atlantic North and Atlantic Central EnZs were preserved as ATN and ATC regions, respectively. The Continental EnZ covers a large part of the eastern European continent, but also includes some areas to the west of the Baltic Sea (Zealand of Denmark, in particular). We choose to separate the Continental EnZ into two sub-regions: a Continental West region (CTW) that covers the eastern islands of Denmark, and a Continental East region (CTE) covering eastern Germany and Poland with a more inland climate. Similar to the Continental EnZ, the Mediterranean North and the Mediterranean South EnZs together also span a wide region from west to east. Therefore, we choose to consider them as a combined Mediterranean region with two sub-regions: Mediterranean West (MDW, Spain and Portugal), and Mediterranean East (MDE, Italy). The Alpine South and Mediterranean Mountains EnZs consist of mostly mountain regions, but account for only a small part of agricultural area for crop and livestock production in Spain and Italy. They also pose a particular challenge to field-level modelling as the altitudinal variations and water flows on the slopes are difficult to simulate. Therefore, they were not considered for field-level modelling. Part of France and the entire Hungary are covered by the Lusitanian and the Pannonian EnZs, respectively. However, lacking of data on soil and field management practices in these EnZs prevented detailed field-level modelling. Therefore, in total, six geoclimatic regions, i.e., ATN, ATC, CTW, CTE, MDW, and MDE, were selected to establish field-level baselines (Figure 2.6).

Secondly, in each of the six geoclimatic regions, one or two farming systems were selected based on the WP1 survey to Nutri2Cycle partners (reported in Deliverable 1.4). Due to lack of proper crop models, permanent farming systems such as orchards, vineyards, or agroforestry cannot yet be simulated by Daisy or SWAP/ANIMO. P is a nutrient that is important in poultry production, however, available data are insufficient to support the modelling of P cycling in a poultry farming system. Therefore, we focus on the dairy, pig, and arable farming systems. A total of ten farming systems (baseline scenarios) are selected in the six regions (Table 2.1), each represents one particular farming typology, and consists of regional climatic conditions, crop rotation, fertiliser composition, and field management practices.

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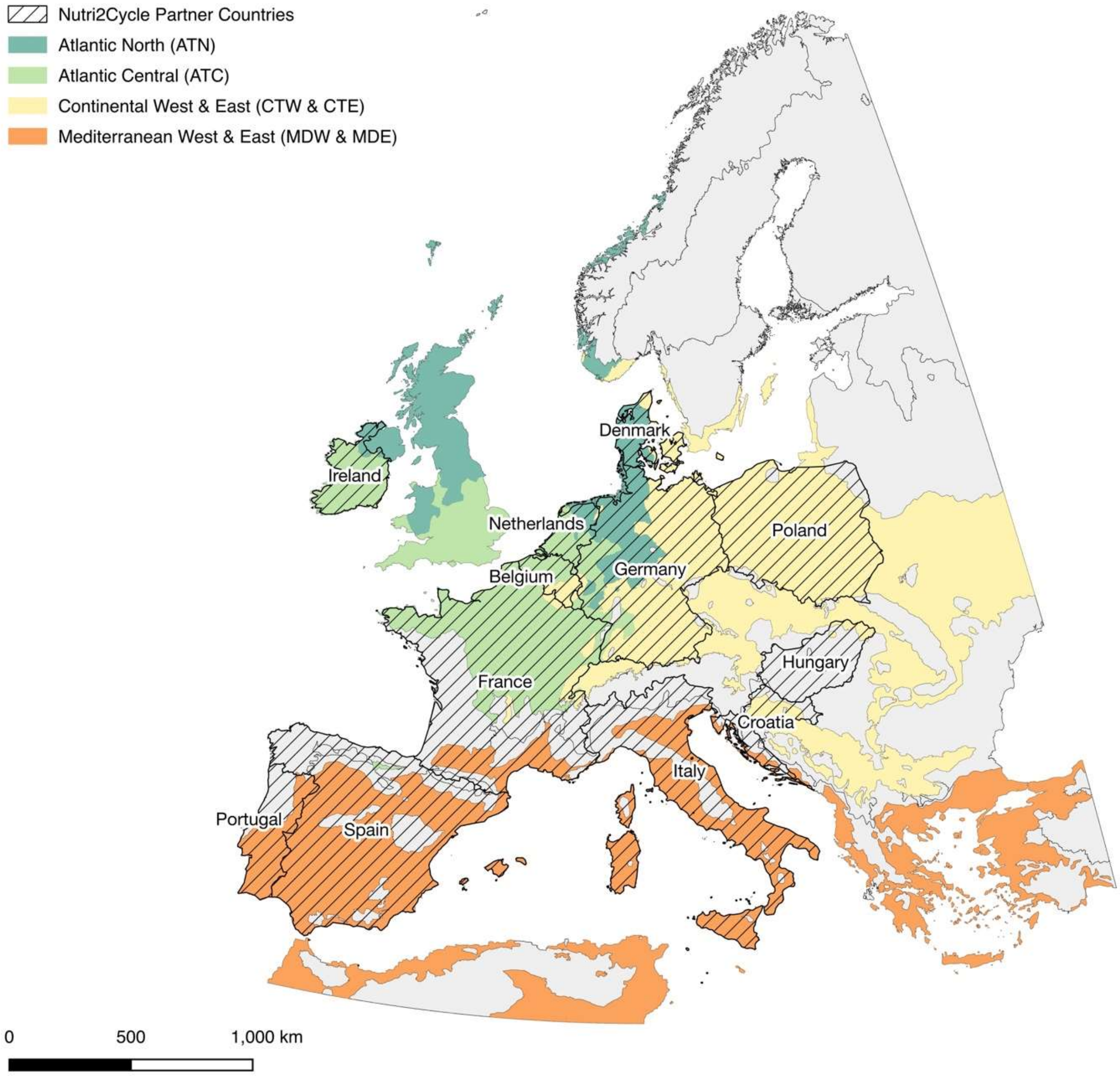

Figure 2.6: Geoclimatic regions selected for baseline scenario modelling, and their coverage of the Nutri2Cycle partner countries.

Finally, for each geoclimatic region, we identified one or two predominant topsoil textures based on Ballabio et al. (2016), and the 25th, 50th, and 75th percentile of topsoil organic carbon content based on data from the LUCAS soil survey and the European Pedotransfer Rules Database (PTRDB). Each baseline scenario will be simulated with corresponding soil texture and the three levels of SOC content in its respective region, so that the simulation results will be able to reflect a wider range of variations in the region, instead of representing only a specific site.

Table 2.1 summarises the selected geoclimatic regions and baseline scenarios. In the following sections, each baseline scenario is characterised in detail.

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Table 2.1: Selected regions and baseline scenarios.

Geoclimatic Region	Atlantic North (ATN)	Atlantic Central (ATC)	Continental West (CTW)	Continental East (CTE)	Mediterranean West (MDW)	Mediterranean East (MDE)
Corresponding EnZ	ATN	ATC	CON	CON	MDS & MDN	MDS & MDN
Coverage of N2C Partner Countries	Western DK Western DE Northern NL	Benelux Northern FR Ireland	Eastern DK	Eastern DE Poland	Spain Portugal	Italy Croatia
Farming Systems	Beef/Dairy Pig	Beef/Dairy Arable	Pig Arable	Pig Arable	Arable (Maize)	Arable (Maize)
Baseline Scenarios	• ATN-Dairy • ATN-Pig	• ATC-Dairy • ATC-Arable	• CTW-Pig • CTW-Arable	• CTE-Pig • CTE-Arable	• MDW-Maize	• MDE-Maize

2.3. Characterisation of baseline scenarios

2.3.1. Atlantic North

The Atlantic North (ATN) region covers the western part of Denmark and Germany, and also part of northern Netherlands. Two baseline scenarios were established (Table 2.2), representing intensive dairy and pig productions, which are common in this region. The field modelling is based on the parameterisation of two hypothetical farms in western Denmark, which have been well modelled and validated in previous studies (Styczen et al., 2004).

Table 2.2: Characterization of the baseline scenarios for the Atlantic North (ATN) region.

	ATN-Dairy	ATN-Pig
Climate	Western Denmark (Foulum)	
Topsoil Texture	Sand (3.9% clay, 6.4% silt, 87.1% sand)	Sandy Loam (8.1% clay, 22.1% silt, 69.8% sand)
Topsoil OC[1]	0.99%, 1.5%, 2.4%	
Fertiliser	Cattle slurry + Mineral N	Pig slurry + Mineral N
Crop Rotation & Fertilisation[2]	- Silage maize (S 125, M 63), - Silage spring barley (S 200, M 33), with undersown ryegrass and white clover (M 67), - Ryegrass & white clover ley (S 200, M 100), - Ryegrass & white clover ley (S 200, M 100), - Ryegrass & white clover ley (S 200, M 100), - Spring barley (S 43, M 22), with undersown ryegrass[3].	- Spring barley (S 101, M 44), - Winter rapeseed (S 150, M 65), - Winter wheat (S 131, M 81), - Winter wheat (S 147, M 65), - Spring barley (S 101, M 44), - Winter barley (S 135, M 59), followed by fodder radish as a winter cover crop[4].
Irrigation	Not irrigated.	Not irrigated.
Drainage	Free drainage.	Tile drainage at 1.2 m depth.

1. The three numbers correspond to the 25th, 50th & 75th percentiles, respectively, of the topsoil organic carbon content in the region.

2. Fertilisation rates (kg N ha^{-1}) are shown in parenthesis following the crop names. S: cattle or pig slurry; M: mineral N fertiliser.

3. Undersown ryegrass is not harvested, and it is left in the field until tillage incorporation in the spring.

4. When used as a winter cover crop, fodder radish is not harvested, and it is left in the field until tillage incorporation in the spring. Fodder radish is simulated as winter rapeseed in both Daisy and SWAP/ANIMO.

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The dairy farm (ATN-Dairy) is located on a sandy-textured soil (JB1 in Danish categorization), and has a 6-year crop rotation consisting of silage and cereal crops, and 3 years of ryegrass and white clover ley. It receives the maximum amount of cattle slurry allowed by the Danish regulations (max. 230 kg total N ha^{-1} $year^{-1}$, a Danish derogation from the EU Nitrates Directive limit of 170 kg N ha^{-1} $year^{-1}$, valid for farms growing more than 80% of the area with roughage crops), and any additional crop N requirement is supplemented with mineral N fertiliser.

The pig farm (ATN-Pig) is situated on a sandy loam soil (JB4 in Danish categorization), and the crop rotation consists of spring and winter cereal crops. It is fertilised with pig slurry to a maximum of 170 kg total N ha^{-1} $year^{-1}$ (according to the EU Nitrates Directive limit), and supplemented with mineral N fertiliser.

2.3.2. Atlantic Central

The Atlantic Central (ATC) region covers most of the Benelux region, part of western Germany, northern and western France, and Ireland. This region, particularly the Benelux area, is characteristic of intensive livestock and arable production. The field modelling of the ATC region is based on conditions of one dairy (Cranendonck) and one arable farm (Vredepeel) in southern Netherlands (Table 2.3).

These two farm sites are selected because they are representative for intensive agricultural practice, and because they have been monitored since the 1990s in terms of fertilization, crop yield, soil composition and soil hydrology. Both sites are located in the sandy region in the south-eastern part of the Netherlands, a region which is quite vulnerable to, and impacted by, agricultural nutrient losses to the environment.

The dairy farm (ATC-Dairy) is located on a sandy-textured soil nearby the village of Cranendonck. It has a 5-year crop-rotation consisting of 4 years of perennial ryegrass for pasture and 1 year of silage maize. The measurements (1997–2012) apply to an experimental plot of 345 m^2 without crop-rotation and with ryegrass only. These measurements include groundwater levels, C-N-P-composition of the upper 30 cm of the soil and the soil water, fertilizer amounts (mineral fertilizer and cattle slurry), grazing (two to three cows during a couple of months in the summer half-year), cutting, and the C-N-P-amount of the grass yield due to cutting and grazing. The field is drained by drainage pipes at a depth of 100 cm, and by ditches. Furthermore, the field receives extra water by sprinkler irrigation during dry summer periods.

The arable farm (ATC-Arable) is located on a sandy soil nearby the village of Vredepeel. It has a 4-year crop-rotation consisting of silage maize, potato, sugar beet and winter wheat. The measurements (1989–2018) include groundwater levels, nitrate concentrations in the upper groundwater, organic matter in the topsoil, fertilizer amounts (mineral fertilizer and pig slurry) and crop yields (dry matter as well as contents of C, N and P). The field is not connected to the surface water and therefore freely drains to the groundwater.

Table 2.3: Characterization of the baseline scenarios for the Atlantic Central (ATC) region.

	ATC-Dairy	ATC-Arable
Climate	South-eastern Netherlands (Cranendonck)	South-eastern Netherlands (Vredepeel)
Topsoil Texture	Loamy Sand (5% clay, 15% silt, 80% sand)	Sand (0% clay, 12% silt, 88% sand)
Topsoil OC[1]	1.7%, 2.2%, 2.9%	
Fertiliser	Cattle slurry + Mineral N	Pig slurry + Mineral N

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	ATC-Dairy	ATC-Arable
Crop Rotation & Fertilisation[2]	- Perennial ryegrass (S 165, M 184), - Perennial ryegrass (S 165, M 184), - Perennial ryegrass (S 165, M 184), - Perennial ryegrass (S 165, M 184), - Silage maize (S 100).	- Silage maize (S 138, M 60), - Potato (S 142, M 140), - Sugar beet (S 142, M 70), - Winter wheat (M 150).
Irrigation	Irrigated during summer.	Not irrigated.
Drainage	Tile drainage at 1 m depth.	Free drainage.

1. The three numbers correspond to the 25th, 50th & 75th percentiles, respectively, of the topsoil organic carbon content in the region.

2. Fertilisation rates (kg N ha^{-1}) are shown in parenthesis following the crop names. S: cattle or pig slurry; M: mineral N fertiliser.

2.3.3. Continental West and East

The Continental West and East regions cover Zealand of Denmark, eastern Germany, and Poland. Pig production is common in this region, where many pig farms rely on a high degree of own-produced cereals (wheat and barley) for feed. The crop rotation and management practices of pig production in these two regions are identical to those of ATN-Pig, but under different climate and on different soils.

The arable production has identical crop rotation to the pig production, except that the arable production receives only mineral N fertilisers without any pig slurry.

Table 2.4: Characterization of the baseline scenarios for the Continental West (CTW) and East (CTE) regions.

	CTW-Pig	CTW-Arable	CTE-Pig	CTE-Arable
Climate	Eastern Denmark (Flakkebjerg)		Central Poland (Warsaw)	
Topsoil Texture	Sandy Loam (12.7% clay, 25.6% silt, 61.7% sand)		Sandy Loam (8.1% clay, 22.1% silt, 69.8% sand)	
Topsoil OC[1]	0.8%, 1.5%, 2.4%		0.9%, 1.2%, 2.0%	
Fertiliser	Pig slurry + Mineral N	Mineral N only	Pig slurry + Mineral N	Mineral N only
Crop Rotation & Fertilisation[2]	- Spring barley (S 101, M 44) - Winter rapeseed (S 150, M 65) - Winter wheat (S 131, M 81) - Winter wheat (S 147, M 65) - Spring barley (S 101, M 44) - Winter barley (S 135, M 59), followed by fodder radish as a winter cover crop[3].	- Spring barley (M 145) - Winter rapeseed (M 215) - Winter wheat (M 212) - Winter wheat (M 212) - Spring barley (M 145) - Winter barley (M 194), followed by fodder radish as a winter cover crop[3].	Same as CTW-Pig.	Same as CTW-Arable.
Irrigation	Not irrigated.			
Drainage	Tile drainage at 1.2 m depth.			

1. The three numbers correspond to the 25th, 50th & 75th percentiles, respectively, of the topsoil organic carbon content in the region.

2. Fertilisation rates (kg N ha^{-1}) are shown in parenthesis following the crop names. S: cattle or pig slurry; M: mineral N fertiliser.

3. When used as a winter cover crop, fodder radish is not harvested, and it is left in the field until tillage incorporation in the spring. Fodder radish is simulated as winter rapeseed in both Daisy and SWAP/ANIMO.

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2.3.4. Mediterranean West and East

A major difference in the Mediterranean to other regions is the climate. The hot, dry Mediterranean summer means that most of the cultivated land must be irrigated. Field crops are the main farming system in this region, with the most common crops being barley, wheat, grass, and olives (Sanchez et al., 2013). Silage maize consists of only 1% of the cultivated area, but is closely linked to livestock production.

The Mediterranean West baseline scenario (MDW-Maize) is based on an arable farm near Girona in north-eastern Spain (Table 2.5). It has an intensified production of continuous silage maize as roughage for neighbouring cattle farms. The site is located on a loamy soil, affluently fertilised (210 kg mineral N fertiliser ha^{-1} year^{-1}), and heavily irrigated (on average 300 mm year^{-1} with an annual rainfall of 650 mm). The soil composition is not measured at the site but is derived from soil databases.

The parameterisation of the Mediterranean East baseline scenario (MDE-Maize) is identical to that of MDW-Maize, except for the climate, which is set to mid-western Italy.

Table 2.5: Characterization of the baseline scenarios for Mediterranean West (MDW) and East (MDE) regions.

	MDW-Maize	MDE-Maize
Climate	North-eastern Spain (Girona)	Mid-western Italy (Rome)
Topsoil Texture	Loam (18% clay, 48% silt, 34% sand)	
Topsoil OC[1]	0.65%, 0.83%, 1.3%	
Fertiliser	Mineral N	
Crop Rotation & Fertilisation[2]	- Continuous silage maize (M 210).	
Irrigation	Irrigated during summer.	
Drainage	Free drainage.	

1. The three numbers correspond to the 25th, 50th & 75th percentiles, respectively, of the topsoil organic carbon content in the region.
2. Fertilisation rates (kg N ha^{-1}) are shown in parenthesis following the crop names. M: mineral N fertiliser.

2.4. Methods for field-level modelling

2.4.1. Model calibration

The goal of model calibration is to fine-tune key process parameters to align the model output with actual field measurements. Data sets available for model calibration include yields of all crops in the rotations from ATN (Denmark), ATC (the Netherlands), and MDW (Spain), and additionally groundwater table from field trials in the Netherlands (for the ATC scenarios).

To ensure that the correct amount of N is taken up by the crops, both the Daisy and SWAP/ANIMO models were first calibrated against dry matter and N yields of crops for all scenarios. For the ATN and CTW/CTE scenarios, the target yields are national averages of respective crops summarised by Danish farming consultant service SEGES. For the ATC and MDW scenarios, yields are obtained from field trials on which the scenarios are based. Approaches for calibration include adjusting the photo synthesis rates, root N uptake rates, partitioning of N among different plant organs, etc. After calibration, the simulated crop yields were generally within ± 10% of the observed or target yields, for both SWAP/ANIMO (Figure 2.7) and Daisy.

