Optimisation of nutrient budget in agriculture

D2.2 Report on the design of the NutriModel Framework and the results of running the baseline for nutrient and carbon flows using the NutriModels

Funded by
the European Union

Cover Delivery Report

Project Information	
Acronym	NutriBudget
Title	Optimisation of nutrient budget in agriculture
Project no.	101060455
Type of Action	RIA
Website	Nutribudget
Deliverable Information	
Title	Report on the design of the NutriModel Framework and results of running the baseline for nutrient and carbon flows using the NutriModels
WP number and title	WP2 – Develop integrated multi-scale NutriModels
Lead Beneficiary	WR
Authors	Chantal Hendriks (WR), Jan Peter Lesschen (WR), Kevin Duan (WR), Karin Nikolaus (WR), Gerard Ros (WU), Wim de Vries (WU), Mengru Wang (WU), Donghao Xu (WU), Salim Belyazid (SU), Anna Strekalovskaya (SU), Francesca Degan (ARVALIS), Anais Bonnard (ARVALIS), Maxime Salin Maradeix (ARVALIS), Harald Sverdrup (INN)
Reviewers	Susan Vrona Bejina (PWC) and Wim Bussink (NMI)
Description	A spatial nutrient and carbon flow analysis of all relevant plant nutrients (N, P, K, S, Mg, Ca, Cu, Zn) and their interactions, including carbon flows for the baseline.
Type	R – Document, report
Dissemination Level	PU - Public
Status	Final version
Submission due date	30 September 2024
History of Changes	
Version 0.1	Draft created by WR (05.07.2024)
Version 0.2	Draft version by WR and revision by PWC and NMI (23.09.2024)
Version 1.0	Final version by WR for submission (30.09.2024)

Preface

The NutriBudget project aims to help the agricultural sector in the transition towards sustainable growth by developing and implementing a prototype of an integrated nutrient management platform that includes a decision support tool (DST) that operates at field level to serve local stakeholders, and insights in regional nutrient (N, P, K, S, Mg, Ca, Cd, Zn) and carbon (C) budgets to serve regional, national and European stakeholders. The models (i.e., NutriModels) and datasets that are used to assess the nutrient budgets at field and regional scale are aligned, which stimulates the conversation on sustainable nutrient and carbon management options among stakeholders. The NutriModels will, in the end, be able to assess the effect of nutrient and carbon mitigation measures. The effect of measures will be pictured along five goals (e.g., soil quality, water quality, GHG emission, biodiversity, and agricultural production) through a user-friendly interface of the DST. In this way, users will get insight in the opportunities and trade-offs regarding the optimisation of agronomically and environmentally sustainable nutrient use in the area they operate. This full picture can stimulate the implementation of measures as it helps making well-founded decisions at different scales.

The NutriModel framework was designed in D2.1, and therefore this report focusses on setting the European baseline for nutrient and carbon budgets. To properly assess the potential of nutrient mitigation measures, we first need to set a baseline. This report aims to present the European baseline of nutrient and carbon budgets. This baseline will be used to assess the impact of measures (WP2, T2.2 and T2.3, WP1, and WP4), and it also helps the development of the Decision Support Tool (WP5). Besides a baseline, this report also presents results of the farm-scale NutriModel (i.e., Nutrifarm) and the two farm-level models that complement the results of NutriFarm. All three models run for one case-study. These results provide insight in the potentials of the two farm-level models to complement the NutriFarm results.

Executive summary

The report is entitled 'The design of the Nutrimodel Framework and results of running the baseline for nutrient and carbon flows using the NutriModels'. The design of the Nutrimodel Framework was already published in D2.1, and therefore this report focusses on a baseline on the nutrient and carbon budget using the regional NutriModel, MITERRA-Europe. The farm-scale models run in a consistent way for a test-dataset. This now allows for further elaborations on the added value of CHN and FSF to the NutriFarm results.