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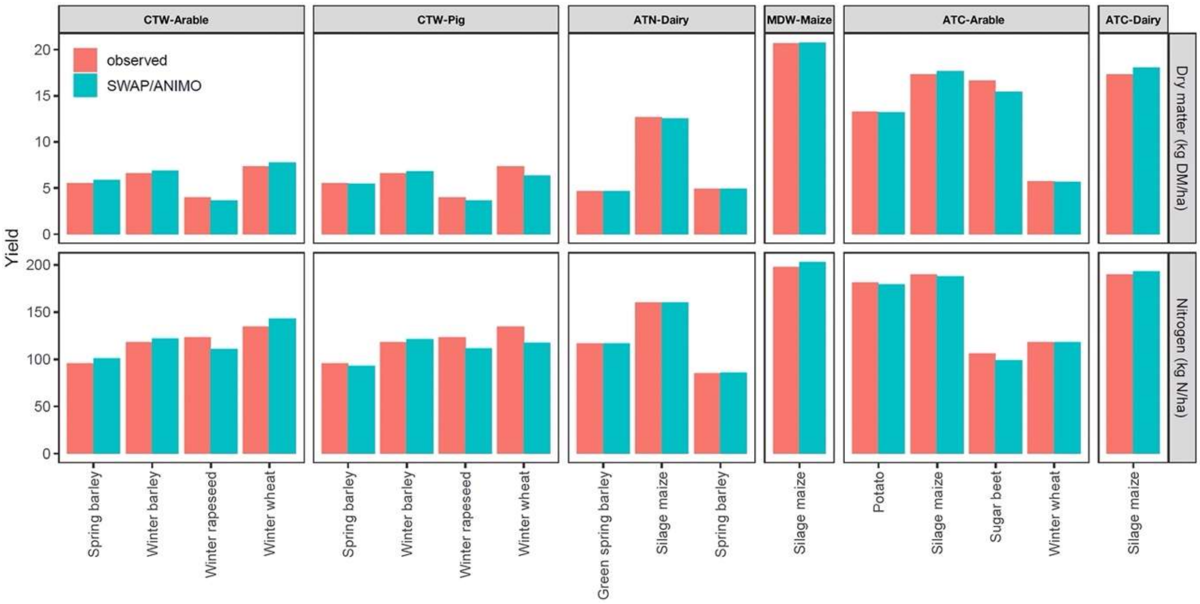

Figure 2.7: Crop dry matter (upper panels) and N yields (lower panels) of six selected scenarios, as simulated by SWAP/ANIMO (blue bars) and compared to observed yields (red bars).

Groundwater levels have an effect on soil water fluxes and thus N transport in soil. For the ATC baseline scenarios where groundwater levels were measured between 1997 and 2011, both Daisy and SWAP/ANIMO were calibrated against the measured groundwater table. After calibration, both models were able to capture the dynamics of groundwater fluxes over the monitoring period, as exemplified for Daisy in Figure 2.8.

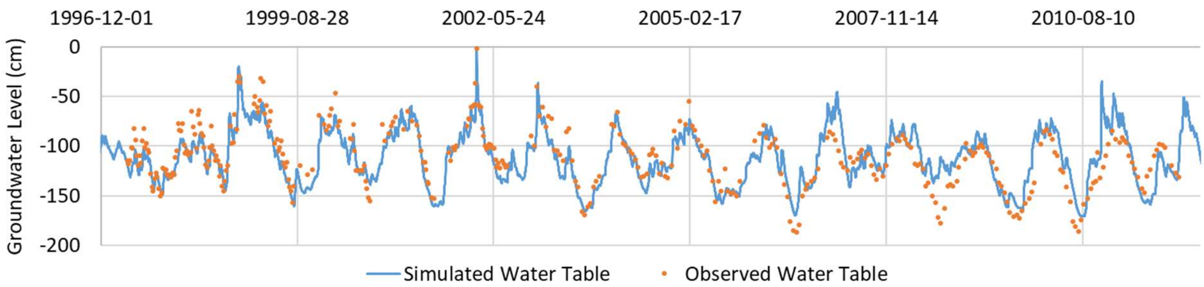

Figure 2.8: Groundwater fluxes simulated by Daisy (line) compared to field measurements (solid circles) of the ATC-Dairy scenario at Cranendonck, NL from 1997 to 2011.

Daisy and SWAP/ANIMO have been used extensively in Denmark and the Netherlands, respectively, and there is substantial accumulated experience with regard to conditions in the two countries and the neighbouring regions. Although model calibration was based on limited data set, we have confidence in the performance of Daisy and SWAP/ANIMO in simulating the selected baseline scenarios. The calibration also showed that the two models are built on the basis of sound physicochemical processes, and therefore should be able to produce reliable results for well characterised systems, even with limited calibration.

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2.4.2. Simulation of CNP flows

Simulation of the baseline scenarios was performed for a period of 60 years, allowing the coverage of complete crop sequences of 4-, 5-, and 6-year rotations. As the 60-year simulation period exceeds the time range of available weather data (approximately 20 years), weather data had to be reused 2 more times after the first 20 years of simulation. For Daisy, year sequences of weather data in the later 40 years were randomized to reduce the occurrences of identical weather-crop combinations. Whereas for SWAP/ANIMO, weather data of the first 20 years were simply repeated two more times to cover the later 40 years, due to difficulties of setting up randomised year sequences.

For both Daisy and SWAP/ANIMO, prior to the simulation period, a "spin-up" period of 30 years was set up with the same crop rotations and field management activities. The estimated annual C inputs from crop residues and roots in this "spin-up" period were used for initialisation of the SOM pool (Bruun & Jensen, 2002).

The ATN-Dairy scenario includes ryegrass and white clover leys where N fixation takes place. The ANIMO model is not able to simulate N-uptake by plants through N-fixation from the air. Therefore, in the ATN-Dairy case, the only baseline case that contains N-fixers in the form of grass-clover ley, we accounted for N-fixation in ANIMO by adding extra N as a fertilizer. The amount of N-fixation was derived from Daisy calculations on ATN-Dairy, indicating that the yearly averaged N-fixation is about 120 kg N ha^{-1} in a year with grass-clover as the main crop (year 3, 4 and 5 of the 6-year crop rotation) and 60 kg N ha^{-1} when grass-clover is undersown and serves as a cover crop (year 2 of the 6-year crop rotation). Half of these yearly N-fixation amounts are added during cutting events. The other half is spread over the days in the period from 1st of June till 1st of October (the growing season) according to the (mean) seasonal temperature, as a proxy for plant growth and associated N-fixation: N-fixation increases (linear) with temperature (in degrees C).

In field trials of the ATC-Dairy and MDW-Maize scenarios, irrigation was performed in drought spells during the summer. However, during simulation over an extended period, it was not possible to perform irrigation on specific days as those in field trials. Therefore, in Daisy, automatic irrigation was activated to apply 30 mm of water over one hour, when soil water pressure dropped below –600 cm in the top 30 cm soil between May and September. In SWAP/ANIMO, the measured irrigation amounts were used.

For analysis of N and P balances at field-scale, the sources of N and P input, output, and stock changes were recorded over the root zone, which is from soil surface to the maximum rooting depth, where relevant biogeochemical processes are most active. In cases where the maximum rooting depth is shallower than the depth of drainage pipes (e.g., ATN-Dairy), the logging depth is extended to at least 50 cm below the drainage depth.

Table 2.6: Capability of Daisy and SWAP/ANIMO to produce output on environmental emissions relevant for life cycle impact assessment (reproduced from Deliverable 1.1).

Nutrient	Emission	Unit	Impact Category	Model Capability	
				Daisy	SWAP/ANIMO
N	N_2O emission to air	kg N ha^{-1} $year^{-1}$	Climate change	●	●
	NH_3 emission to air	kg N ha^{-1} $year^{-1}$	Acidification	●	●
	NO_3^- emission to water	kg N ha^{-1} $year^{-1}$	Eutrophication	●	●
P	Total P emission to water	kg P ha^{-1} $year^{-1}$	Eutrophication		●
C	C sequestration in soil	kg C ha^{-1} $year^{-1}$	Climate change	●	●

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Simulation results of key environmental emissions that are relevant for life cycle impact assessment, as specified in Deliverable 1.1 (Table 2.6), were logged for analysis. Both Daisy and SWAP/ANIMO are capable of simulating C and N losses to surface/groundwater and atmosphere, but P losses can only be simulated by SWAP/ANIMO. Based on the simulated emission results, several environmental indicators, including N use efficiency, eutrophication, acidification, toxicity, etc., were calculated according to Deliverable 1.1.

2.5. Results of simulated CNP flows at field level

The following results are presented: field N balances (section 2.5.1), field P balances (section 2.5.2), long term changes in soil organic C and N (section 2.5.3), and environmental emissions and indicators (section 2.5.4).

2.5.1. Field-level N balances

Table 2.7 summarises the annual inputs, outputs, and stock changes of N at field level. N inputs include: (1) the mineral and organic fractions of fertilisers; (2) atmospheric deposition; (3) N dissolved in irrigation water (or fertigation); and (4) fixation of atmospheric N by leguminous plants. Daisy additionally tracks the small amount of N input from crop seeds. Sources of N output are: (1) losses to ground and surface water via leaching, drainage, and runoff; (2) emissions to atmosphere via volatilisation, nitrification, and denitrification; and (3) N taken up by crops and removed from field during harvest. The N stock in soil and crop biomass remaining in the field can be either increasing (positive value), indicating that the N input is greater than the output, contributing to the build-up of soil N stock; or the stock change can be declining (negative value; input < output), suggesting net mineralisation of soil organic N.

Table 2.7: Annual field N balance simulated by Daisy.

	Source (kg N ha^{-1} year^{-1})	ATN		ATC		CTW		CTE		MDW	MDE
		Dairy	Pig	Dairy	Arable	Pig	Arable	Pig	Arable	Maize	Maize
Input	Fertiliser (mineral fraction)	218.5	182.7	219.3	168.0	182.7	186.5	182.7	186.5	210.0	210.0
	Fertiliser (organic fraction)	91.9	42.4	80.7	42.5	42.4	0.0	42.4	0.0	0.0	0.0
	Deposition	13.2	13.2	25.7	25.7	11.9	11.9	10.5	10.5	15.7	14.1
	Irrigation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.0	8.9
	Plant N fixation	98.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Seed	1.9	4.0	0.5	3.1	4.0	4.0	4.0	4.0	2.0	2.0
	Total Input	**423.4**	**242.2**	**326.2**	**239.2**	**241.0**	**202.4**	**239.6**	**201.0**	**234.8**	**235.0**
Output	Leaching below rootzone	131.4	60.0	24.0	71.6	35.5	24.8	55.8	42.4	34.7	29.7
	NH_3 Volatilization	22.0	19.8	5.9	4.6	19.8	2.4	19.8	2.4	2.7	2.7
	N_2O by Nitrification	9.2	4.7	7.1	4.5	5.0	3.6	5.0	3.6	3.2	3.3
	N_2O and N_2 by Denitrification	0.3	3.9	14.3	10.5	9.3	8.5	1.1	0.9	15.7	15.5
	Removal by harvest	246.3	157.9	275.2	170.3	173.8	168.6	163.7	159.5	187.6	190.6
	Total Output	**409.2**	**246.2**	**326.5**	**261.4**	**243.5**	**207.8**	**245.4**	**208.8**	**243.8**	**241.7**

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	Source (kg N ha⁻¹ year⁻¹)	ATN		ATC		CTW		CTE		MDW	MDE
		Dairy	Pig	Dairy	Arable	Pig	Arable	Pig	Arable	Maize	Maize
Stock Change	Soil mineral N stock	-0.7	1.1	0.9	0.0	2.3	2.0	-3.8	-2.9	0.3	0.1
	Soil organic N stock	16.1	-4.1	-1.1	-22.4	-3.7	-6.2	-0.5	-3.4	-9.3	-6.8
	N in crop residues	-1.3	-1.0	-0.1	0.2	-1.2	-1.2	-1.5	-1.5	0.0	0.0
	Total Stock Change	**14.2**	**-4.0**	**-0.3**	**-22.3**	**-2.5**	**-5.4**	**-5.8**	**-7.8**	**-9.1**	**-6.7**

ATN: Atlantic North; ATC: Atlantic Central; CTW: Continental West; CTE: Continental East; MDW: Mediterranean West; MDE: Mediterranean East.

Table 2.8: Annual field N balance simulated by SWAP/ANIMO.

	Source (kg N ha⁻¹ year⁻¹)	ATN	ATC		CTW		MDW
		Dairy	Dairy	Arable	Pig	Arable	Maize
Input	Fertiliser (mineral fraction)	235.3	216.5	168.2	187.2	187.2	210.5
	Fertiliser (organic fraction)	92.2	83.5	42.7	42.5	0.0	0.0
	Deposition	13.0	25.6	25.8	12.0	12.0	14.7
	Irrigation	0.0	0.0	0.0	0.0	0.0	6.2
	Plant N fixation	70.0	0.0	0.0	0.0	0.0	0.0
	Seed	0.0	0.0	0.0	0.0	0.0	0.0
	Total Input	**410.5**	**325.6**	**236.6**	**241.7**	**199.2**	**231.5**
Output	Leaching below rootzone	98.2	32.6	30.6	9.6	4.3	63.5
	NH_3 Volatilization	23.4	5.7	4.7	20.7	4.9	4.5
	N_2O by Nitrification	4.4	3.9	2.4	2.1	1.4	0.7
	N_2O and N_2 by Denitrification	24.2	45.9	59.0	22.4	15.7	0.1
	Removal by harvest	217.9	240.8	190.4	194.4	200.4	202.5
	Total Output	**368.0**	**328.8**	**287.2**	**249.2**	**226.7**	**271.3**
Stock Change	Soil mineral N stock	-3.7	-1.9	-0.7	-0.4	-0.8	-0.2
	Soil organic N stock	46.2	-1.4	-49.9	-7.1	-26.8	-39.6
	N in crop residues	/	/	/	/	/	/
	Total Stock Change	**42.5**	**-3.3**	**-50.5**	**-7.5**	**-27.6**	**-39.8**

ATN: Atlantic North; ATC: Atlantic Central; CTW: Continental West; MDW: Mediterranean West. Scenarios in the CTE and MDE regions were not modelled in SWAP/ANIMO.

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2.5.2. Field-level P balances

P balance was calculated in a similar way to the calculation of N balances. Since Daisy is incapable of tracking P flows, P balance results are only available from SWAP/ANIMO. At this stage, there were not enough data on the soil-P status to set up the P balance for the Spanish scenario.

Table 2.9: Annual field P balance simulated by SWAP/ANIMO.

<table>
<tr><th rowspan="2"></th><th rowspan="2">Source
(kg N ha^{-1} $year^{-1}$)</th><th>ATN</th><th colspan="2">ATC</th><th colspan="2">CTW</th><th>MDW</th></tr>
<tr><th>Dairy</th><th>Dairy</th><th>Arable</th><th>Pig</th><th>Arable</th><th>Maize</th></tr>
<tr><td rowspan="5">Input</td><td>Fertiliser
(mineral fraction)</td><td>38.6</td><td>53.0</td><td>32.3</td><td>39.1</td><td>0.0</td><td rowspan="12">P flows were not simulated because there is not enough data on soil P status to set up a reliable model.</td></tr>
<tr><td>Fertiliser
(organic fraction)</td><td>9.2</td><td>8.4</td><td>5.5</td><td>6.2</td><td>0.0</td></tr>
<tr><td>Deposition</td><td>1.8</td><td>2.3</td><td>2.3</td><td>1.6</td><td>1.6</td></tr>
<tr><td>Irrigation</td><td>0.0</td><td>0.0</td><td>0.0</td><td>0.0</td><td>0.0</td></tr>
<tr><td>Total Input</td><td>49.6</td><td>63.7</td><td>40.2</td><td>46.9</td><td>1.6</td></tr>
<tr><td rowspan="3">Output</td><td>Leaching below rootzone</td><td>1.1</td><td>0.1</td><td>0.6</td><td>0.1</td><td>0.1</td></tr>
<tr><td>Removal by harvest</td><td>18.0</td><td>33.9</td><td>19.3</td><td>22.3</td><td>26.4</td></tr>
<tr><td>Total Output</td><td>19.0</td><td>34.0</td><td>19.9</td><td>22.4</td><td>26.5</td></tr>
<tr><td rowspan="3">Stock Change</td><td>Soil mineral P stock</td><td>25.9</td><td>29.9</td><td>27.2</td><td>25.2</td><td>-22.3</td></tr>
<tr><td>Soil organic P stock</td><td>4.7</td><td>-0.2</td><td>-6.9</td><td>-0.7</td><td>-2.7</td></tr>
<tr><td>Total Stock Change</td><td>30.6</td><td>29.7</td><td>20.3</td><td>24.5</td><td>-24.9</td></tr>
</table>

ATN: Atlantic North; ATC: Atlantic Central; CTW: Continental West; MDW: Mediterranean West. Scenarios in the CTE and MDE regions were not modelled in SWAP/ANIMO.

2.5.3. Long-term soil organic carbon and nitrogen changes

Figure 2.9 and Figure 2.10 show the simulated long-term changes in soil organic carbon (SOC) and nitrogen (SON) content over a period of 60 years. In most scenarios, there is a decline in SOC and SON over the years. However, dairy farming systems with grass leys (ATN-Dairy and ATC-Dairy) are good at maintaining or building up soil organic matter. Field-application of manure/slurry is also beneficial to soil quality in terms of organic matter build-up, as shown by the slower decline in SOC/SON as compared to scenarios receiving only mineral fertiliser (e.g., CTW-Pig vs. CTW-Arable).

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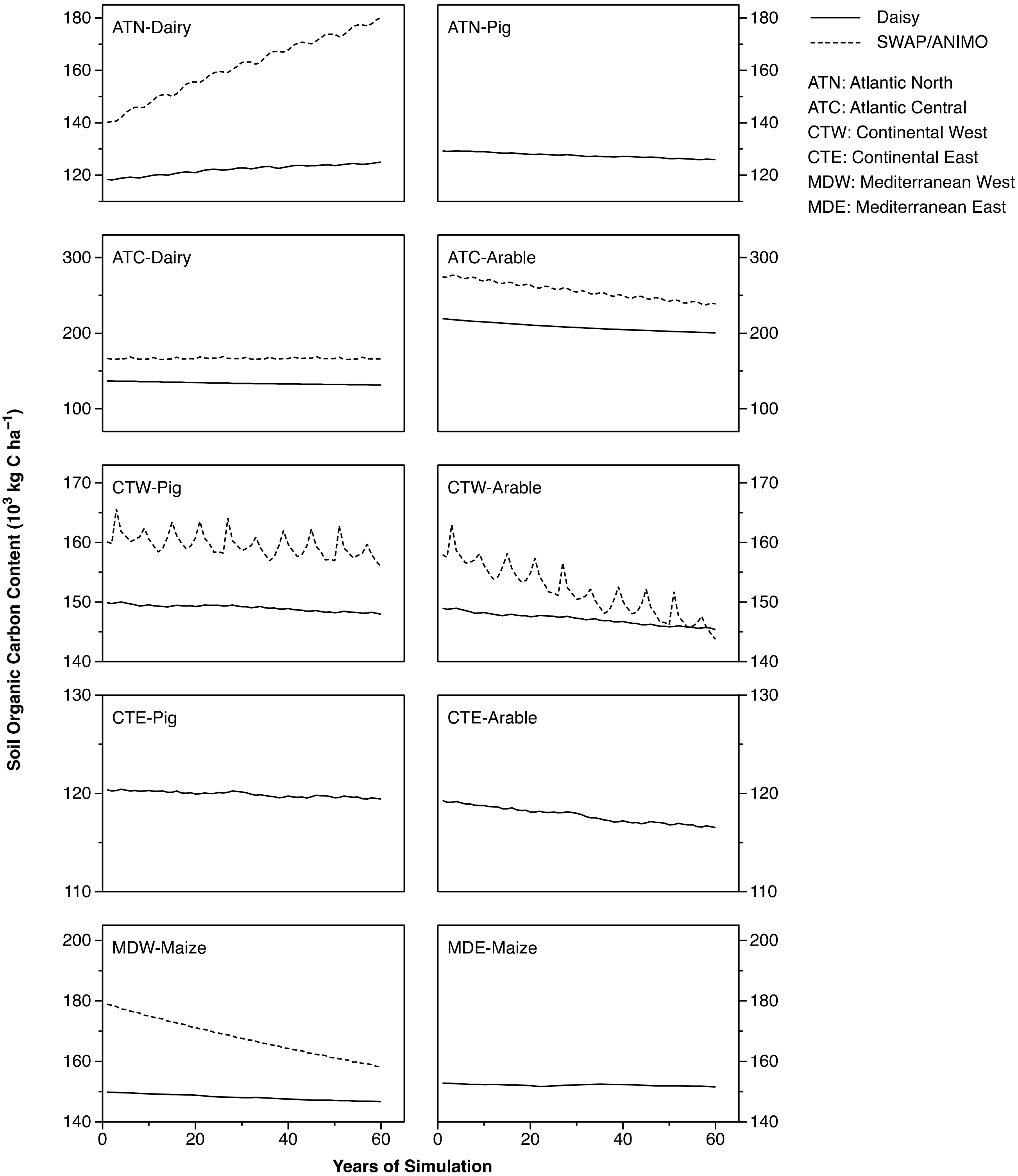

Figure 2.9: Soil organic C change in the logging depth over 60 years simulated by Daisy (solid line) and SWAP/ANIMO (dashed line). Changes were logged over the root zone, or 50 cm below the drain depth, whichever is deeper.