The report is part of Work Package 2 (WP2), Task 2.1, where inclusive measure-impact models for the nutrient management platform are developed and implemented. These so-called NutriModels spatially predict nutrient (N, P, K, S, Mg, Ca, Cd, Cu, Zn) and carbon (C) flows of major European farming systems from regional to farm scale. The farm-level NutriModel, NutriFarm, will communicate through an application programming interface (API) with the decision support tool (DST). The input data required for MITERRA-Europe is used to create a default dataset for NutriFarm. The NutriModels can assess the nutrient budget and the effect of nutrient and carbon mitigation measures. Therefore, these models are a key element of the NutriBudget project as they provide direct results to the nutrient management platform (NutriPlatform), which facilitates the calculation of management adaptation options for improved nutrient and carbon budgets.

Insight in nutrient budgets is agronomically and environmentally important to feed a growing population in a sustainable way. **Chapter 1** provides some more background information on how the NutriModels contribute to the overall project goal. This chapter also explains the importance of a baseline on nutrient and carbon budgets in Europe.

A short description of the regional NutriModel (MITERRA-Europe) is provided in **Chapter 2**, because the full description was already published in D2.1. The baseline, including an initialisation approach and assumptions on the modelling approach, were described. Assumptions were mainly needed because of a lack in data at the required level of detail (NUTS2), or the data was not provided in the required context.

In Chapter 3 the field-scale models are described. Although the algorithms of MITERRA-Europe and Nutri-Farm are aligned, there are some processes that differ slightly from each other because of the scale at which both models operate. These deviations are described in **Chapter 3**. Nutri-Farm will be complemented by the results of two additional farm-level models, namely CHN and FSF. Therefore, the deviation of the complementary farm-level models CHN and FSF from NutriFarm is also described in this Chapter.

The results of the baseline of MITERRA-Europe and the test run by the farm-level models were described in **Chapter 4**. This baseline will be used to test the effect of measures (WP1 and WP4) that help moving towards the desired state (D3.4), but also to start de design of the Decision Support Tool (WP5). These next activities, together with the next steps to fulfil Task 2.1, are described in **Chapter 5**.

Table of Contents

List of Figures

List of Abbreviations

API	Application Programming Interface
BC	Base Cation
BIO	Microbial biomass
C	Carbon
Ca	Calcium
Cd	Cadmium
CEC	Cation Exchange Capacity
CH_4	Methane
CO_2	Carbon dioxide
CORINE	Coordination of Information on the Environment
Cu	Copper
DPM	Decomposable plant material
DST	Decision Support Tool
FSF	ForSafe-FarmFlow model
GAINS	Greenhouse Gas - Air Pollution Interactions and Synergies
HUM	Humified organic matter
IOM	Inert organic Matter
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
LAI	leaf area index
Mg	Magnesium
N	Nitrogen
N_2O	Nitrous oxide
NH_3	Ammonia
NO_x	Nitrogen oxide
P	Phosphorus
RPM	Resistant plant material
S	Sulphur
Zn	Zink

1. Introduction

1.1 Background and objective

European agricultural systems are under high pressure. On one hand, the demand for food and feed is increasing because of the growing population (Shah and Wu, 2019), and on the other hand nutrient losses, e.g., caused by excessive use of fertilizers, need to be reduced by at least 50% by 2050 according to the goal set in the Farm to Fork Strategy; one of the central pillars of the European Green Deal (Fetting, 2020). The Horizon Europe project NutriBudget was launched to help decision makers in their choice selecting sustainable agronomic and environmental nutrient management practices by developing and implementing a prototype of an integrated nutrient management platform as a decision-support tool (DST) for farmers, advisors, European policymakers and regional authorities.

Where the emphasis of the previous report (D2.1) was on the design of the NutriModel Framework, the emphasis of this report is on setting a European baseline for soil nutrient (N, P, K, S, Mg, Ca, Cd, Cu, Zn) and carbon (C) budgets based on the results of the MITERRA-Europe model. The NutriModel Framework exists, besides of the MITERRA-Europe model, also of the farm-level model Nutri-Farm. The algorithms of NutriFarm and MITERRA-Europe are aligned, and the model assesses the same nutrient and carbon budgets as MITERRA-Europe. The results of NutriFarm will be complemented by two other farm-level models; 'Carbon, Water and Nitrogen' (CHN) (Laberdesque et al., 2017), and 'ForSafe-FarmFlow' (FSF) (Gaudio et al., 2015; Zanchi et al., 2021; Modin-Edman et al., 2007; Stockwell et al., 2012). The CHN model focusses on carbon and nitrogen flows. The processes used to describe these flows are more detailed in comparison to NutriFarm. Besides, the model CHN includes a crop-growth model whereas NutriFarm relies on static crop yields. The FSF model simulates the same nutrient and carbon budgets as NutriFarm and MITERRA-Europe, but the soil-processes are described in more detail compared to NutriFarm, which can help improving the results of NutriFarm. This report also includes a case study of the farm-level models with the preliminary results of these three models. Based on these results, an approach on how FSF and CHN can complement the NutriFarm model was be made. This report (D2.2) is part of Work Package 2 (WP2), Task 2.1. The goal of WP2 is to develop and implement an inclusive measure-impact model for the nutrient management platform. This model can spatially predict soil nutrient and carbon flows of major European farming systems from regional to farm scale.

The baseline will be used to picture the effect of nutrient and carbon management measures and is therefore an important element of WP2 as well as for the entire NutriBudget project. This baseline helps to identify areas with nutrient surpluses and deficits, and areas with carbon sequestration potential, but it also helps to test, or even monitor, the effect of nutrient and carbon management measures. The latter links to the research carried out in WP1, 3, 4 and 5.

1.2 NutriModel Framework

The NutriModel Framework, described in D2.1, is provided in Figure 1 and illustrates how WP 2 contributes to the overall objective of the NutriBudget project. The framework consists of the regional model MITERRA-Europe, the farm scale-model NutriFarm and two other farm-scale models that aim to complement the results of NutriFarm; the CHN and FSF model. At the moment, the model MITERRA-Europe calculates nutrient budgets at NUTS2 level for EU-25. Some inconsistencies in the input data still occur for Cyprus and Malta. Also, the UK and Switzerland require some additional data from local authorities. The input data used to run the MITERRA-Europe model are downscaled to pixel-level and used as default data for NutriFarm. However, a user can overwrite default data, if more reliable data are available. The calculation steps of MITERRA-Europe and NutriFarm are aligned.

A user will only see the user-friendly interface of a decision support tool (DST) (WP5). Through this tool, a request for assessing nutrient and carbon budgets at a certain field can be made. This request will be sent to an API (Application Programming Interface), which is connected to the default input data and the NutriFarm model. On the background the CHN and FSF model will complement the farm-level results depending on the region and the nutrients that these two models support. The CHN and FSF model describe soil nutrient and crop nutrient processes in more detail compared to NutriFarm. Potential improvements on the results of the NutriFarm model are part of the modelling approach, and therefore included in the results exposed by the API.