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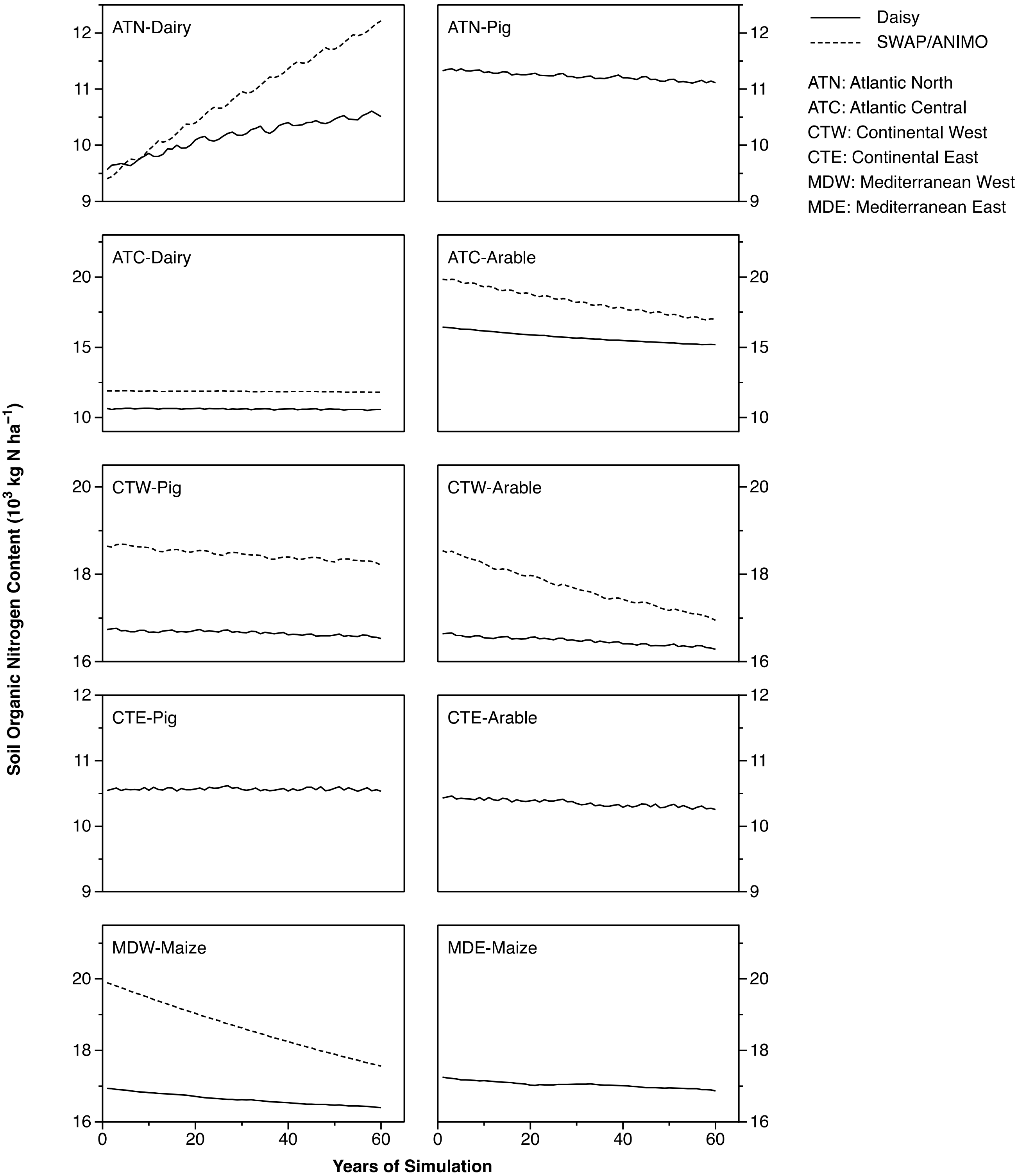

Figure 2.10: Soil organic N change in the logging depth over 60 years by simulated Daisy (solid line) and SWAP/ANIMO (dashed line). Changes were logged over the root zone, or 50 cm below the drain depth, whichever is deeper.

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2.5.4. Environmental emissions and indicators

Table 2.10 and Table 2.11 shows environmental emissions of N, P, and C, simulated by Daisy and SWAP/ANIMO. Values are averaged over the simulation period of 60 years. The N_2O emissions to air include N_2O from both nitrification and denitrification. Daisy is able to simulate denitrification, however, emission is reported as collective denitrification emission ($N_2O + N_2$). The N_2O emission from denitrification is estimated by assuming a N_2/N_2O ratio of 4 (Vinther & Hansen, 2004). For SWAP/ANIMO, the N_2O emission is estimated from the calculated amount of denitrification and nitrification, assuming that 3.5% of denitrified N is N_2O-N, and 1.3% of nitrified N is N_2O-N, which is within the range of reported values for sandy and loamy soils in temperate climate regions (de Vries et al., 2003). Based on these simulated emissions, a set of environmental indicators were calculated in Table 2.12.

Table 2.10: Environmental emissions simulated by Daisy.

	Emissions (kg N, or C ha^{-1} year^{-1})	ATN		ATC		CTW		CTE		MDW	MDE
		Dairy	Pig	Dairy	Arable	Pig	Arable	Pig	Arable	Maize	Maize
N	N_2O emission to air	9.3	5.4	9.9	6.6	6.9	5.3	5.2	3.7	5.9	6.4
	NH_3 emission to air	21.7	19.8	5.4	4.5	19.8	2.3	19.8	2.3	2.6	2.6
	NO_3^- emission to water	130.9	60.0	24.4	71.0	35.4	24.7	55.8	42.4	28.4	29.7
C	Soil C sequestration	107.2	-56.1	-88.7	-312.9	-34.2	-61.8	-16.3	-46.6	-53.9	-23.2

ATN: Atlantic North; ATC: Atlantic Central; CTW: Continental West; CTE: Continental East; MDW: Mediterranean West; MDE: Mediterranean East.

Table 2.11: Environmental emissions simulated by SWAP/ANIMO.

	Emissions (kg N, P, or C ha^{-1} year^{-1})	ATN	ATC		CTW		MDW
		Dairy	Dairy	Arable	Pig	Arable	Maize
N	N_2O emission to air	5.4	5.7	4.5	3.0	2.0	0.7
	NH_3 emission to air	23.4	5.7	4.7	20.7	4.9	4.5
	NO_3^- emission to water	90.8	28.6	28.9	8.9	3.8	62.9
P	Total P emission to water	1.1	0.1	0.6	0.1	0.1	/
C	Soil C sequestration	672.3	29.3	-644.5	-59.9	-229.4	-349.8

ATN: Atlantic North; ATC: Atlantic Central; CTW: Continental West; MDW: Mediterranean West. Scenarios in the CTE and MDE regions were not modelled in SWAP/ANIMO.

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Table 2.12: Environmental indicators calculated from Daisy and SWAP/ANIMO simulation results.

Model	Environmental Indicator	ATN		ATC		CTW		CTE		MDW	MDE
		Dairy	Pig	Dairy	Arable	Pig	Arable	Pig	Arable	Maize	Maize
Daisy	N use efficiency	0.6	0.7	0.9	0.8	0.8	0.9	0.7	0.8	0.9	0.9
	Eutrophication, marine (kg N eq ha^{-1})	134.2	62.4	24.7	72.2	37.9	25.1	58.2	42.7	35.0	30.1
	Eutrophication, terrestrial (kg N eq ha^{-1})	1937.9	928.5	361.8	1022.3	586.1	357.9	869.8	604.2	497.5	428.1
	Acidification (mol H^+ eq ha^{-1})	67.4	60.8	34.2	26.6	60.7	7.3	62.3	7.4	0.3	0.4
	Ecotoxicity, freshwater (CTUe ha^{-1}) [1]	3860.1	3480.4	1042.4	808.6	3478.7	416.6	3476.9	413.1	472.8	467.6
	Human toxicity, non-cancer (CTUh ha^{-1}) [2]	4.4E-08	4.0E-08	1.2E-08	9.2E-09	4.0E-08	4.7E-09	3.9E-08	4.7E-09	5.4E-09	5.3E-09
	Human toxicity, non-cancer, inorganics (CTUh ha^{-1})	3.8E-07	3.4E-07	1.0E-07	8.0E-08	3.4E-07	4.1E-08	3.4E-07	4.1E-08	4.7E-08	4.6E-08
	Particulate matter (kg PM_{10} eq ha^{-1})	6.0E-04	5.4E-04	1.6E-04	1.3E-04	5.4E-04	6.5E-05	5.4E-04	6.5E-05	7.4E-05	7.3E-05
	Global warming[1] (kg CO_2 eq ha^{-1})	4354.1	2544.7	4655.7	3078.5	3234.9	2465.1	2450.1	1749.5	2955.8	2979.2
SWAP/ ANIMO	N use efficiency	0.6	/	0.8	0.9	0.9	1.1	/	/	1.0	/
	Eutrophication, marine (kg N eq ha^{-1})	101.1	/	33.3	31.2	12.1	3.7	/	/	64.1	/
	Eutrophication, terrestrial (kg N eq ha^{-1})	1479.6	/	481.3	449.8	227.6	66.2	/	/	908.7	/
	Acidification (mol H^+ eq)	71.7	/	32.7	27.3	63.6	15.1	/	/	0.4	/
	Ecotoxicity, freshwater (CTUe ha^{-1})	4104.5	/	994.9	831.4	3640.4	866.6	/	/	791.0	/
	Human toxicity, non-cancer (CTUh ha^{-1})	4.7E-08	/	1.1E-08	9.4E-09	4.1E-08	9.8E-09	/	/	9.0E-09	/
	Human toxicity, non-cancer, inorganics (CTUh ha^{-1})	4.0E-07	/	9.8E-08	8.2E-08	3.6E-07	8.5E-08	/	/	7.8E-08	/
	Particulate matter (kg PM_{10} eq ha^{-1})	6.4E-04	/	1.6E-04	1.3E-04	5.7E-04	1.4E-04	/	/	1.2E-04	/
	Global warming[3] (kg CO_2 eq ha^{-1})	4301.7	/	6143.0	6648.7	3089.7	2114.8	/	/	1785.1	/

ATN: Atlantic North; ATC: Atlantic Central; CTW: Continental West; CTE: Continental East; MDW: Mediterranean West; MDE: Mediterranean East. Scenarios in the CTE and MDE regions were not modelled in SWAP/ANIMO.

1. CTUe: Comparative Toxic Unit for ecosystems.

2. CTUh: Comparative Toxic Unit for humans.

3. The global warming indicator only includes the contribution of N (N_2O) emissions, not CO_2 emissions.

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2.6. Discussion

2.6.1. Comparison of simulation results to field observations

It is important to validate model simulation results against actual observations. However, only three of the baseline scenarios (ATC-Dairy, ATC-Arable, and MDW-Maize) were based on actual field trials. Moreover, the lack of data on N_2O emissions or N leaching from the Dutch and Spanish field experiments make it impossible to validate the simulation results on the most important N dynamics. Therefore, we instead choose to compare our simulation results against other studies with similar environmental variables and field practices. The following discussion compares baseline simulation results with field studies from corresponding regions, whereas a more detailed characterisation of regional emissions will be laid out in chapter 3.

Schelde et al. (2012) reported N_2O emissions, and the emission/N-input ratios (in parenthesis), from two Danish arable farms to be 5.5 kg N ha^{-1} $year^{-1}$ (2.5%) and 17.5 kg N ha^{-1} $year^{-1}$ (7.7%), respectively. The two farms are located on sandy loam soils, cultivated with cereal crops and oilseed rape, and fertilised with similar amounts of manure and mineral N fertilisers as the CTW scenarios. The simulated N_2O emissions for the CTW-Pig scenario by Daisy is 6.9 kg N ha^{-1} $year^{-1}$ with an emission/N-input ratio of 3.1%, which is comparable to the field observations. The SWAP/ANIMO results are 3.0 kg N ha^{-1} $year^{-1}$ and 1.3%, which are in the lower end of the range of observations. N_2O emissions from grassland on Dutch mineral soils is expected to be about 0.5% to 2.0% from the total N input, as derived from Dutch experiments (Velthof and Mosquera, 2011). For the ATC-Dairy case with a total N-input of about 300 kg N ha^{-1} $year^{-1}$, this amounts to a N_2O emission of 1.5 to 6.0 kg N_2O-N ha^{-1} $year^{-1}$. The simulated N_2O emission by SWAP/ANIMO (5.7 kg N_2O-N ha^{-1} $year^{-1}$) was fairly within this range, but the results by Daisy (9.9 kg N_2O-N ha^{-1} $year^{-1}$) was 65% higher than the upper bound.

N leaching from sandy loam soils cultivated with spring and winter cereals in Denmark, which are similar to the settings of the ATN-Pig and the CTW scenarios, was between 15 and 36 kg N ha^{-1} $year^{-1}$ (Jabloun et al., 2015; Knudsen et al., 2006). The N leaching of the CTW scenarios simulated by Daisy (25 and 35 kg N ha^{-1} $year^{-1}$) were well within the reported range, whereas the ATN-Pig scenario had a much higher leaching (60 kg N ha^{-1} $year^{-1}$), possibly due to a topsoil texture with higher composition of sand that is more prone to leaching. However, the N leaching of CTW scenarios simulated by SWAP/ANIMO (4.3 and 9.6 kg N ha^{-1} $year^{-1}$) was significantly lower than those reported due to the high crop uptake. In the Netherlands, the N leaching and the associated nitrate concentration in the shallow groundwater have been monitored since 1992 at about 450 agricultural sites (Fraters et al. 2002). According to these measurements, the nitrate concentration of the soil water that leaches to the groundwater is about 40 to 80 mg NO_3 L^{-1} for grassland on sandy soils, associated with a N leaching of about 20 to 50 kg N ha^{-1} $year^{-1}$. The model results for the ATC-Dairy case are well within this reported range, as SWAP/ANIMO predicted an N leaching of 33 kg N ha^{-1} $year^{-1}$, and Daisy simulated an N leaching of 24 kg N ha^{-1} $year^{-1}$.

2.6.2. Comparison of simulation results from Daisy and SWAP/ANIMO

Efforts were made to simulate the scenarios in Daisy and SWAP/ANIMO with identical initial conditions. However, due to differences in the internal mechanisms of the modelling tools and their respective data requirements, variations in simulation results do exist.

Theoretically, the estimation of N input by Daisy and SWAP/ANIMO should be the same. While this is generally the case, some slight discrepancies are observed in the simulation results (Table 2.7 and Table 2.8). Firstly, SWAP/ANIMO does not consider N input from crop seeds, though this only accounts for an insignificant fraction of N input. Secondly, the minor difference in N from irrigation could be ascribed to different amount of water applied, as Daisy and SWAP/ANIMO adopted different irrigation schemes during the simulation. Finally,

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differences in atmospheric N deposition could occur when Daisy and SWAP/ANIMO simulations were run with different weather sequences (as mentioned in the section 2.4.2).

After calibration, the estimated crop dry matter and N yields by both Daisy and SWAP/ANIMO were similar and correspond well to the target yields. However, there is often a 20–30 kg N ha^{-1} difference in harvest removal between Daisy and SWAP/ANIMO results. This discrepancy is likely due to the differences of the two models in partitioning of N into crop parts such as stems and leaves, which are removed as part of harvest but do not count as yields (refer only to the storage organ for non-silage crops). This also indicates that N contents in crop residues estimated by the two models are different, and as a consequence this would lead to some differences in predicted N leaching and SON turnover. To correct for this discrepancy, detailed calibration of crop modules for the two models is needed, however, that is beyond the scope of this project.

The differences in simulated N output between Daisy and SWAP/ANIMO are mainly in denitrification and N leaching. SWAP/ANIMO almost consistently estimated higher denitrification than Daisy, except for the MDW-Maize scenario. With regard to N leaching, Daisy predicted higher leaching in ATN-Dairy, ATC-Arable, and CTW-Pig/Arable scenarios than SWAP/ANIMO, whereas the estimated leaching for the CTW scenarios by SWAP/ANIMO (4–10 kg N ha^{-1} year^{-1}) were probably too low. Some of these differences may be explained by different mechanisms of the two models in estimating soil organic matter mineralisation and immobilisation, such as the MDW-Maize case, where the higher leaching simulated by SWAP/ANIMO was corroborated by the higher amount of decline in the SON stock. However, this explanation is not valid to the other cases. These differences in simulated data suggest that the two models handle soil N and organic matter turnover differently, and careful investigation is still needed to validate their accuracy with respect to realistic environmental emissions when evaluating a specific shortlisted solution. Nonetheless, the differences in most of the simulation results between Daisy and SWAP/ANIMO are well within the margin of error.

2.6.3. Conclusions

Six geoclimatic regions and ten baseline scenarios were selected as field-level modelling baselines to represent typical European agricultural production. These baseline scenarios include dairy, pig, and arable farming systems, and cover wide geoclimatic regions from the Nordic to the Mediterranean, and from the Atlantic to Central Europe. The CNP flows and calculated environmental indicators in the baseline scenarios will form the benchmark for evaluation of the environmental performances of shortlisted solutions at field-level.

The baseline scenarios were simulated using field-level modelling tools, i.e., Daisy and SWAP/ANIMO. The presented results on field CNP flows showed that both models are capable of simulating field-level environmental emissions and nutrient balances. Despite some differences in the simulated data between the two models, the simulated results are generally comparable to field observations. The use of two different models to simulate the baselines can also reduce the risk of modelling error or significant deviation in results than a single model approach.

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3. Integrated assessment of CNP flows in farming systems at regional and national levels

3.1. Introduction

Analysing the CNP flows at regional and national scale for all EU member countries gives a complete overview of the current situation and major losses in the CNP cycles. This baseline assessment can be used as a starting point for the analysis of innovations that enhance circular agriculture. In WP3 the solutions developed in Nutri2Cycle will be assessed at field scale with detailed process models (Chapter 2) and using LCA approaches. In addition, the impact of the solutions when implemented at regional scale will also be assessed. For this regional assessment, the deterministic and static model MITERRA-Europe will be used. First the model is used to assess the current situation on CNP flows in EU agriculture and provide the baseline against which the solutions can be tested.