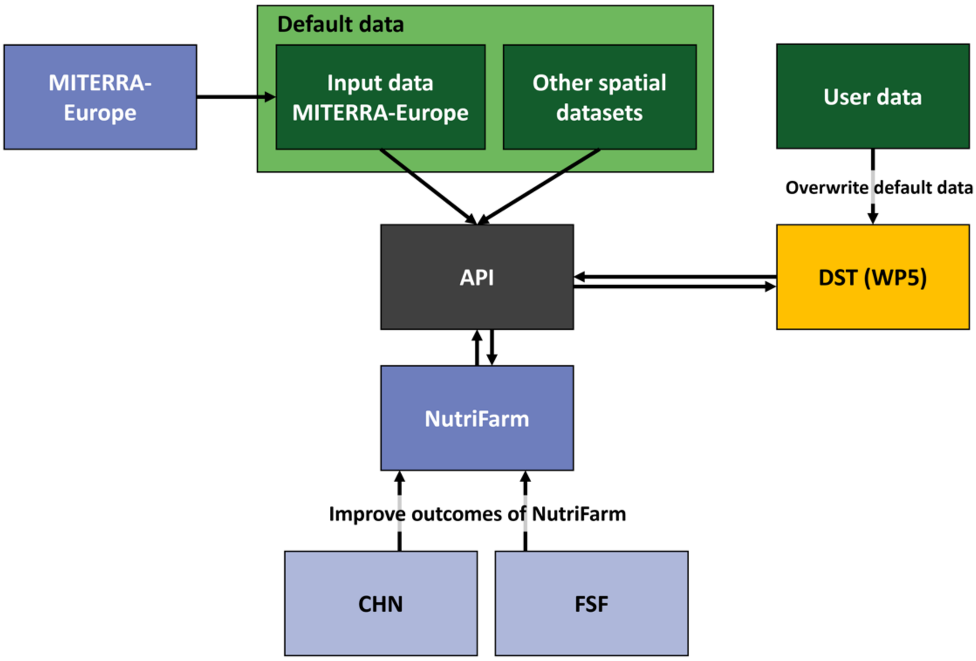


Figure 1. The design of the NutriModel framework.

2. Description of regional NutriModel: MITERRA-Europe

2.1 Model description

The regional NutriModel MITERRA-Europe builds upon the existing dynamic nutrient flow models MITERRA-Europe (Velthof et al., 2009) and INTEGRATOR (Reinds et al., 2012; De Vries et al., 2023). These models have successfully been applied in European studies (e.g., Duan et al., 2020; Lesschen et al., 2011; Velthof et al., 2014; Kros et al., 2018). The algorithms of INTEGRATOR (for P, K, S, Mg, Ca, Cl, Cu, Zn) based on De Vries et al. (2023) will be integrated into MITERRA-Europe which assesses N and C flows based on Velthof et al. (2009) and Coleman and Jenkinson (2014). MITERRA-Europe is a deterministic emission and nutrient flow model, that calculates greenhouse gas emissions (CO_2, CH_4 and N_2O), nitrogen emissions (N_2O, NH_3, NO_x and NO_3), N and soil organic carbon (SOC) 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 Nomenclature of Territorial Units for Statistics (NUTS) 2 level in the EU-28 (Velthof et al., 2009; de Vries et al., 2011, Velthof et al., 2014). The MITERRA-Europe model was originally based on the models CAPRI (Common Agricultural Policy Regionalised Impact, http://www.capri-model.org) and GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies, Höglund-Isaksson et al., 2020) model, and was supplemented with a N leaching module, a soil carbon module and a module for greenhouse gas mitigation measures. The MITERRA-Europe model is described in more detail by Velthof et al. (2009), Lesschen et al. (2011) and Duan et al. (2022).

A short description of the carbon and nutrient modelling and the initialisation of the different elements of the elaborated and renewed MITERRA-Europe model are described below. The exhaustive calculation steps of MITERRA-Europe were described in D2.1.

- Carbon: in mineral soils, the turnover of carbon (C) pools is calculated with the RothC model (Coleman and Jenkinson, 2014). This model requires relatively little input data, including soil, climate and farm activity data, which is available at European level and often also collected at farm level. Therefore, the model is practically implementable at different scales. The model distinguishes 5 carbon pools: decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO), humified organic matter (HUM) and inert organic matter (IOM). The model will be linked to the mineralisation of organic N, P, S, Ca, Mg and K via carbon-nutrient ratios (C/N, C/P, C/S, C/Ca, C/Mg and C/K) (De Vries et al., 2023). The current carbon inputs are used to deviate the initial soil organic carbon stock over the different pools.
- Nitrogen: the nitrogen fluxes are assessed using a steady state linear approach (Velthof et al., 2009). Emissions of ammonia and nitrous oxides and N surface runoff are included as a non-linear function of N input, and N leaching as a function of N surplus, while accounting for relevant site properties, including soil texture, soil organic matter content, ground water level and precipitation surplus. The soil organic nitrogen (SON) turnover is included by introducing C:N ratios to each SOM compartment (Bonten et al., 2016).
- Phosphorus: the phosphorus fluxes are included by using a Langmuir equilibrium, supplemented with rate limited diffusion based on De Vries et al. (2023). Phosphorus is partly in equilibrium and partly not, and therefore initialisation is required. The input data of 2020 (i.e., the base year) is used to run the model for 10 years using the same input data for each year. The calculated P balance in year 10 is taken as the initial starting point to run the model.
- Sulphur: sulphur fluxes are included by an extended Freundlich equation, where extended refers to the inclusion of pH impacts on the adsorption constant (Gustafsson et al., 2015). The amount of $S_{adsorbed}$ is set in equilibrium with S inputs and outputs in 2020 for the initialisation. Note that this implies that we assume that there is no S adsorption at the starting year.
- K, Mg, Ca: the sum of these base cations (BC) is included by a charge balance relationship where BC release is derived by equating BC leaching to anion leaching (where anions include NO_3, SO_4, Cl and HCO_3) and accounting for BC input and BC uptake to get BC release according to De Vries et al (2023). The change in pH is then derived by a simple literature-based pH-Base saturation relationship. Finally, the division in Ca, Mg and K is based on the fractions of Ca, Mg and K on the exchange complex. These nutrients do not require initialisation, because it is a well buffered system. Base cation accumulation or release follows from the input minus the uptake and leaching. A change in base cations results in a change in pH that is affected by the Cation Exchange Capacity (CEC).
- Cu, Cd, and Zn: for these heavy metals a Freundlich equation is used with an adsorption constant that depends on clay, SOM and pH (De Vries et al., 2022; De Vries et al., 2023). These nutrients do not require initialisation, because accumulation or release is based on the input minus the crop uptake and leaching. The initial soil Cu, Cd and Zn content is determined by: (i) the dissolved concentrations in solution and thereby the leaching, and (ii) the concentrations in the crop and thereby the crop uptake. Crop uptake depends on the soil conditions for Cd and Zn, but not for Cu.