This Chapter starts with a literature review of EU wide studies that assessed nitrogen, phosphorus or carbon balances, flows and stocks in EU agriculture. This provides a first overview on CNP cycling in agriculture and also serves as a kind of verification of the results of the MITERRA-Europe model. Section 3.3 and 3.4 describe the MITERRA-Europe model and the data sets that have been used. Finally in section 3.5 the results are presented as tables and graphs at EU or country level, and also spatially explicit results at NUTS2 (comparable to provinces) level will be presented.

3.2. Literature review on CNP flows and balances in Europe

3.2.1. Nitrogen flows and balances

Various studies on N flows in Europe have been performed in the past two decades, using different indicators (e.g., Nitrogen Use Efficiency (NUE) or Relative Nitrogen Efficiency (RNE)), models (e.g., Capri, MITERRA-Europe and IMAGE) and input data. All flows and budgets in these studies are based on data from pre-2010. No articles have been published with more recent data on N flows in Europe to the best of our knowledge. The most recent study on this topic was published by Godinot et al. (2016), which averaged data for the years 2000 to 2008. An overview of relevant studies, i.e., peer-reviewed studies, concerning N flows or budgets in Europe published in the past decade, is provided in Table 3.1. Westhoek et al. (2014) provide a nice overview of the different N flows of the EU food system (Figure 3.1). Sutton et al. (2011) provide in the European Nitrogen Assessment a very complete overview of the nitrogen sources, effects and policy perspective, with an example of the nitrogen inputs to the soil illustrated in Figure 3.2.

Table 3.1: The main nitrogen flows as reported in various studies of the past decade.

Study	Godinot et al., 2016 [1]	Westhoek et al., 2014	Leip et al., 2013	de Vries et al., 2011 [2]	Sutton et al., 2011	Leip et al., 2011
Scale	EU27	EU27	EU25 [3]	EU25 / EU27	EU27	EU27
Reference year	Average of 2000-2008	2004	2004	2000	2002	2002
Total N input/year	N.A.	17.7 [4] Tg	21.2 Tg	23.3–25.7 Tg	25.5 Tg	27.8 Tg

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Study	Godinot et al., 2016 [1]	Westhoek et al., 2014	Leip et al., 2013	de Vries et al., 2011 [2]	Sutton et al., 2011	Leip et al., 2011
Mineral fertiliser N input/year	60 kg N ha^{-1}	11.3 Tg	10.9 Tg	11.3–11.5 Tg	11.4 Tg	N.A.
Manure input (to soil)	N.A.	8.0 Tg	7.2 Tg	8.8–10.4 Tg	7.07 Tg	N.A.
Feed import	32 kg N ha^{-1}	2.5 Tg	2.7 Tg	N.A.	N.A.	N.A.
Atmospheric deposition	11 kg N ha^{-1}	3.2 Tg	2.1 Tg	2.0–2.8 Tg	2.06 Tg	N.A.
Biological N fixation	7 kg N ha^{-1}	0.7 Tg	1.0 Tg	0.8–1.4 Tg	1.0 Tg	N.A.
Animal output	N.A.	2.2 Tg	2.7 Tg	N.A.	N.A.	N.A.
Crop N output/year	N.A.	11.4 Tg	11.3 Tg	Net N uptake 11.3–15.4 Tg	11.7 Tg	17.6 Tg
Losses to the environment	N.A.	13.2 Tg	11.5 Tg	N.A.	11.9 Tg	10.1 Tg
NUE	35%	22%	N.A.	N.A.	N.A.	31% (farm) 65% (soil)

1. Per hectare agricultural area. Other indicators information available. Both animal output and crop output information are available, but these are referring to final animal and crop output, without considering the internal feed flows.

2. Evaluation with several models, i.e., INTEGRATOR, IDEAg, MITERRA and IMAGE.

3. EU25: EU27 without Malta and Cyprus.

4. Sum of feed import, fertiliser, fixation, and deposition.

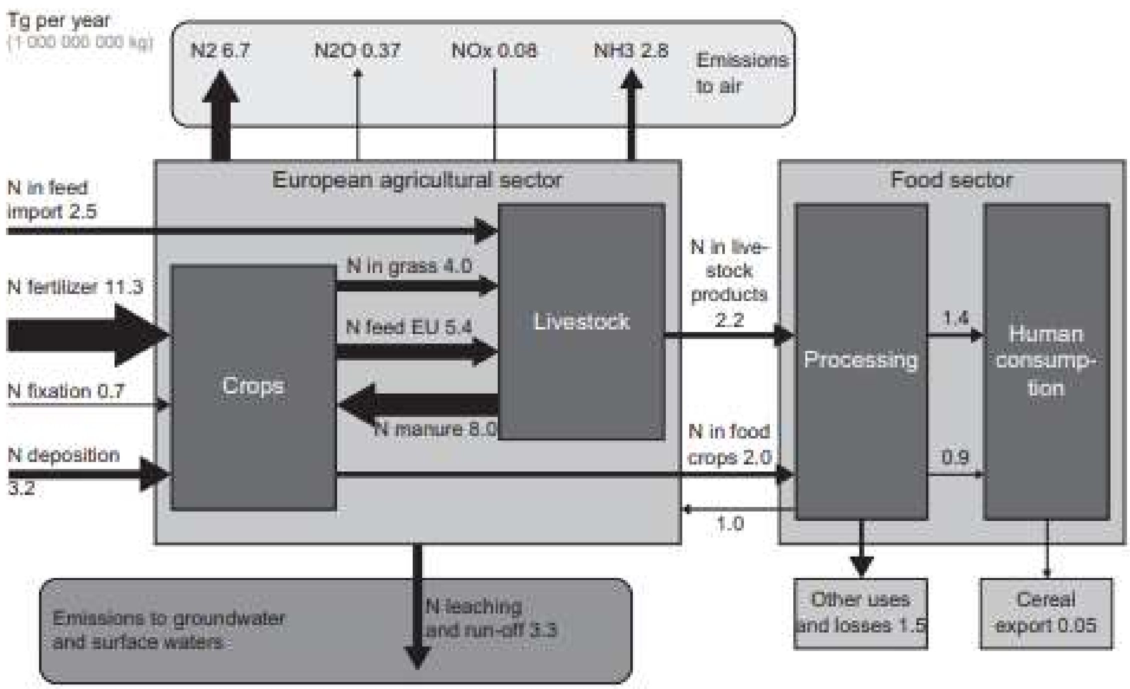

Figure 3.1: Nitrogen flows (in Tg N) in European agriculture in 2004 (Westhoek et al., 2014).

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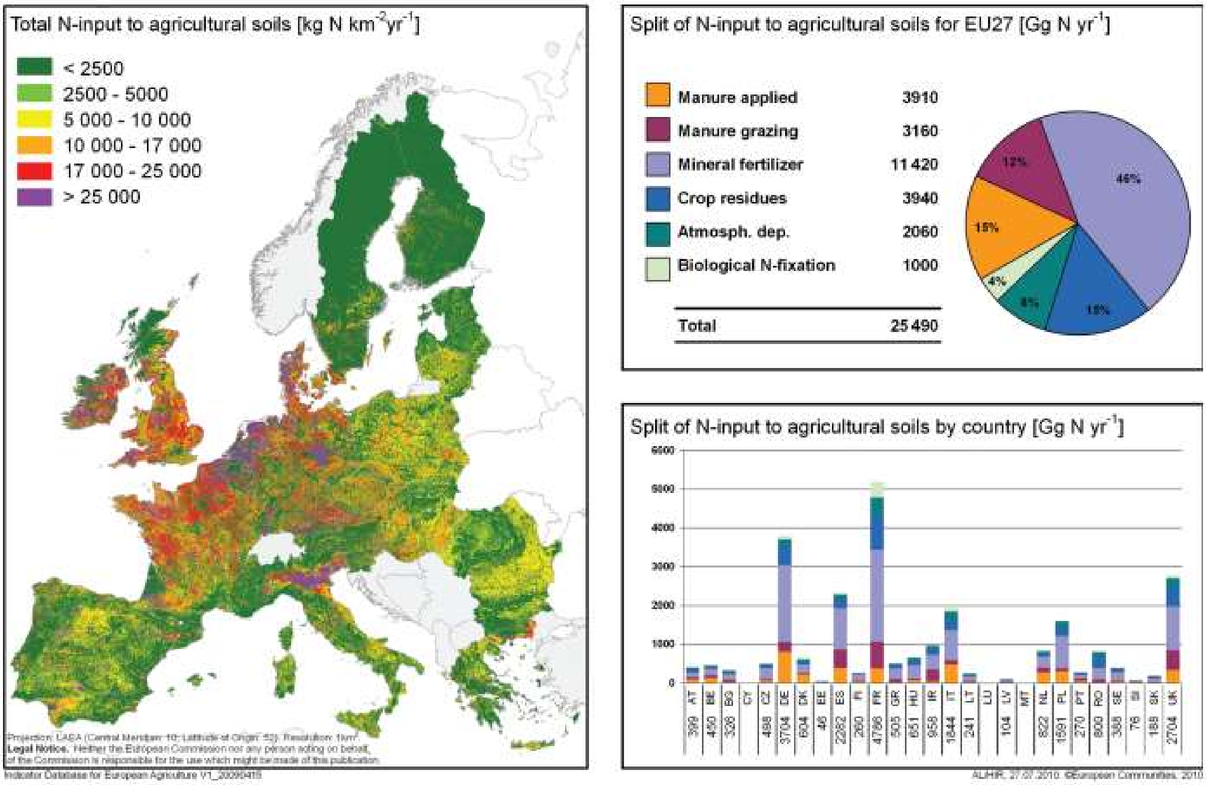

Figure 3.2: Nitrogen input to agricultural soils in EU27 for the year 2002, spatial distribution and the source of the N inputs is provided (Sutton et al., 2011).

Based on data of 2005, central and eastern European countries had negative N and P balances and decreased their N and P soil status, whereas in general the EU-15 countries had a strong positive N and P balance, with an oversupply of N and P that could lead to environmental and ecological threats. This oversupply, however, was on the decline for many of these countries (Csathó & Radimszky, 2009). The nitrogen surplus was on average 55 kg ha^{-1} year^{-1} for soils and 67 kg ha^{-1} year^{-1} for farms in 2002 according to Leip et al. (2011). This surplus was particularly high (> 300 kg ha^{-1} year^{-1}) for countries with a high livestock density, such as the Netherlands and Malta (Leip et al., 2011). For these countries, the feed import was also reported to be high: for the average of 2000-2008, feed import (per hectare of agricultural land) was highest for Cyprus, the Netherlands and Malta (Godinot et al., 2016).

3.2.2. Phosphorus flows and balances

Two recent studies provided an elaborate overview of the flows of P in European agriculture (Ott & Rechberger, 2012; van Dijk et al., 2016), based on the EU-15 and the EU-27 countries, respectively. Flow diagrams of both are provided in Figure 3.3 and Figure 3.4. For seven countries of the EU (Austria, Germany, France, the Netherlands, Sweden, Switzerland, and the United Kingdom), Jedelhauser and Binder (2015) provide a separate P flow chart (not shown here).

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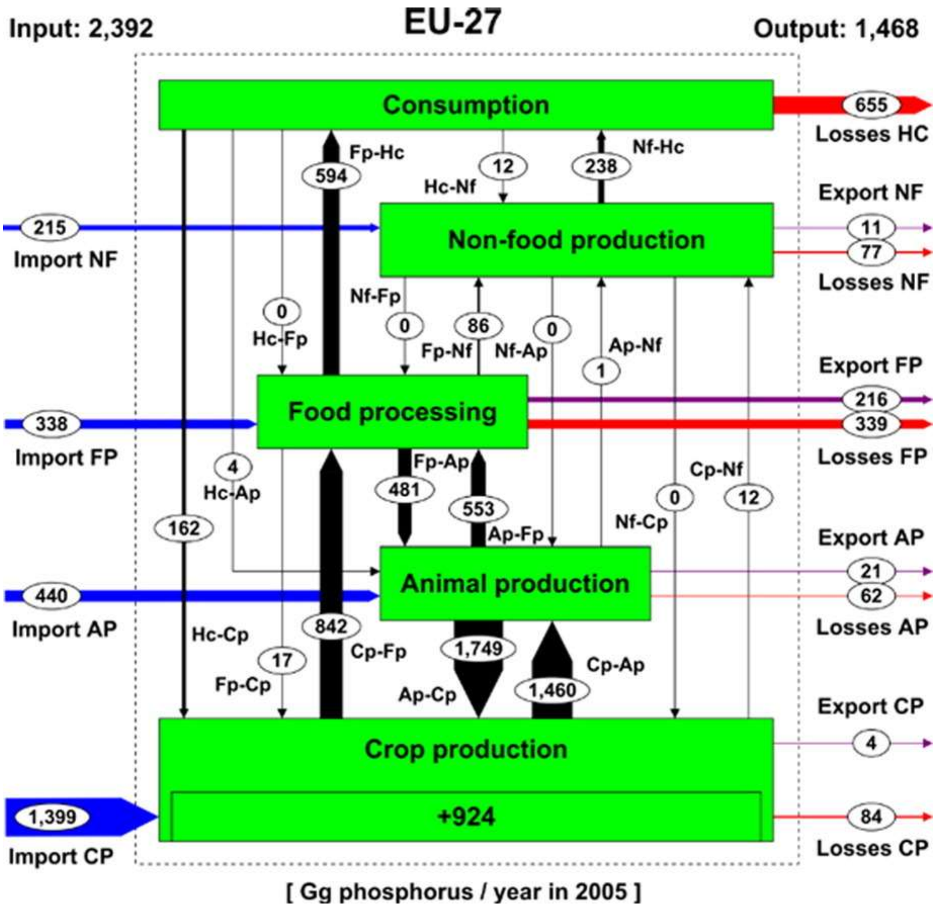

Figure 3.3: Flow diagram of phosphorus in Europe (EU-27) for the year 2005 (van Dijk et al., 2016).

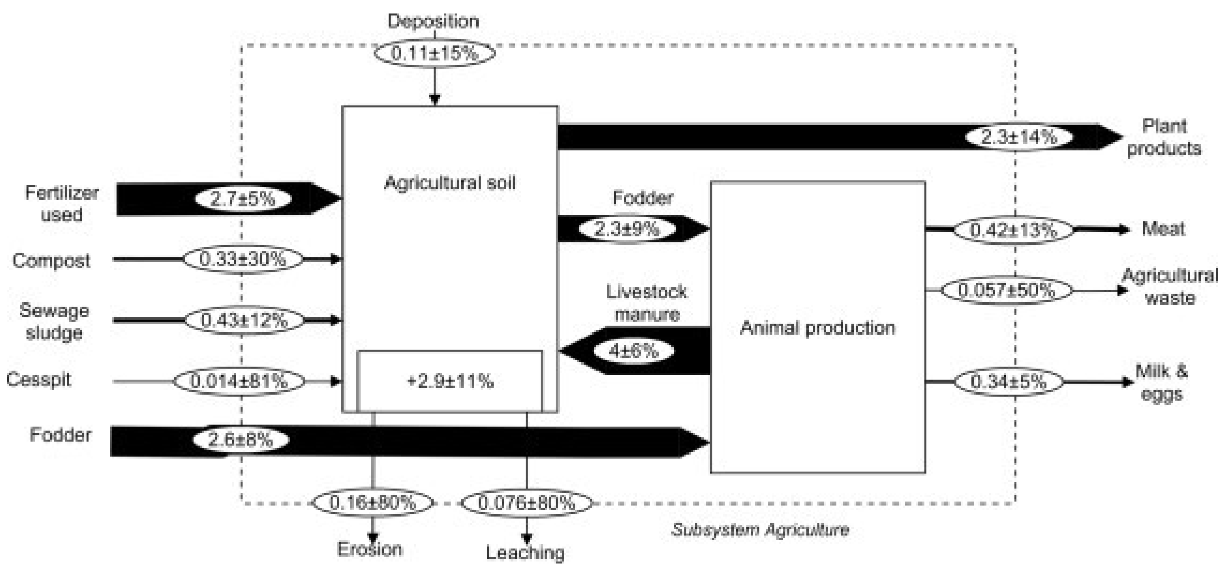

Figure 3.4: Flow diagram of phosphorus in Europe (EU-15) (Ott & Rechberger, 2012).

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The EU-27 imported 2.4 Tg P in 2005, half of which accumulated in agricultural soils (924 Gg) and half was lost as waste (1217 Gg) (van Dijk et al., 2016). On average, P accumulation in soils was 4.9 kg P ha^{-1} $year^{-1}$. The crop P uptake efficiency was approximately 70% (van Dijk et al., 2016). In the study of Ott and Rechberger (2012), it was found that for the average of 2006-2008 4.7 kg P was used per capita per year, of which only 1.2 kg P/year reached the consumer and as little as 0.77 kg P/year was recycled. The main losses were accumulation in agricultural soils (2.9 kg P/capita/year), losses to landfills (2.9 kg P/capita/year) and to the hydrosphere (0.55 kg P/capita/year).

The estimated annual required P input for agriculture in the EU is 3.85 Tg, based on data from 2009 and 2012 (Tóth et al., 2014). The north-western regions of the EU had higher P surpluses than the rest of the continent, and Central and Eastern European countries had lower surpluses than the EU-15 countries (Tóth et al., 2014). Furthermore, the import of food and feed has increased in Europe. A decrease of the use of mineral fertiliser was linked to an increase of feed import in countries with high animal densities, such as the Netherlands (van Dijk et al., 2016). The phosphorus balance of EU-27 countries is provided in Figure 3.5.

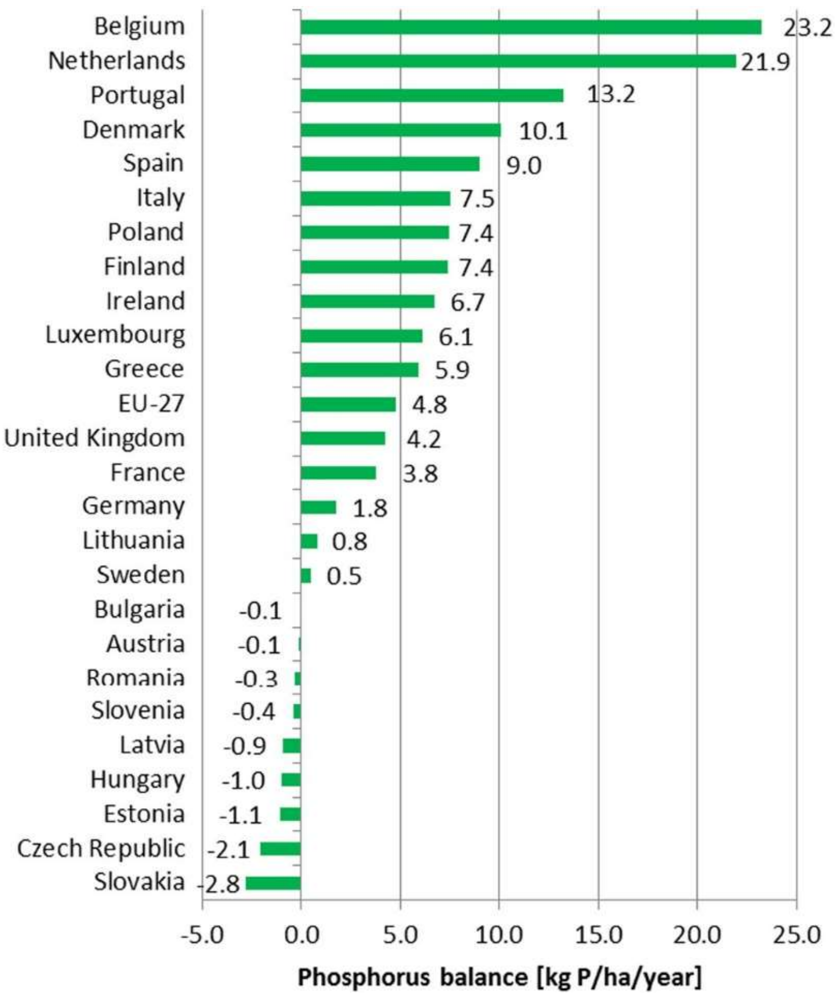

Figure 3.5: Phosphorus balance for European countries (EU-27) (van Dijk et al., 2016).