2.2 Baseline

The goal of NutriBudget is to optimise nutrient budgets in agriculture. To establish a benchmark for evaluating the agronomic mitigation measures selected in WP1, a baseline scenario that represents nutrient and carbon accumulation in or release through the soil (e.g., through emissions and leaching) must be set up. The boundary conditions of the baseline are:

- The baseline covers EU-25 (Cyprus, Malta, the UK and Switzerland still to be included).
- The results are provided at NUTS2 level.
- This baseline is based on current agricultural practices.
- The baseline provides results at an annual time step and represent the year 2020. Input data is updated to 2020. For variables that deviate each year (e.g., crop yield), an average of the years 2019, 2020 and 2021 is taken. For variables that do not have data in 2020 available, most recent data are selected. More information on the input data is described in section 4.1.
- Soil nutrient (N, P, K, S, Mg, Ca, Cd, Cu, Zn) and carbon fluxes are assessed for the topsoil (0-30cm), although the rooting depth is considered for the assessment of the concentration of nutrients in soil water.

The model distinguishes the following livestock sectors: dairy and beef cows, pigs, poultry and laying hens, sheep and goats. Further, it includes about 50 arable and perennial crops, based on the CAPRI model (Heckelei and Britz, 2001) and monitored by Eurostat, and grassland. The nutrient and carbon budgets are assessed by calculating the nutrient and carbon inputs, including crop residues, animal excretion during grazing or the application of organic fertilizers, chemical fertilizers, atmospheric deposition and biological fixation, and the nutrient and carbon outputs, including atmospheric emissions (e.g., CO_2, CH_4, NH_3, N_2O, and NO_x), runoff to surface water and leaching to groundwater (e.g., NO_3^-, N_{part}, NH_4^+, DON), and plant uptake. The nutrient and carbon budgets are assessed based on the difference between the inputs and outputs. An example of the nitrogen balance of an agricultural system is given in Fig. 2. A change in the flow rate of one N flow, has consequences for others, depending also on the storage capacity of the system. The system inputs should balance the system outputs for an optimal nutrient budget.

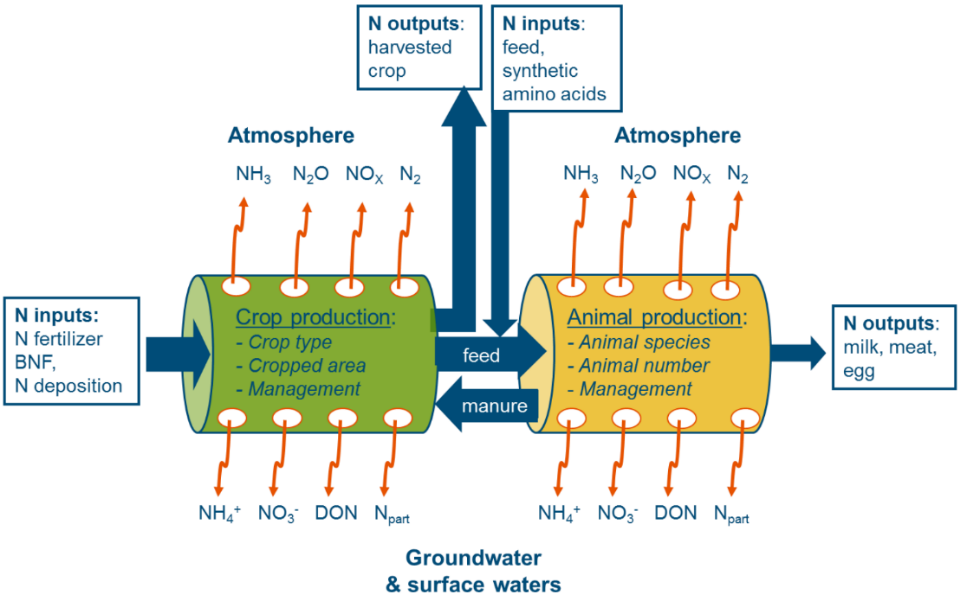


Figure 2. Conceptualization of the nitrogen inputs and outputs in an agricultural system based on Oenema et al. (2009).

The farming system boundary, also explained in D2.1 (Hendriks et al., 2024), illustrates the boundaries of the NutriModels (Fig.3). The soil-related applications and removals of nutrients and carbon are included in the modelling approach.

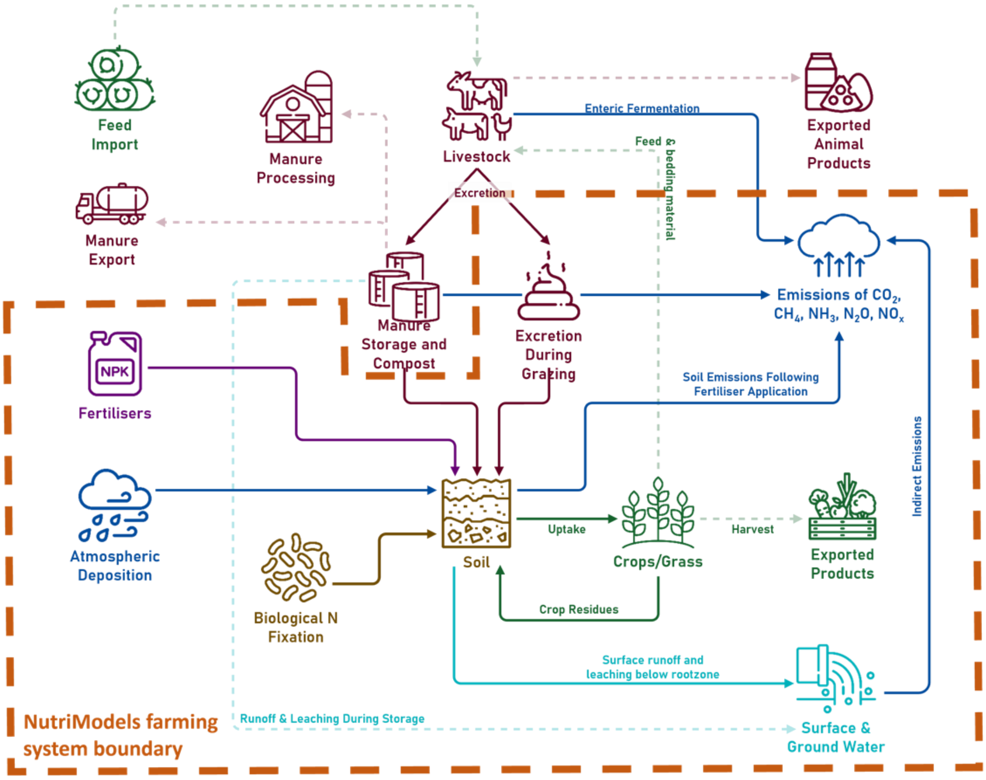


Figure 3. The modules included by the MITERRA-Europe model (and the NutriFarm model). arrows show the interactions between modules and the dashed arrows show the outflows. The orange dashed box illustrates the farming system boundary of the NutriModels.