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3.2.3. Soil carbon stocks and balances

Different outcomes have been reported in studies concerning soil carbon sequestration: it is argued that European soils are losing C, gaining C or do not significantly change in terms of C (Kätterer et al., 2012). This is in agreement with the results of Brilli et al. (2017), who found that results of different model simulations of C sequestration and greenhouse gas source or sink status were contradictory. This could be due to different interpretations of physical and biogeochemical processes (Brilli et al., 2017).

The soil organic carbon stock of agricultural soils was 17.6 Tg for the EU Member States, Serbia, Bosnia and Herzegovina, Croatia, Montenegro, Albania, Former Yugoslav Republic of Macedonia and Norway together based on SOC data from 2009 for the top 30 cm (Lugato et al., 2014). The average SOC content was found to be 82.4 tonne C ha^{-1} (Lugato et al., 2014). The soil organic carbon stock of all of Europe's (EU-27) soils was estimated to be 73 to 79 Tg (Schils et al., 2008). It is important to note that about 20% of the European soil carbon stock is in peatlands, despite the fact that they only cover 8% of the EU-27 surface area (Schils et al., 2008).

Around 45% of soils in Europe have low or very low (< 3.5%) organic matter content (Figure 3.6). Figure 3.7 shows a more recent map of measured topsoil organic carbon content from the 2009 LUCAS soil survey, and predictions based on these data points are shown in Figure 3.8.

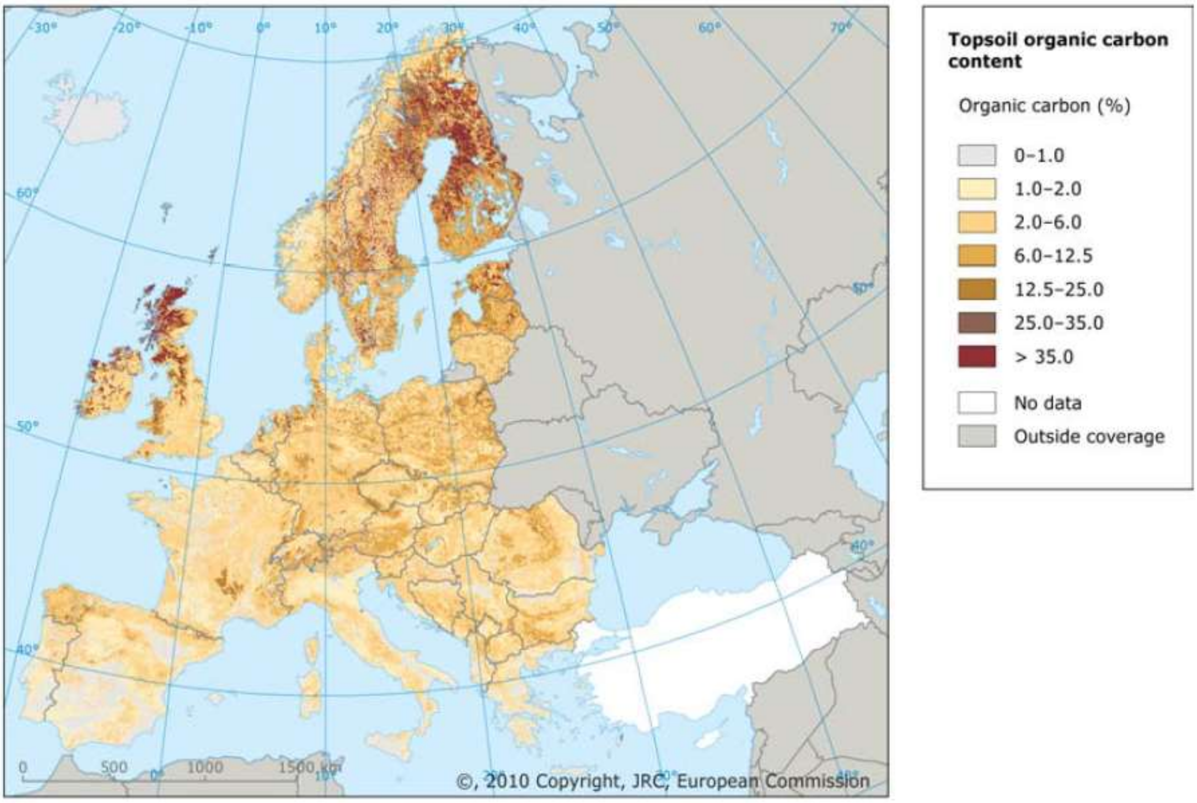

Figure 3.6: Topsoil organic carbon content (Jones et al., 2005)

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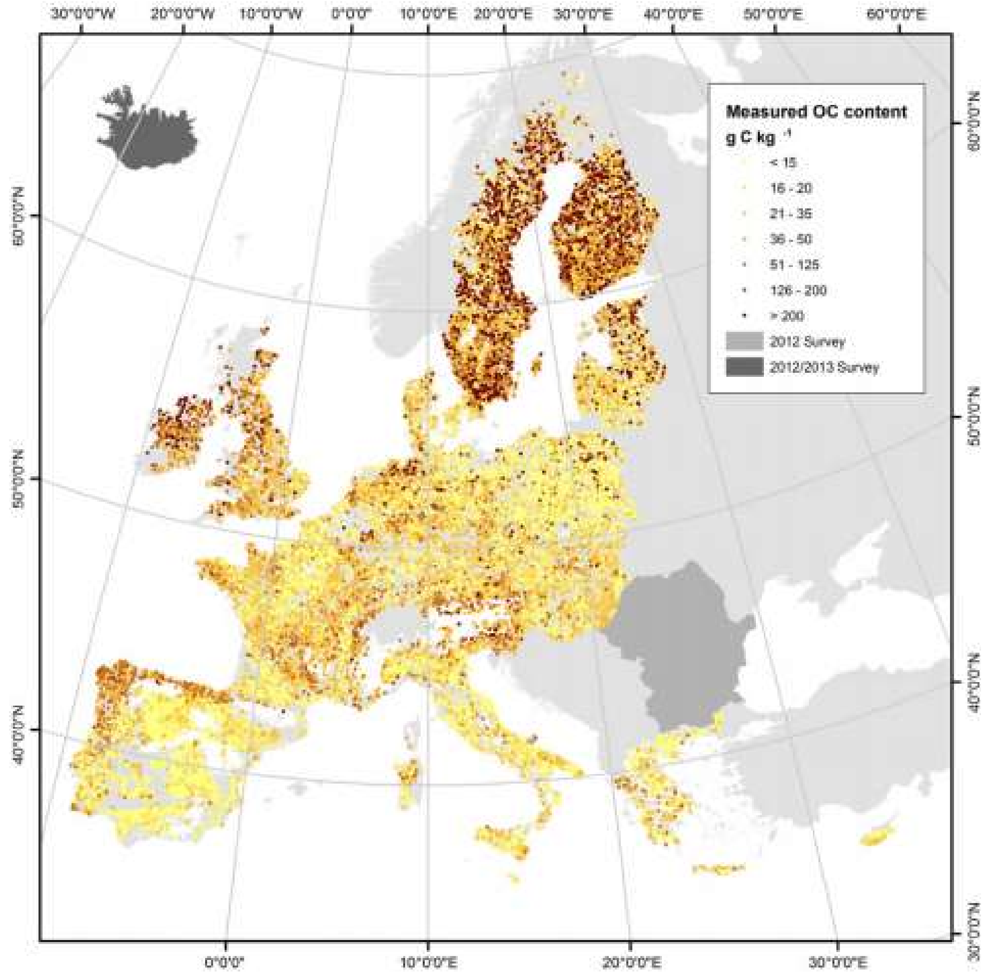

Figure 3.7: Measured topsoil organic carbon content (g C kg^{-1}) in 2009 (de Brogniez et al., 2015).

The Century model used by Lugato et al. (2014) predicted soil carbon loss in the south and east of Europe and SOC increase in the central and northern regions, resulting in an overall increase of the SOC stock. For the different climate scenarios, higher soil respiration was predicted, but this was compensated by higher C inputs caused by increased CO_2 concentrations and improved crop growing conditions, especially in northern Europe (Lugato et al., 2014). Also, Schulze et al. (2010) reported European soils as a carbon sink, sequestering 114 Tg per year, but when emissions of other greenhouse gases were taken into account, soils are a source of 26 Tg CO_2 equivalent per year instead (Schulze et al., 2010).

EU wide studies that provide information on the current agricultural SOC balances or changes in SOC stocks over the last decade, have not been published yet, as far as we are aware. However, several national studies of countries in Europe that investigated changes in SOC stocks or content have been published (e.g., Bellamy et al., 2005; Lettens et al., 2005; Reijneveld et al., 2009). Bellamy et al. (2005) found that carbon was lost from soils in England and Wales at a mean rate of 0.6% per year, which was irrespective of land use. The higher the carbon content of the soil, the larger the carbon loss (Bellamy et al., 2005). On the contrary, Reijneveld et al. (2009) found that organic carbon contents tended to increase in the Netherlands, especially in regions with low SOC contents. In line with Bellamy et al. (2005), they found decreases in SOC content in regions with relatively high

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SOC contents. Lettens et al. (2005) found increases mainly in grassland soils in northern Belgium and (although insignificant, possibly due to a low amount of data points) forests, but decreases on loamy cropland soils (Lettens et al., 2005).

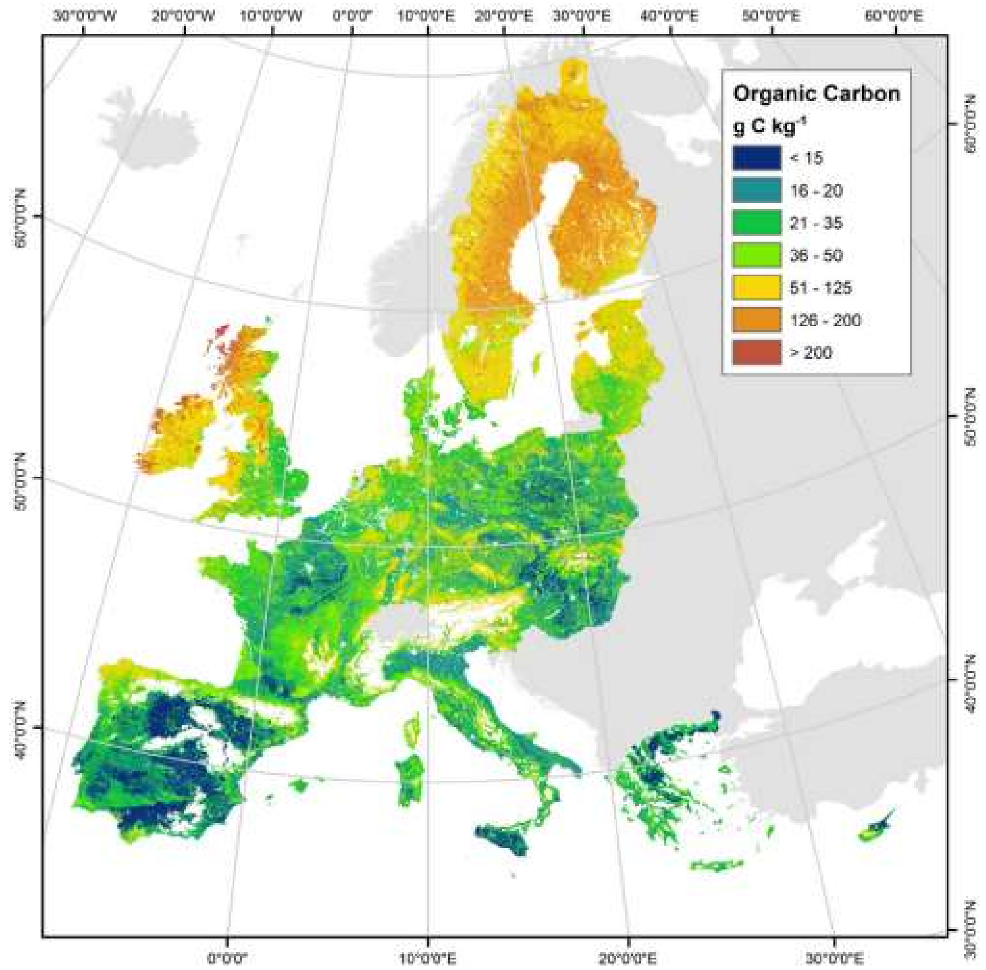

Figure 3.8: Predicted topsoil organic carbon content (g C kg^{-1}) (de Brogniez et al., 2015).

3.3. Model description MITERRA-Europe

MITERRA-Europe is a deterministic emission and nutrient flow model, which calculates greenhouse gas (CO_2, CH_4 and N_2O) emissions, nitrogen emissions (N_2O, NH_3, NO_x and NO_3), N and P flows and soil organic carbon stock changes on annual basis, using emission factors and leaching fractions. The model was developed to assess the effects and interactions of policies and measures in agriculture on N losses on a NUTS-2 (Nomenclature of Territorial Units for Statistics) level in the EU-28 (Velthof et al., 2009; de Vries et al., 2011). The MITERRA-Europe was originally based on the models CAPRI (Common Agricultural Policy Regionalised Impact), and GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies), and was supplemented with a N leaching module, a soil carbon module, and a module for greenhouse gas mitigation measures. Figure 3.9 shows a schematic

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representation of the model with the system boundary and CNP flows and emissions that are simulated. The MITERRA-Europe model is described in more detail in Velthof et al. (2009) and Lesschen et al. (2011).

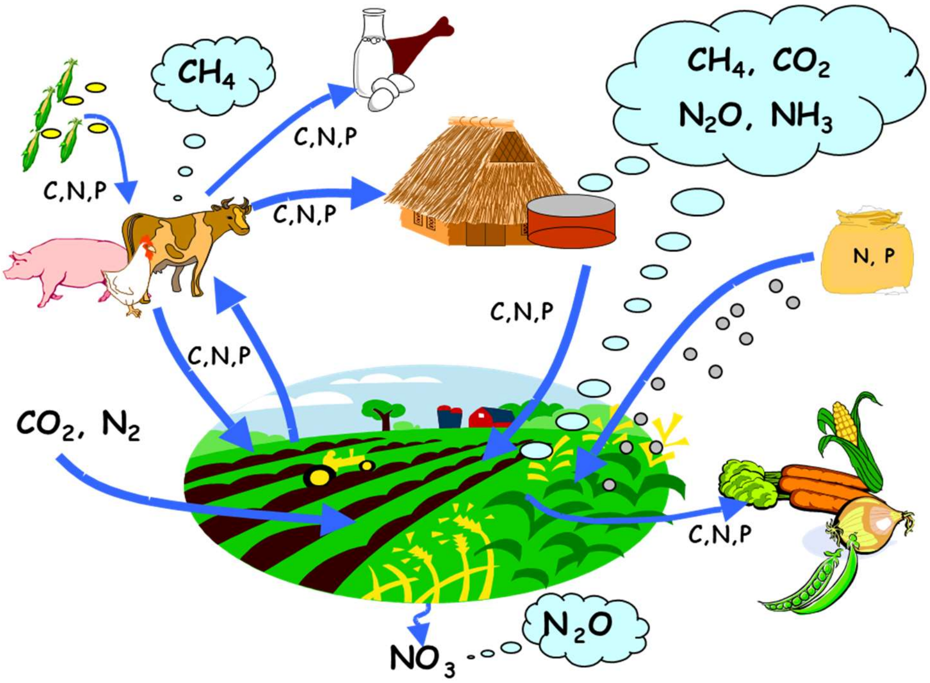

Figure 3.9: Schematic illustration of the system boundary and CNP flows and emissions that are modelled in MITERRA-Europe.

Input data consist of activity data (e.g., livestock numbers and crop areas and yield from CAPRI, Eurostat and FAOSTAT), spatial environmental data (e.g., soil and climate data), GHG emission factors (IPCC), and NH_3 emission factors, excretion factors and manure management system data (GAINS). These are described in more detail in section 3.3. For soil carbon, the calculation rules of the well-known soil carbon model RothC are used. The model includes measures to simulate carbon sequestration and mitigation of GHG and NH_3 emissions and NO_3 leaching. The model can also assess all GHG and nitrogen emissions following a LCA approach until the farm-gate (Lesschen et al., 2011). Effects of mitigation policies and measures can be assessed, as are long-term scenarios (e.g., de Wit et al., 2014), based on activity inputs from other economic models (e.g., CAPRI or AGMEMOD).

The RothC model is incorporated in MITERRA-Europe to enable the assessment of changes in soil organic carbon (SOC). RothC (version 26.3; Coleman et al., 1997; Coleman and Jenkinson, 2014) is a model for the turnover of organic carbon in non-waterlogged soils that takes effects of soil type, temperature, moisture content and plant cover on the turnover process into account. It uses a monthly time step to calculate total organic carbon (ton C ha^{-1}) on a year-to-century timescale. In the RothC model, SOC is split into four active compartments and a small amount of inert organic matter. The four active compartments are decomposable plant material, resistant plant material, microbial biomass and humified organic matter. Each compartment decomposes by a first-order process with its own characteristic rate. RothC requires the following input data on a monthly basis: rainfall (mm), open pan evaporation (mm), average air temperature (°C), clay content of the soil (as a percentage), input of plant residues (ton C ha^{-1}), input of manure (ton C ha^{-1}), estimate of the decomposability of the incoming plant material (DPM/RPM ratio), soil cover (if the soil is bare or vegetated in a particular month) and soil depth

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(cm). Initial carbon content can be provided as an input or calculated according to long term equilibrium (steady state).

3.4. Description of data sets

The input data were obtained from different sources, including existing databases and models. An overview of the data sources that were used in MITERRA-Europe is given in Table 1. Each data source is supplemented with some background information. For this study, the average data of the period 2016-2018, as far as available, were selected from these data sources and the spatial resolution is at NUT2 level.

Table 3.2: The databases that were used as input data for the model MITERRA-Europe

Dataset	Source	Website
FAOSTAT	Food and Agriculture Organization of the United Nations, 1997. FAOSTAT statistical database. Rome: FAO.	http://www.fao.org/faostat/en/#data
EUROSTAT	European Commission, 2019a. Eurostat statistical database. Brussels: European Commission.	https://ec.europa.eu/eurostat/data/database
CAPRI	Britz, W., Witzke, P., 2014. CAPRI model documentation 2014. Bonn, Institute for Food and Resource Economics.	https://www.capri-model.org/dokuwiki/doku.php
LUCAS - European Soil Data Centre	Tóth, G., Jones, A., Montanarella, L. (eds.) 2013. LUCAS Topsoil Survey. Methodology, data and results. JRC Technical Reports. Luxembourg. Publications Office of the European Union, EUR26102 – Scientific and Technical Research series.	https://ec.europa.eu/eurostat/web/lucas/data/database
NIS	United Nations Framework Convention on Climate Change, 2019. National Inventory Submissions 2019. Bonn: United Nations Climate Change	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
FSS	European Commission, 2019b. Farm Structure Survey - Survey Coverage. Brussels, European Commission.	https://ec.europa.eu/eurostat/statistics-explained/index.php/Farm_structure_survey_%E2%80%93_survey_coverage
GAINS	International Institute for Applied Systems Analysis, 2018. The GAINS model. Laxenburg: IIASA.	https://www.iiasa.ac.at/web/home/research/researchPrograms/air/GAINS.html
IPCC Reports	IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4, Agriculture, Forestry and Other Land Use. IPCC National Greenhouse Gas Inventories Programme. Institute for Global Environmental Strategies (IGES), Kanagawa, Japan.	https://www.ipcc-nggip.iges.or.jp/public/2006gl/

FAOSTAT
FAOSTAT provides food and agriculture data for over 245 countries and territories and covers all FAO regional groupings from 1961 to the most recent year available.

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Data on fertilizer use and milk yield between 2016-2018 were selected from FAOSTAT for the 28 EU Member State countries.

EUROSTAT
The Eurostat Dissemination Database provides official statistics on the European Union at different NUTS levels. Many agricultural data sets are available at Eurostat.

Data on the fat and protein content of milk between 2016-2018 were selected from EUROSTAT at a national level and the percentage of natural grassland and data were selected at NUT2 level.

Common Agricultural Policy Regional Impact (CAPRI) model
CAPRI is a multi-purpose modelling system that analyses market and environmental policies, changes in exogenous drivers, and premium systems. The system includes cropping areas, livestock and production numbers, farm policy instruments and income indicators per activity and region at NUTS2 level. Most of the data is derived from Eurostat, but a gap filling procedure and consistency check is applied, which make these data better than the data directly derived from Eurostat.

Data on animal numbers and crop areas and crop yields were selected from CAPRI.

Land Use and Coverage Area frame Survey (LUCAS) - European Soil Data Centre
Land Use and Coverage Area frame Survey is a harmonised land use and soil surveys across all EU Member States organised by EUROSTAT with the aim to gather information on land cover, land use and soil information across the EU. Since 2009 also soil samples are included, which resulted in a consistent spatial database of the soil cover and properties over the topsoil (0-20cm). Approximately 20,000 points were selected out of the main LUCAS grid for the collection of soil samples in 25 Member States of the EU. Bulgaria and Romania were sampled in 2012 and results have been added to the database. Soil samples were analysed on main soil properties (Toth et al., 2013). The benefit of LUCAS data is that it is recently observed data, data are harmonised and analysed in a single laboratory and there is a clear link to land use. In 2015 and 2018 additional soil surveys have been performed, (including bulk density in the 2018 survey, but these data are not yet publicly available. So far the soil bulk density is estimated using the pedo-transfer function of Hollis et al. (2012).

Soil data on coarse fragments, texture, pH, organic carbon content, availability of $CaCO_3$, NPK content, cation exchange capacity, bulk density and data on perennial grass cover were obtained from the LUCAS database.

National Inventory Submission (NIS)
National Inventory Submissions include National Inventory Reports (NIRs) that include descriptive and numerical information, and Common Reporting formats (CRFs) that contain national summaries, sectoral and trend tables for all greenhouse gas emissions and removals. The data source also includes sectoral background data tables for reporting implied emission factors and activity data.

Data on N excretion of animals and CH_4 emissions from manure management and enteric fermentation were selected from the CRF databases for the most recent year (2017).

Farm Structure Survey (FSS) and the Survey on Agricultural Production Methods (SAPM)
The Farm Structure Survey is carried out by all EU Member States, following a common methodology on a regular basis and provides therefore comparable and representative statistics across countries and time, at regional levels (down to NUTS 3 level). Every 3 or 4 years the FSS is carried out as a sample survey, and once in ten years as a census. FSS includes data on land use, livestock numbers, rural development, management and farm labour input.

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In the 2010 FSS an additional Survey on Agricultural Production Methods (SAPM) was included, which collected data at farm level on agro-environmental measures. This survey has only been executed a single time so far, and is therefore a relevant baseline for the implementation of agro-environmental measures. Data is available on type of manure storages, animal housing, grazing and several soil related practices, such as type of tillage (conventional, reduced and zero tillage), soil cover, crop rotations, irrigation, and manure application.

Data on arable farm size, farming system, crop rotation, livestock units, and areas with organic farming, irrigation, crop cover, and grass cover were selected from the FSS database.

Greenhouse Gas - Air Pollution Interactions and Synergies (GAINS) model
The Greenhouse Gas - Air Pollution Interactions and Synergies model explores cost-effective emission control strategies that also improve local air quality and reduces greenhouse gas emission. GAINS is implemented for the whole world, including 48 European countries. The spatial scale of the model is national level and the temporal scale is 5 years.

Data on NH_3 emission factors and the implementation of NH_3 mitigation measures were selected from GAINS.

Reports of the Intergovernmental Panel on Climate Change (IPCC)
The IPCC is the United Nations body for assessing the science related to climate change. The reports contain internationally accepted and acknowledged reference data. So far, most of the emission factors used in MITERRA-Europe are derived from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, as these are currently the standard for the official reporting of member states to the EU and UNFCCC. In 2013, the IPCC published a supplement to the 2006 IPCC Guidelines on Wetlands and in 2019, important updates of the 2006 guidelines were published. In the next version of the MITERRA-Europe model, these updates in emission factors and calculation rules will be included where relevant.

Data on N_2O emission factors and global warming potentials (GWP) are used from the IPCC reports.

3.5. Baseline results of CNP flows in European farming systems

3.5.1. N and P flows in EU agriculture

The main flows of N and P in European agriculture have been derived from statistics and the model results of MITERRA-Europe and are presented in the food system approach following an adapted diagram from van Dijk et al. (2016). Figure 3.10 shows the amount of N and P for the current European food system, where recycling through manure and residue processing is still very limited. The flows related to processing of manure and crop residues, which is where most of the Nutri2Cycle solutions are focussing on, should contribute to a better closure of the nutrient cycles. However, as (statistical) data for these flows is so far very limited available at European scale, these flows could only be roughly estimated or not quantified at all for the baseline situation.

Three main options exist to improve nutrient cycling in agriculture: 1) reduce losses to the environment, 2) reduce mineral fertilizer input, and 3) reduce import of feed. The import of mineral fertilizers is the largest flow into the agricultural system for N, for P the amount of mineral fertilizer is lower, as less losses occur within the system. For N only the reactive nitrogen losses (NH_3, N_2O, NO_x and N leaching and runoff) have been provided in the diagram. If losses of the harmless dinitrogen (N_2) were also included, the losses would increase by 4.7 Mton N. Import of feed comprises with about 20% an important contribution of the external inputs of nutrients into the European agricultural system.

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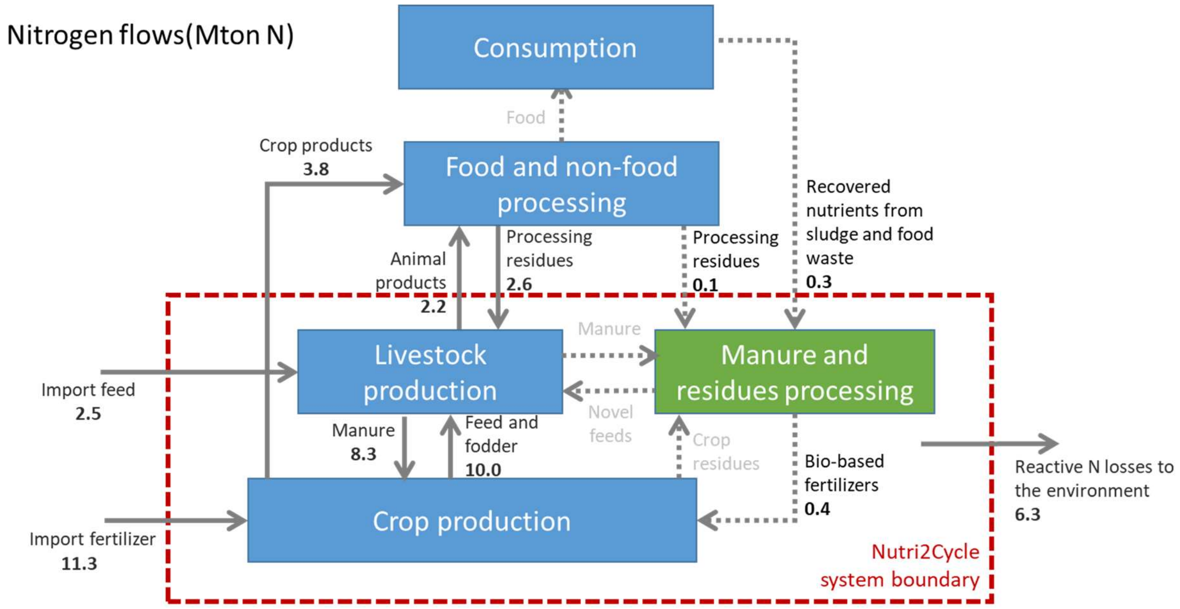

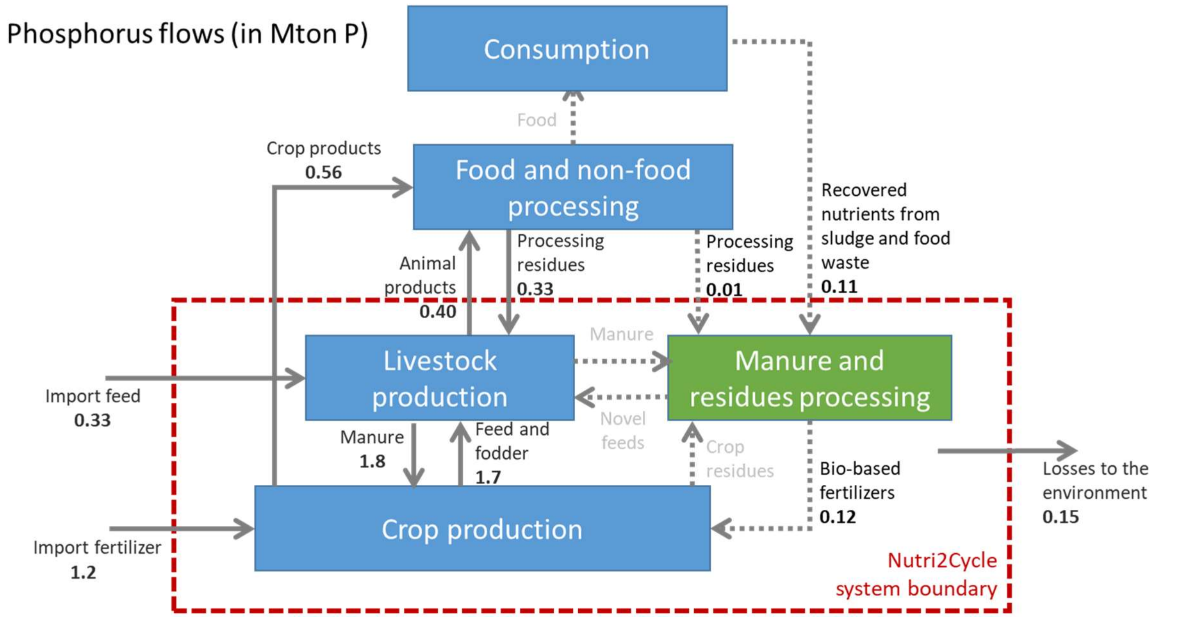

Figure 3.10: Schematic representation of the main nitrogen (upper figure) and phosphorus (lower figure) flows (in Mton N/P) in the food system (based on van Dijk et al., 2016) and the system boundary to be used in the assessments in Nutri2Cycle (dashed red box), the dashed arrows are not included or very uncertain in the baseline results, as these are not yet mainstream flows and only limited data is available.

3.5.2. Soil nutrient and carbon balances

The amount of N applied to agricultural land as mineral fertiliser, manure, urine and dung deposits during grazing, nitrogen deposition and nitrogen fixation are the main nitrogen inputs of the farming system. Sludge and compost are small sources of nitrogen, but their importance differs per country. In some countries the use

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of sludge on agricultural soils is prohibited by legislation. The soil N balance is the difference between N inputs and N output by the removal of crop products. A negative balance indicates a N deficit, whereas a positive balance indicates a N surplus. Most of the N surplus will be lost as nitrogen that leaches to groundwater or to surface waters through (sub)surface runoff, or emissions of NH_3, N_2O or NO_x to the atmosphere.

Figure 3.11 present the N input, crop N uptake and net soil N balance on arable land in the EU member states. Belgium and the Netherlands have clearly the highest input per hectare, but also the highest crop uptake. The high use of mineral N fertilizer for Lithuania is remarkable, given the relatively low crop uptake, this might be related to an error in the fertilizer statistics. Also, the low N surplus for Ireland and United Kingdom is remarkable, as these countries have relatively high crop uptake. One reason can be the occurrence of soils rich in organic matter, which provide nitrogen through mineralisation. This is in line with the negative soil carbon balance for these countries (Figure 3.13). The N balance at provincial level for all agricultural areas (including grassland) of the EU Member States is given in Figure 3.13. N surplus is highest for Lithuania, the Netherlands, Belgium and Luxembourg. These surpluses correspond with the high amount of mineral fertiliser and the high amount of manure used per hectare of agricultural land, which is highest for these countries.

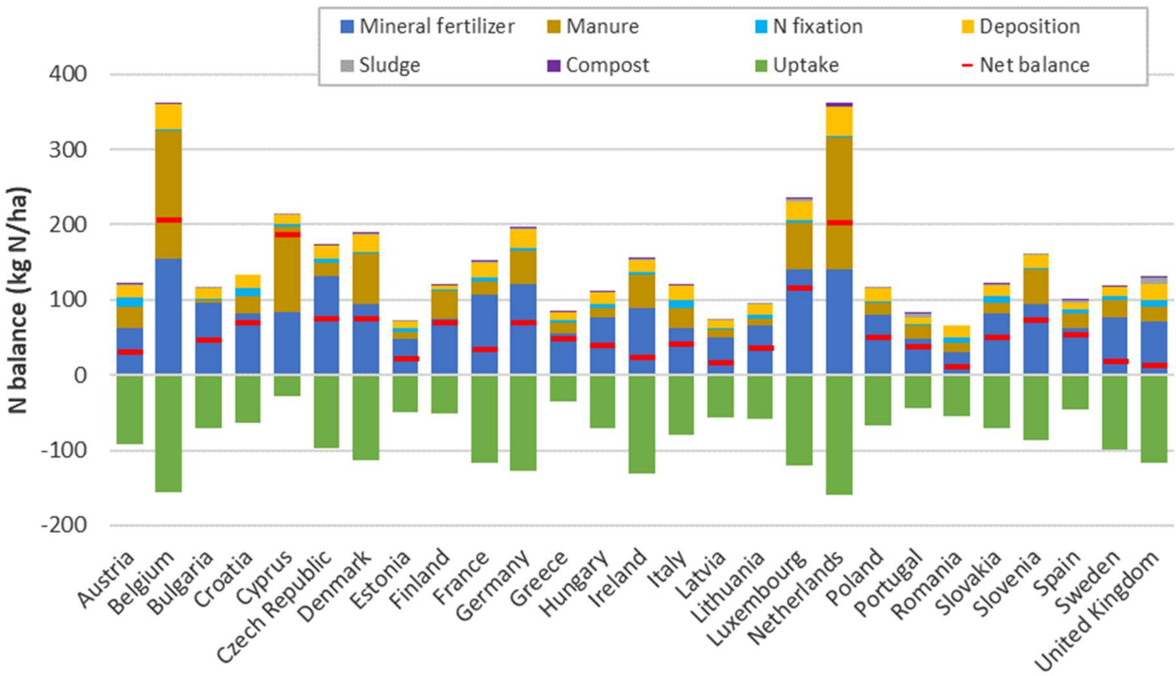

Figure 3.11: Soil nitrogen balance for arable land for EU member states

For phosphorus the pattern is more or less similar with the highest inputs for Belgium, the Netherlands and also Cyprus (Figure 3.12). Most of the P input is derived from mineral fertilizers, although in livestock dense countries, manure P is the main input. In some countries, e.g., United Kingdom, Spain and Portugal, also sewage sludge is an important source of P. The spatial distribution of the soil P balance is shown in Figure 3.13, where highest surpluses occur in the Netherlands, Belgium, and some regions in Mediterranean countries. In the Netherlands and Belgium, the reason for the high P surplus is the high livestock density and related manure surplus (RVO, 2019). The maximum allowance of manure application is limited by the P status of the soils in these countries. Therefore, manure processing and export of manure is taken place. Manure processing is however not well

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covered yet in the model, which might lead to too high manure P application rates for the Netherlands and Belgium. According to these results, several countries have negative soil P balances, which means that soil fertility in these countries is declining. Long term soil monitoring, e.g., via the LUCAS soil monitoring, could verify if this is indeed the case. However, there is also quite some uncertainty in the crop uptake data, as nutrient content of the crops can be quite variable. The MITERRA-Europe model currently uses P contents of crops that have been derived from studies in the Netherlands, these might be higher than in other countries, due to the high P status of the soils.

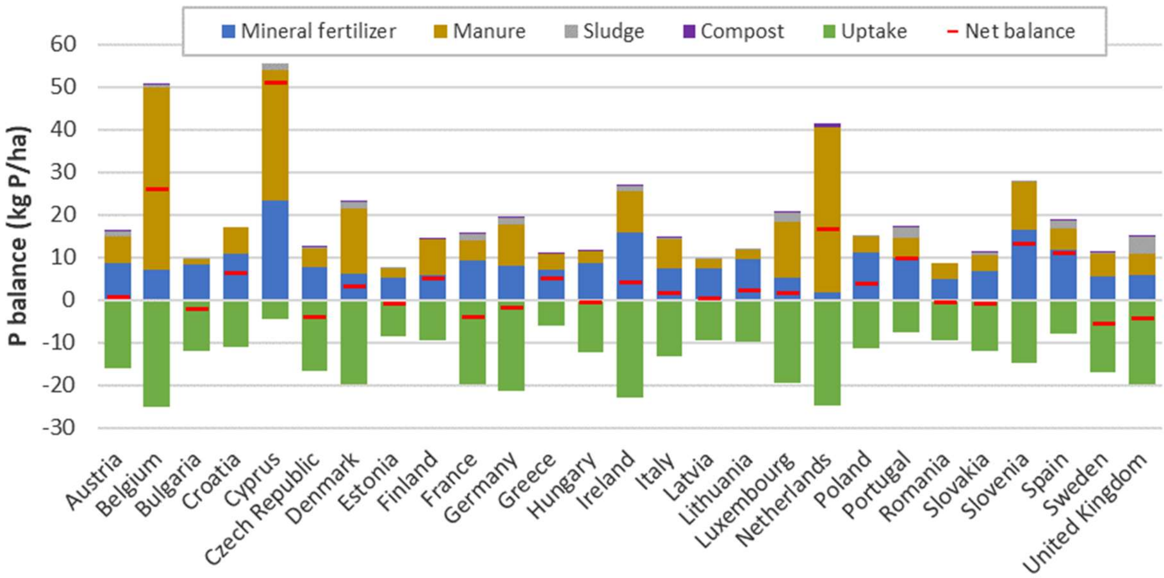

Figure 3.12: Soil phosphorus balance for arable land for EU member states

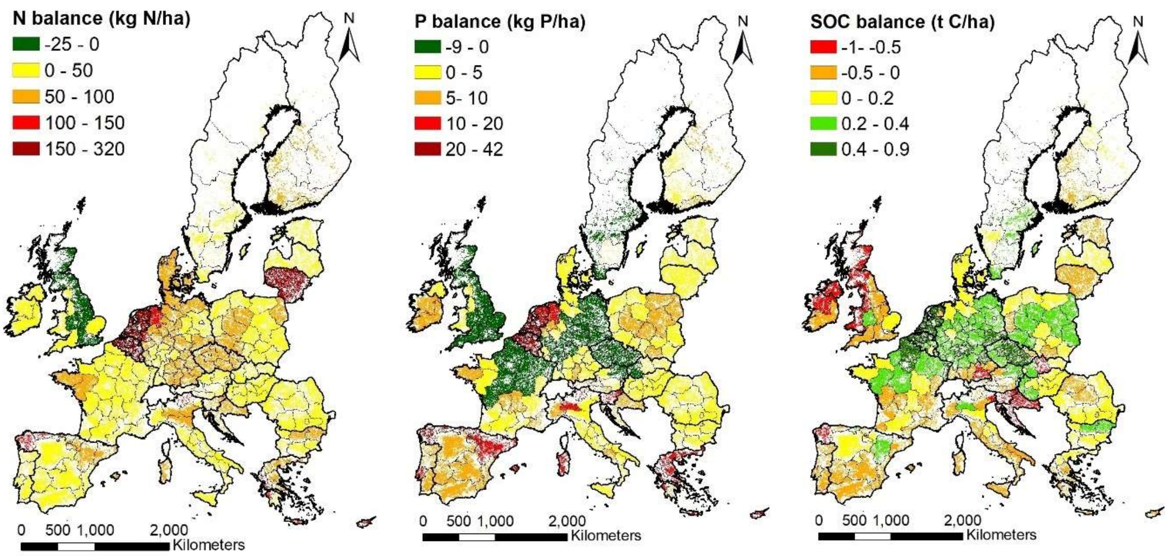

Figure 3.13: The nitrogen (N), phosphorous (P) and soil organic carbon (SOC) balances at provincial level for the agricultural areas of the EU Member State countries.