To model nutrient and carbon budgets at regional level for the whole of Europe, some assumptions had to be made. These assumptions are a consequence of a lack in data at the required level of detail (NUTS2), or the data is not provided in the required context (e.g., the data of chemical fertilizer consumption does not come with information on the crops that received the fertilizer). The model describes the nutrient and carbon flows at a certain level of detail depending on a balance between available and required data. Most important assumptions of the MITERRA-Europe model are:

1) Fertilizers: crop nutrient demands are calculated to assess the distribution of chemical fertilizer over crops, because data on chemical fertilizer use is only available at national level in Eurostat and the International Fertilizer Association, and these data do not provide information on the crop application. The amount of chemical fertilizer applied to the soil is assessed by the N crop demand minus the crop available N from applied manure, grazing, deposition and crop residues. The N crop demand is assessed based on the N in harvested material and residuals multiplied by an efficiency factor of 1 for grass and permanent crops (except fruit and olive trees), 1.1 for straw crops and 1.25 for other crops.
2) Atmospheric deposition: deposition maps of all nutrients are available, except for P. For P, only a global dataset is available (Mahowald et al., 2008). At the moment, MITERRA-Europe still uses a fixed deposition rate of 1 kg/ha/yr for the whole of Europe. This number should be replaced by e.g., the global dataset, as it is likely that P deposition varies among the EU Member States as indicated by Panagos et al. (2022).

3) Biological N fixation: for arable land without N fixing crops (e.g., soya and pulses) biological N fixation is set at 2 kg N/ha; a standard value for free living soil bacteria that can fix N (Velthof et al., 2009). For grassland, the value is set at 7.5 kg N/ha (Baddeley et al., 2013). For N fixing crop soybean an N fixation of 80% of the amount of N in the aboveground plant part was used following Smaling et al. (2008). For pulses an average value of 70% was used based on Baddeley et al. (2013).

3) Excretion during grazing: a housing fraction (i.e., time livestock spends in the stable) is determined per country (based on the Common Reporting Format (CRF) data of the National Inventory Reporting) to assess the manure produced in the stable and the manure produced during grazing. To assess the excretion rate of grazing livestock, there is assumed that temporary grassland receives the same amount of manure as permanent grassland, whereas natural grassland receives 50%. Besides this, it is assumed that 50% of the temporary grassland is also used for grazing. From the amount of carbon that enters the soil system through excretion from grazing livestock, a N loss of 7% is assumed.

4) Organic manure application after storage: manure application is based on available manure within a NUTS2 region and the required N input by crops grown in that area. The maximum amount allowed to be applied is 170 kg N/ha, except for regions under derogation (210 kg N/ha). The model corrects for the maximum amount of P allowed to be applied. For compost application, there is assumed that 51% is used in agriculture (based on Saveyn and Eder, 2013), except for Belgium (where only 20% is applied in agriculture) and the Netherlands (where 55% is applied in agriculture).

5) Crop residues: for straw crops the amount of crop residues is assessed based on yield (Scarlat et al., 2010). For the other crops no relation between yield and the amount of residues was found, and therefore the carbon input was assessed based on a crop-specific harvest index and residue removal fraction. The ratio of straw:stubbles/chaff is estimated at 55:45 based on different studies (e.g., McCartney et al., 2006). Belowground carbon input is calculated according to Taghizadeh-Toosi et al. (2014).

6) Surface runoff and leaching: water flows are based on the water flux model of Keuskamp et al. (2012). Total precipitation surplus is divided over waterflow to groundwater and to surface water. Surface runoff fractions were derived as a function of slope, land use, soil texture, and depth to hard rock. Leaching fractions were derived as a function of soil texture, temperature, rooting depth, land use and soil organic carbon content.