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Carbon can be added to the soil through the application of manure or other organic fertilisers, through grazing, or crop residues on the land. Crop products are a loss of carbon, which needs to be compensated to avoid a reduction in the soil organic carbon (SOC) stock. A negative SOC stock means that the amount of carbon applied to agricultural land is lower compared to the amount of carbon lost through decomposition. A positive SOC balance means that carbon builds up in the topsoil, i.e., soil carbon sequestration). The SOC stock increases in countries as the Netherlands, Germany, Czech Republic, and Poland, but the SOC stock is degrading in Mediterranean and Balkan countries, and in the United Kingdom.

3.5.3. Environmental indicators

Looking at the total N leaching, NH_3 emissions and GHG emissions a clear hotspot can be identified covering the Netherlands, Belgium and north-western Germany (Figure 3.14). Leaching of N is also high in Lithuania due to the large amounts of mineral fertilisers used in this region. Lombardia (Italy), Bretagne (France) and Galicia (Spain) are also characterised by intensive agriculture, which results in relatively high emissions.

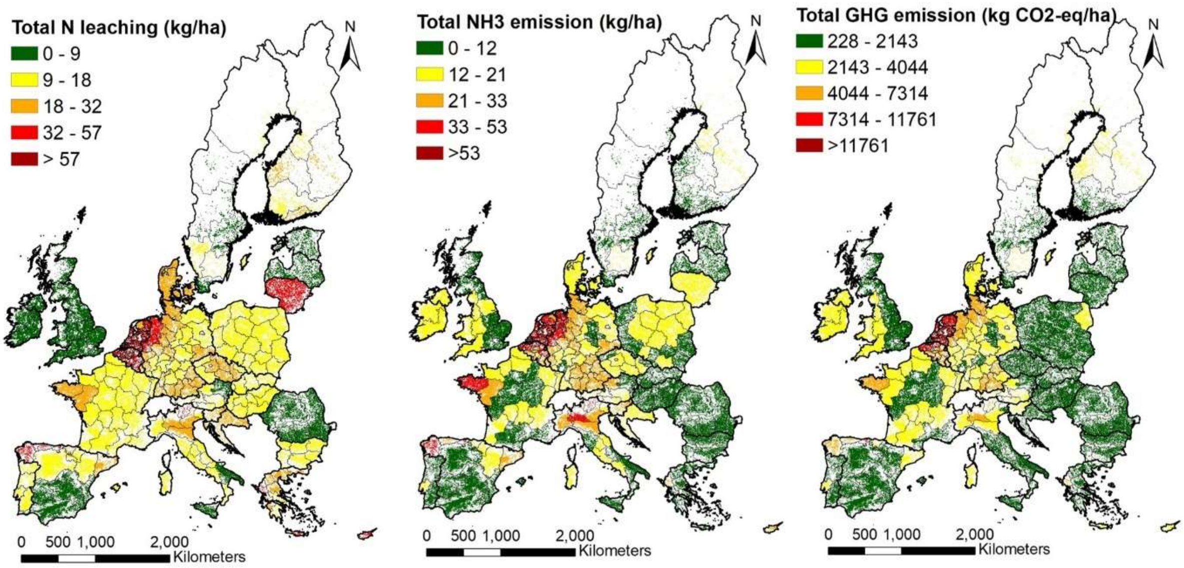

Figure 3.14: Intensity of nitrogen leaching and runoff to groundwater and surface water, ammonia (NH_3) emission, and greenhouse gas (GHG) emission from agriculture (sum of N_2O and CH_4 emissions).

Nutrients can be lost when they dissolve in water. The MITERRA-Europe model distinguishes the following losses through water: surface runoff of N and P, N leaching to groundwater and N leaching to surface water. Phosphorus leaching mainly occurs in soils with high phosphate status, however, this process is not modelled yet in MITERRA-Europe. The amount of leaching and (sub)surface runoff are given in Figure 3.15. Leaching of N to groundwater contributes significantly to the total loss of N to water bodies in Belgium, Denmark, Finland, the Netherlands, and Poland. These are all countries with a large fraction of sandy soils, which are prone to leaching. The amount of (sub)surface runoff contributes significantly to the total loss of N to water bodies in Germany, France, Hungary, Spain and Italy. Again, the Netherlands and Belgium show much higher N leaching and runoff compared to other EU countries.

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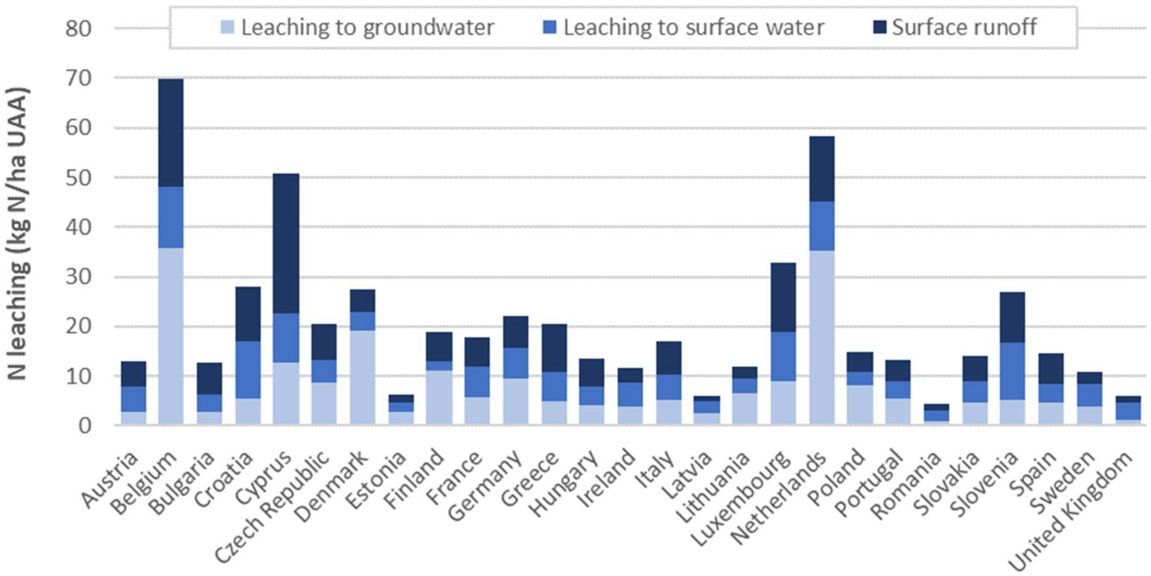

Figure 3.15: National N leaching and runoff subdivided into leaching to groundwater, leaching to surface water and surface runoff (in kg N ha^{-1} utilized agricultural area (UAA)).

Manure management, soils and enteric fermentation are most important sources of GHG emissions. Manure management and soils contribute to the direct and indirect emission of N_2O, whereas enteric fermentation and manure management contribute to the emission of CH_4. A more detailed look at these four sources of GHG emission shows that, in most EU member states, the CH_4 emitted through enteric fermentation is highest, followed by the N_2O emitted by the soil (Figure 3.16). N_2O emitted through manure management is only a very small source of GHG emissions. CH_4 emissions from manure management can be significant, especially in countries with liquid manure systems and pig production.

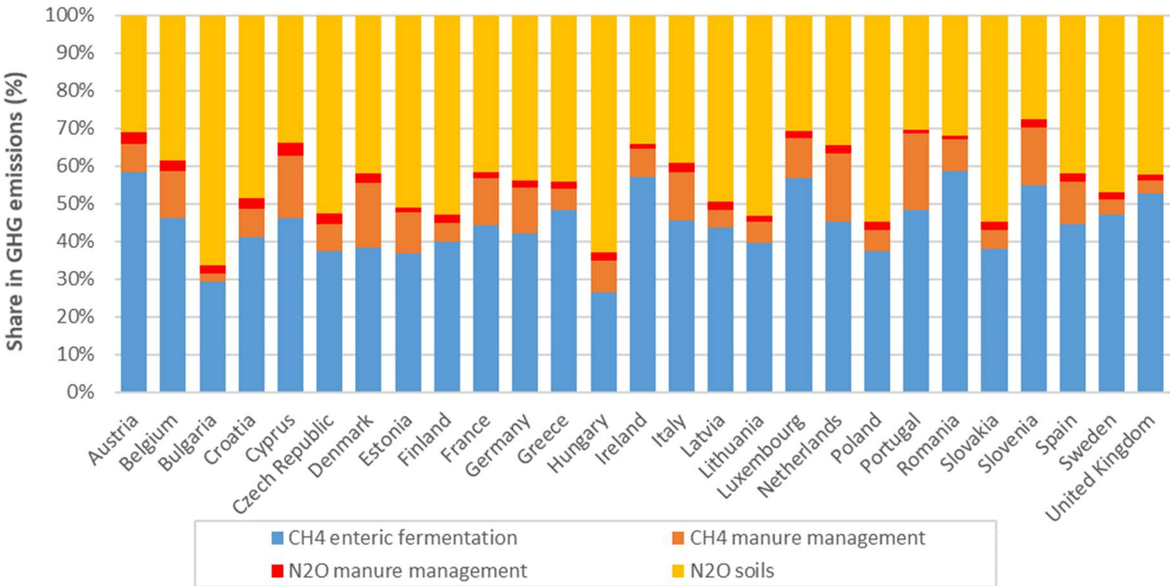

Figure 3.16: Share in agricultural GHG emission sources per EU member state (only the emission sources reported in the UNFCCC emission sector Agriculture are included).

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3.5.4. Indicators for improving nutrient and carbon cycles

As mentioned before, there are three main pathways to improve nutrient cycling: 1) reduce mineral fertilizer input, 2) reduce import of feed and 3) reduce losses to the environment. The third option is the most important, as this will have direct benefits to the environment, e.g., better air and water quality. The other pathways reduce the input of nutrients into the farming systems, and if the same production can be maintained, the losses will decrease as a result. Reducing feed import and mineral fertilizer use will often have positive external effects, e.g., less pressure on agricultural land outside the EU, which reduces the risk of deforestation, and in case of mineral fertilizers less energy use (N fertilizers) and less dependence on finite resources (P fertilizers). Which pathway to address differs among member states and agricultural systems. Based on the MITERRA-Europe baseline modelling results, indicators for improved closing of nutrient cycles can be derived. Table 3.3 provides results for EU member states for some of the possible indicators. For example, the percentage of imported N in feed (relative to total feed N intake), shows to what extent countries are depending on feed import. For example, the Netherlands and Italy have a relatively high import, and could close the nutrient cycles better if more local feed would be produced. The SOC balance is a good indicator for where practices to increase or maintain soil carbon would be most effective.

Table 3.3. Indicators that provide information on the current status of nutrient and carbon cycling. Malta and Cyprus are excluded, because of unrealistic results, probably due to uncertainty in the statistical data (UAA: utilized agricultural area).

Country	Imported N in Feed (%)	N Losses (kg N ha^{-1} UAA)	Mineral N Fertilizer (%)	Mineral P Fertilizer (%)	SOC Balance (ton C ha^{-1} UAA)
Austria	19	55	38	33	0.01
Belgium	22	243	39	13	0.49
Bulgaria	6	50	69	64	0.15
Croatia	N.A.	86	52	48	-0.74
Czech Republic	28	83	65	43	0.32
Denmark	22	98	45	23	0.05
Estonia	16	32	54	48	-0.09
Finland	12	75	58	38	-0.03
France	17	63	50	37	0.15
Germany	16	92	50	29	0.19
Greece	20	83	35	30	-0.13
Hungary	24	51	63	62	0.18
Ireland	3	65	36	36	-0.52
Italy	30	67	38	33	-0.11
Latvia	5	23	60	65	0.01
Lithuania	8	42	61	69	-0.01
Luxembourg	12	154	46	17	0.49
Netherlands	28	249	35	5	0.49

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Country	Imported N in Feed (%)	N Losses (kg N ha^{-1} UAA)	Mineral N Fertilizer (%)	Mineral P Fertilizer (%)	SOC Balance (ton C ha^{-1} UAA)
Poland	16	64	61	59	0.17
Portugal	21	53	36	40	-0.38
Romania	2	20	40	47	0.04
Slovakia	22	54	58	48	0.00
Slovenia	10	106	41	36	-0.67
Spain	22	62	45	45	-0.04
Sweden	8	37	55	36	0.28
United Kingdom	12	33	40	26	-0.34

3.6. Final remarks

The aim of this Chapter was to provide an overview of the current CNP flows and balances in EU agriculture, which will serve as baseline for the assessment of the Nutri2Cycle solutions. Based on this baseline, and information on the solutions that will become available from WP2, a selection of the solutions will be made, and their environmental impact at regional scale will be assessed with the MITERRA-Europe model. The economic consequences will be simulated by the CAPRI model in WP4.

The results clearly show that there is a large diversity in environmental impacts within the EU, with high emission intensities in livestock dense regions such as The Netherlands and Flanders, whereas in other regions negative nutrient and soil carbon balances occur. For each region target solutions should be found to improve nutrient cycling and reduces losses to the environment. The results presented, but also other indicators that can be derived from the model results, will be used to select which practices and techniques will be simulated, and in which regions they will be applied. Finally, scenario's will be set up with regionally diverse packages of practices and techniques for improving nutrient cycling. These will be used for model simulation with MITERRA-Europe to assess their impact on the environment.

During the analysis of the results, it was possible to identify some issues that will require extra attention for future modelling work. One improvement is a better incorporation of feed intake estimates and the net trade of feed products. Ideally a dynamic feed intake approach should be applied as developed by Hou et al. (2016). Some of the statistical input data could be improved, e.g., fertilizer statistics are probably not correct for some countries. The results presented should therefore not be considered as final values, as some improvements in the model and input data sets will be implemented in the coming period, before doing the environmental impact assessment and scenario analysis in WP3 and WP4.

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4. General discussion and conclusions

4.1. Linkage of field-level modelling tools and LCA approach

A shortlist of innovative solutions was compiled as part of the work of WP2. The shortlist contains 45 specific solutions categorised into 24 sub-research lines and 5 research lines, including nutrient recovery from organic waste, anaerobic digestion, precision fertilisation, etc. In the next phase of the project (WP3), a subset of these shortlisted solutions will be analysed using life cycle assessment (LCA) tools to evaluate their environmental performances.

Time- and workload-wise, it is not possible to evaluate all 45 solutions or 24 sub-research lines individually. Therefore, a system analysis of the shortlist was performed to compare the similarities of these solutions, which will enable the evaluation of similar solutions under a uniform framework for data collection, field modelling, and life cycle impact assessment. The steps for system analysis are:

1. Shortlisted solutions were checked to see if they consist of common processes (e.g., nutrient recovery) or technical components (e.g., anaerobic digestion).
2. Several conceptual groups were generalised from identified common processes and technical components. Shortlisted solutions were placed into these groups based on their technological similarities.
3. Flowcharts were used to illustrate processes, inputs, and emissions, and data requirement for field level modelling and LCA were summarised.

The system analysis revealed that more than half of the shortlisted solutions are related to treatment of livestock (cattle, pig, or poultry) manure and slurry, or agricultural organic waste. These solutions produce bio-based fertilisers, either in inorganic form (e.g., N fertilisers produced from nutrient recovery), or as organic products (e.g., digestate, organic soil enhancers). To evaluate their life cycle impact on the environment, environmental performances during field application must be considered, including:

- Replacement value for conventional fertilisers,
- Effect on crop yields,
- Emissions to the atmosphere,
- Emissions to surface and groundwater,
- Changes in soil organic C and N pools.

Field-level modelling tools, Daisy and SWAP/ANIMO, can produce (at least some of) these data in simulated systems, as summarised in Table 2.6. The scenarios described in section 2.1.2 will serve as the baseline, in which the application of mineral or organic fertilisers in accordance with conventional local practices will be simulated. For the shortlisted solution to be evaluated, the novel fertiliser products will be applied to completely or partially replace conventional fertilisers, and the simulated effects on crop yields and environmental emissions will be compared against those from the baseline scenarios.

Figure 4.1 illustrates the processes in a crop production system that will be simulated by Daisy or SWAP/ANIMO, as well as associated data requirement. Data on soil, weather, crop rotation, and field management activities are essential to establish the simulation. Characterisation of the novel fertiliser product is key to properly simulating the flow of nutrients and associated environmental consequences. Data required to characterise the fertiliser are: C:N ration, total C, N, and P fractions, N composition of NH_4^+ and NO_3^-, and NH_4^+ volatilization rate. For organic fertilisers and soil enhancers, additional information such as dry matter fraction, organic fraction, and turnover rate of organic matter are desired. In particular, organic matter turnover rate is a crucial parameter

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for correct simulation of the degradation of organic matter and its distribution into soil organic matter pools. To obtain such information, laboratory incubation experiments are usually required.

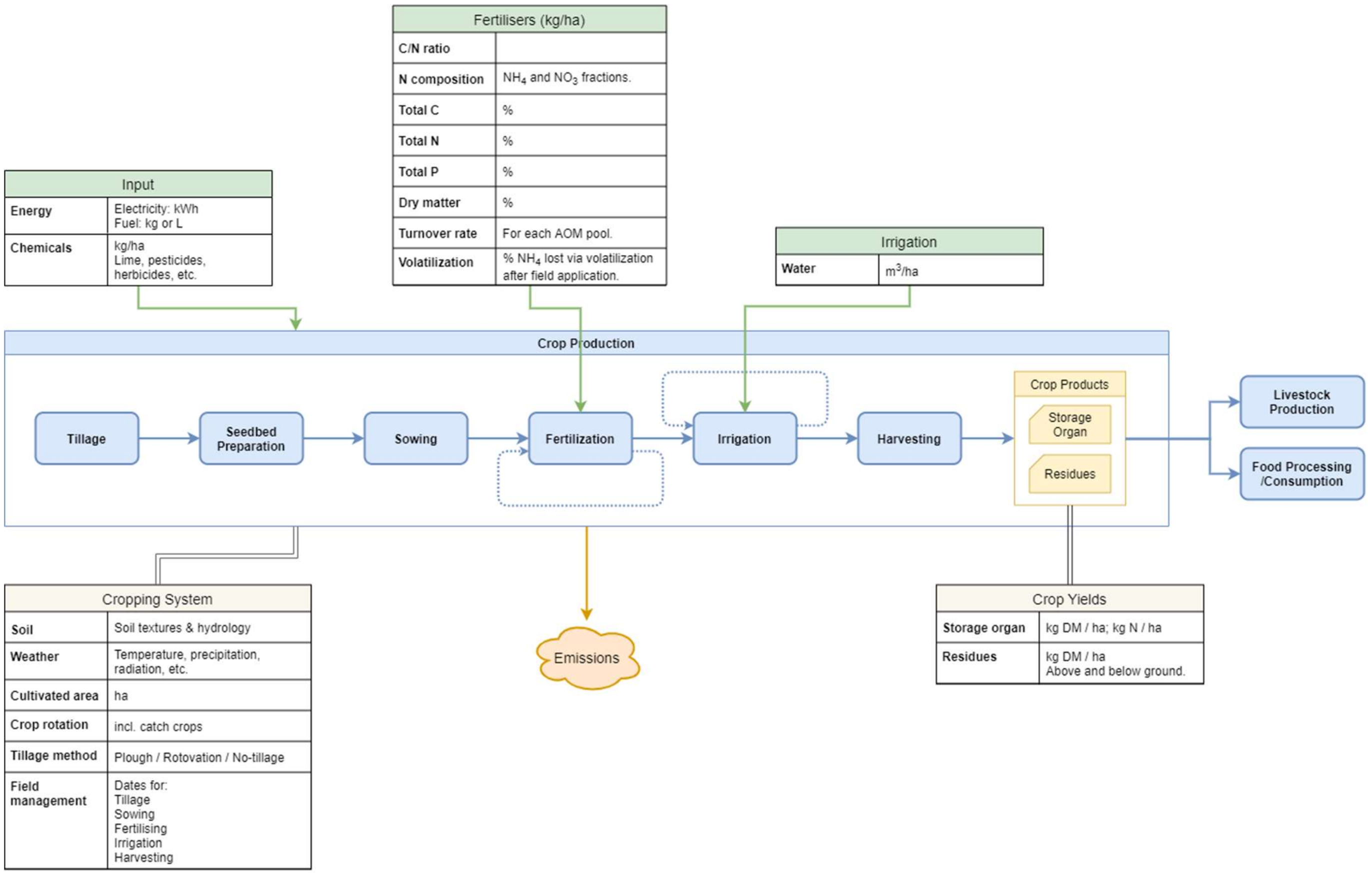

Figure 4.1: Schematic illustration of the processes and data requirement for the evaluation of environmental performances of novel fertilisers at field level.

4.2. Selection of proper modelling tools for evaluation of shortlisted solutions

Modelling tools have their own intrinsic limitations, and may not be suitable for all systems and conditions. For Daisy and SWAP/ANIMO, constraints in current versions limit their capability of being applied in the evaluation of certain shortlisted solutions. This precludes their application in certain conditions, or simulating specific types of crops. Therefore, the shortlisted solutions were evaluated for their feasibility to be analysed using field modelling tools Daisy and SWAP/ANIMO, based on the following criteria:

- Capability of modelling tools to simulate C, N, and P flows.

  Daisy and SWAP/ANIMO are both capable of simulating C and N flows, although they don't always make the same assumptions regarding the system, and may have different emphasis on different aspects. The final choice on the modelling tool for a specific solution need to be assessed on a case-by-case basis.

  Daisy is not able to simulate P flows, and SWAP/ANIMO must be used for solutions involving P fertilisers.

- Capability of modelling tools to simulate specific crops.

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Not all crops can be readily simulated in Daisy and/or SWAP/ANIMO. Crops that can be simulated, with some degree of recalibration, include: common cereal crops (wheat, barley, maize, etc.), oilseed rape, potato, beet, ryegrass, white clover, and a few selected vegetables. Most types of vegetables, fruits, and trees cannot be properly simulated at the moment. Therefore, shortlisted solutions applicable mainly to orchards, vineyards, and agroforestry cannot be simulated using Daisy nor SWAP/ANIMO.

- Data availability for modelling requirement.

  The accuracy of the simulation results depends on the range and detail of the data that can be used to calibrate the model, or supplied as model input. For most shortlisted solutions, information on field management activities and characterisation of fertilisers are crucial for successful model simulation. It is not advisable to simulate systems in which key information is lacking, or where a lot of assumptions have to be made.

Based on these criteria, a "traffic light" system was developed (Table 4.1), in which the feasibility of shortlist solutions for field-level modelling was indicated by green ✓ (feasible), yellow ⚠ (possible, depending on subsequent data availability), or red ◆ (unfeasible) lights.

Table 4.1: Feasibility assessment of shortlisted solutions for field-level modelling using Daisy or SWAP/ANIMO.

Research Line	SL#	Shortlist Solution	LL#	Long-list Abstract Title	Feasibility: Daisy	Feasibility: SWAP/ ANIMO
2. Innovative soil, fertilisation & crop manage-ment systems & practices	1	Practices for increasing soil organic matter content	16	Using digestate, precision agriculture and no-tillage focusing on OM stocking in an area characterize by the lack of OM in sandy soil	✓	✓
			17	Crop farmer using a variety of manure and dairy processing residues to recycle and build soil C, N, P fertility	✓	✓
			71	Practices for increasing soil organic matter content in Dutch soils	✓	✓
	2	Catch crops to reduce N losses in soil and increase biogas production by anaerobic co-digestion	21	Catch crops to reduce N losses in soil and increase biogas production by anaerobic co-digestion	✓	✓
4. Bio-based ferti-lisers (N, P) and soil enhancers (OC) from agro-residues	3	Substituting external mineral nutrient input from synthetic fertilisers by recycled organic based fertilizers in orchards & agroforestry	66	Application of digestate in large scale orchards	◆	⚠
			57	Recovered organic materials and composts for precision fertilization of apple orchards and vineyards	◆	⚠
			15	Closing the loops at the scale of farm: using the livestock manure to fertilize the feeding crop on agroforestry plots	◆	⚠
			14	Substituting mineral inputs with organic inputs in organic viticulture	◆	⚠
	4	Substituting external mineral nutrient input from synthetic fertilisers by recycled organic based fertilizers in arable farming	1	Ammonium stripping / scrubbing and NH4NO3 as substitute for synthetic N fertilizers	✓	✓
			2	Ammonium stripping / scrubbing and NH4SO4 as substitute for synthetic N fertilizers	✓	✓
			6	Concentrate from vacuum evaporation/ stripping as nutrient-rich organic fertilizer	✓	✓
			9	Liquid fraction of digestate as a substitute for mineral N & K fertilizer	✓	✓
	5		62	Blending of raw and treated organic materials to produce organic fertilisers (NPC)	✓	✓

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Research Line	SL#	Shortlist Solution	LL#	Long-list Abstract Title	Feasibility	
					Daisy	SWAP/ ANIMO
		Blending of raw and treated organic materials to produce organic fertilisers or growth substrates	47	Production of growing substrates for horticulture application from poultry manure, solid state digestate and biochar through composting	⚠	⚠
	6	P recovery from organic waste(water) streams via struvite crystallization	65	Struvite as a substitute of synthetic P fertilizer	♦	✔
			49	Nitrogen and phosphorus recovery from pig manure via struvite crystallization and design of struvite based tailor-made fertilizers	♦	✔
			52	Pilot-scale crystallizer for P recovery	♦	✔
	7	Pig manure processing and replacing mineral fertilizers	23	Pig manure refinery into energy (biogas) and fertiliser using a combination of techniques applicable at industrial pig farms	✔	✔
			55	Manure processing and replacing mineral fertilizers in the Achterhoek region	✔	✔
			20	Low temperature ammonium-stripping using vacuum	✔	✔
			43	Pig manure evaporation plant	✔	✔
	8	P recovery from animal bones	22	BIO-PHOSPHATE: high temperature reductive thermal process recovery of concentrated Phosphorus from food grade animal bones	♦	✔
5. Novel animal feeds produced from agro-residues	9	Insect breeding as an alternative protein source on solid agro-residues (manure and plant wastes)	40	Insect breeding as an alternative protein source on solid agro-residues (manure and plant wastes)	⚠	⚠
	10	Domestic cultivation of protein crops	25	Soybeans in Poland - innovative solutions in the cultivation, plant protection and feeding on farms	♦	⚠
			45	INPULSE: Innovating towards the use of Spanish legumes in animal feed	♦	⚠
	11	Utilization of crop residues in animal feed	34	Secondary harvest: additional valorisation of crop harvest and processing residues	✔	✔
	12 a	Floating wetland plants grown on liquid agro-residues as a new source of proteins	41	Floating wetland plants grown on liquid agro-residues as a new source of proteins	♦	♦
	12 b	Algae grown on liquid agro-residues as a new source of proteins		Algae grown on nutrient rich liquid agro-effluents as a new source of proteins	♦	♦
1. Innovative solutions for optimized nutrient & GHG in animal husbandry	13	Anaerobic digestion strategies for optimized nutrient and energy recovery from animal manure	10	Small/Farm scale anaerobic digestion of agro-residues to increase local nutrient cycling & improve nutrient use efficiency	✔	✔
			48	Recovery of energy from poultry manure and organic waste through anaerobic digestion	✔	✔
	14	Tailor made digestate products (tool development)	61	Tailor made digestate products (tool development)	✔	✔
	15	Organic matter recovery from manure and associated valorisation strategies	11	Recycling fibres of manure as organic bedding material for dairy cows	⚠	⚠
			24	Adapted stable construction for separated collection of solid manure and urine in pig housing (followed by separate post-processing)	⚠	⚠
			8	Acid leaching of P from organic agro-residues in order to produce OM-rich soil enhancers and P-fertilizers	♦	✔
	16	Use of an inoculate of microbiota and enzymatic pre-cursors to reduce ammonia emissions and optimize nutrient use efficiency in poultry manure	27	Use of an inoculate of microbiota and enzymatic pre-cursors to reduce ammonia emissions and optimize nutrient use efficiency in poultry manure	♦	⚠

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Research Line	SL#	Shortlist Solution	LL#	Long-list Abstract Title	Feasibility	
					Daisy	SWAP/ ANIMO
	17	Slurry acidification to reduce NH3 volatilisation from animal production	18	Slurry acidification with industrial acids to reduce NH3 volatilisation from animal husbandry	✔	✔
			19	Slurry bioacidification using org. waste products to reduce NH3 volatilisation and increase fertiliser value	✔	✔
	18	Nutrient mass flow analysis to better map and understand NPC flows at farm level	32	Annual Nutrient Cycling Assessment (ANCA)	◆	⚠
3. Tools, tech-niques & systems for higher-precision fertilisation	19	Precision farming coping with heterogeneous qualities of organic fertilizers in the whole chain	30	Precision farming coping with heterogeneous qualities of organic fertilizers in the whole chain	✔	⚠
	20	Field assessment of precision fertilization of maize & cereals using bio-based fertilizers	28	Precision farming and optimised application: under-root application of liquid manure for maize and other row crops	✔	✔
			63	Precision fertilization of Maize using organic materials	✔	✔
	21	Field assessment of precision arable farming using bio-based fertilizers in potato growing	73	Precision arable farming using bio-based fertilizers in potato growing	✔	⚠
	22	Integration of UAV/Drone and optical sensing technology into pasture systems	68	Integration of UAV/Drone and optical sensing technology into pasture systems	✔	⚠
	23	Nitrogen sensor technology to make real-time crop assessment	13	Sensor technology to assess crop N status	✔	⚠
			76	Nitrate sensor for optimal grassland management	✔	⚠

4.3. Selection of baseline scenarios for evaluation of shortlisted solutions

In chapter 2, ten baseline scenarios were selected and their CNP flows modelled at field-level. Table 4.2 presents a preliminary assessment on the applicability of the baseline scenarios for evaluating the environmental performances of shortlisted solutions. These baseline scenarios are most relevant to assess solutions associated with manure/slurry recycling and processing, but they may also be useful for evaluation of other solutions such as precision fertilisation. Certain shortlisted solutions are not suitable to be assessed on these baseline scenarios (shaded in red), or can only be assessed with some limitations/compromises (shaded in yellow), either because of the lack of proper crop modules, or unclear definition of what the current “baseline” is. Other solutions may be evaluated on all or part of the baseline scenarios, however, further adaptation may still be necessary depending on the specific case.

The selection of appropriate baseline scenario is dependent on the context of how each shortlisted solution will be evaluated. Therefore, it is an iterative approach, and the selection will be further refined during WP3, when shortlisted solutions are assessed more closely to determine what type of analysis will be performed (LCA, field-modelling, etc.), and against which baseline scenarios they will be evaluated.

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Table 4.2: Preliminary assessment on the applicability of baseline scenarios for evaluation of the shortlisted solutions. Solutions that are not suitable to be assessed on existing baseline scenarios, or can only be assessed with some limitations/compromises, are marked with red and yellow shading, respectively.

Research Line	SL#	Shortlist Solution	Applicability of Baseline Scenarios
2. Innovative soil, fertilisation & crop management systems & practices	1	Practices for increasing soil organic matter content	Relevant to all baseline scenarios, especially the Mediterranean region where topsoil organic content is usually low.
	2	Catch crops to reduce N losses in soil and increase biogas production by anaerobic co-digestion	Relevant to all baseline scenarios.
4. Bio-based fertilisers (N, P) and soil enhancers (OC) from agro-residues	3	Substituting external mineral nutrient input from synthetic fertilisers by recycled organic based fertilizers in orchards & agroforestry	Present baseline scenarios do not apply due to lack of proper crop modules for orchards and agroforestry.
	4	Substituting external mineral nutrient input from synthetic fertilisers by recycled organic based fertilizers in arable farming	Most relevant to CTW-/CTE-Arable, which receives exclusively mineral N fertilisers that can be replaced by organic-based fertilisers. But can also be assessed on other scenarios where mineral N is applied.
	5	Blending of raw and treated organic materials to produce organic fertilisers or growth substrates	Relevant to all baseline scenarios.
	6	P recovery from organic waste(water) streams via struvite crystallization	Relevant to all scenarios where manure/slurry is produced (ATN-/ATC-Dairy, ATN-/CTW-/CTE-Pig).
	7	Pig manure processing and replacing mineral fertilizers	Most relevant to baseline scenarios with pig production (ATN-/CTW-/CTE-Pig). But the processed manure products may also be applied to other farming systems.
	8	P recovery from animal bones	Relevant to all baseline scenarios.
5. Novel animal feeds produced from agro-residues	9	Insect breeding as an alternative protein source on solid agro-residues (manure and plant wastes)	The fate of the agro-residues may be assessed on ATC-Dairy/Arable if they are alternatively field-applied.
	10	Domestic cultivation of protein crops	LL#25 (soybean cultivation in Poland) may be evaluated against CTE-Arable.
	11	Utilization of crop residues in animal feed	Relevant to ATC-Arable (the region where the technology is developed), but needs further adaptation.
	12a	Floating wetland plants grown on liquid agro-residues as a new source of proteins	Unable to model the emissions from wetland plants or algae production due to lack of proper crop modules. The fate of the agro-residues may be assessed on ATC-Dairy/Arable if they are alternatively field-applied.
	12b	Algae grown on liquid agro-residues as a new source of proteins	
1. Innovative solutions for optimized nutrient & GHG in animal husbandry	13	Anaerobic digestion strategies for optimized nutrient and energy recovery from animal manure	Relevant to all dairy and pig production scenarios where manure/slurry is produced and field-applied (ATN-/ATC-Dairy, ATN-/CTW-/CTE-Pig).
	14	Tailor made digestate products (tool development)	
	15	Organic matter recovery from manure and associated valorisation strategies	
	16	Use of an inoculate of microbiota and enzymatic pre-cursors to reduce ammonia emissions and optimize nutrient use efficiency in poultry manure	No baseline is available for poultry manure application. However, if the solution can be applied to other manure types, it may be evaluated on dairy/pig scenarios.
	17	Slurry acidification to reduce NH3 volatilisation from animal production	Most relevant to pig production scenarios (ATN-/CTW-/CTE-Pig), as pig slurry is most often acidified. But may also be relevant to dairy farming systems (ATN-/ATC-Dairy).

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Research Line	SL#	Shortlist Solution	Applicability of Baseline Scenarios
	18	Nutrient mass flow analysis to better map and understand NPC flows at farm level	The solution is a tool to give farmers insight in CNP flows, not something to be modelled.
3. Tools, techniques & systems for higher-precision fertilisation	19	Precision farming coping with heterogeneous qualities of organic fertilizers in the whole chain	These solutions are not site-specific, therefore may be assessed on any baseline scenario.
	20	Field assessment of precision fertilization of maize & cereals using bio-based fertilizers	
	21	Field assessment of precision arable farming using bio-based fertilizers in potato growing	
	22	Integration of UAV/Drone and optical sensing technology into pasture systems	
	23	Nitrogen sensor technology to make real-time crop assessment	

4.4. Overall conclusions

In this report, we established the baseline for evaluation of the environmental performances of the shortlisted solutions. A total of six geoclimatic regions and ten baseline scenarios were selected to represent the variance in geo-climate and farming typologies within the EU. Mechanistic modelling tools, Daisy and SWAP/ANIMO, were used to simulate the CNP flows of these scenarios at field-level. The simulated data are comparable to field observations, and both models are capable of producing reliable results for later analysis in connection with environmental performance assessment by LCA.

The aim of Chapter 3 was to provide an overview of the current CNP flows and balances in EU agriculture, which will serve as baseline for the assessment of the Nutri2Cycle solutions. Based on this baseline, as derived from the modelling with MITERRA-Europe, and information on the solutions that will become available from WP2, a selection of the Nutri2Cycle solutions will be made, and their environmental impact at regional scale will be assessed. The results clearly show that there is a large diversity in environmental impacts within the EU, with high emission intensities in livestock dense regions, whereas in other regions negative nutrient and soil carbon balances occur. For each region target solutions should be found to improve nutrient cycling and reduces losses to the environment.

The approach that couples field-level model simulation and LCA is highly relevant to the Nutri2Cycle project. A system analysis on the shortlist was performed to help identify shortlisted solutions that can be simulated using Daisy and/or SWAP/ANIMO. Many of the solutions produce novel bio-based fertilisers or soil enhancers. Their effect on crop yields, environmental emissions during field application, etc. will be simulated using Daisy and/or SWAP/ANIMO, and the simulated data will be used as input for LCA. The environmental performances of the shortlisted solutions will be evaluated against the baseline scenarios.

The feasibility of using Daisy and SWAP/ANIMO to evaluate the field-level environmental performances was assessed for each shortlisted solution individually. Both models are capable of simulating field-level N dynamics, but only SWAP/ANIMO is able to simulate P flows. However, some limitations in the modelling tools prevent the modelling of certain solutions, such as those applied in orchards, agroforestry, and soybean production.

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