7) Crop uptake: The uptake of nutrients by the crop depends on the amount of N available from organic fertilizer, deposition and crop residues, and the amount of N demanded by the crop. There is assumed that crops always meet the N demand. The N uptake by cover crops is based on Schroder et al. (1997), which provides N yields in cover crops per environmental zone. The N yield in cover crops is also used to assess the amount of carbon input from cover crops based on an average CN ratio of 25.

8) Soil emissions: soil N_2O and CO_2 (for peatland) emission factors (EF) are based on the IPCC 2019 guidelines, and NH_3 emission factors are based on the GAINS model (Winiwarter, 2005).

Of course, the intrinsic soil properties also play a role in the nutrient and carbon fluxes. For example, base cation weathering depends on a combination of soil texture class and acidity level of the parent material, and mineralization of soil organic carbon releases nutrients as well. These interactions are included and are simultaneously a way of downscaling the results.

3. Description of field scale models

3.1 NutriFarm

Within the EU Horizon 2020 project Nutri2Cycle, a farm-level model that can assess C and N flows was established. The calculation steps of this model are aligned with the MITERRA-Europe model and were therefore used as a starting point for the development of the NutriFarm model.

NutriFarm quantifies nutrient budgets and flows at farm scale (including fields) by integrating various key nutrients and trace elements. The NutriFarm model simulates the C cycling, and the soil solution chemistry of all nutrients, including changes in total soil concentrations of C and N (total), adsorbed concentrations of P and S, exchangeable concentrations of Ca, Mg and K and dissolved concentrations of N (NH_4, NO_3), P, S, Ca, Mg, K, Cu and Zn and pH. The cycling of C is based on the RothC model (Coleman and Jenkinson, 2014), for N as included in MITERRA-Europe (Velthof et al., 2009) and for the other elements as described by De Vries et al. (2022;2023) and Schulte-Eubing and De Vries (2021). The soil solution chemistry of included nutrients is determined by the element input of mineral and organic fertilizers, biosolids (compost, sludge, manure) and deposition (and fixation in case of N), net uptake by plants, net mineralization/immobilization as well as by soil buffering processes, including adsorption-desorption (P, S, Cu and Zn), cation exchange, and weathering (Ca, Mg and K), while nitrification and denitrification play a role in N transformations. The nutrient concentrations are simulated by a set of: (i) rate limited and linear equations for C and N cycling due to microbial processes and (ii) mass balance equations combined with equilibrium equations or empirical relationships for the other elements.

3.1.1 Deviation of NutriFarm with MITERRA-Europe

Like MITERRA-Europe, NutriFarm includes a top layer of 0-30cm, while it also includes a bottom layer of 30-100cm to ensure that the root zone of all included crops is covered. The fraction of the transpiration and of the element uptake in each layer is based on the fine root distribution of the included crops. The runoff of elements to surface water is calculated as an aggregated value for the surface and the interflow of the two soil layers, while leaching to groundwater is calculated a depth of 100 cm, comparable to the water flux model used by Keuskamp et al. (2012) with results at a 1 km x 1km resolution at the European scale (see Figure 4).

Therefore, though the simulations of nutrient fluxes are similar to MITERRA-Europe, the concentration of nutrient X (N, P, S, K, Ca, Mg, Cu and Zn), and of Cd, in view of its potential toxic impact, is calculated for the distinguished two layers in NutriFarm. For each nutrient, the concentration in each layer is determined by a nutrient mass-balance equation, that describes the inputs and outputs and accumulation, divided by the water flux according to:

$$[X]_1 = (X_{in1}-X_{up1}-X_{acc1})/ (Q_{eff1}+Q_{int1}) \tag{3.1}$$

$$[X]_2 = (X_{le1} - X_{up2}-X_{acc2})/(Q_{eff2}+Q_{int2}) \tag{3.2}$$

where is [X] is the concentration in the soil solution of nutrient X (g m^{-3} or $mg.l^{-1}$), X_{in} is the total nutrient input to the field entering the topsoil, $X_{up,1}$ and $X_{up,2}$ is the crop nutrient uptake, and $X_{acc,1}$ and $X_{acc,2}$ is the nutrient accumulation from the topsoil (0-30cm) and the subsoil (30-100 cm), respectively (kg ha^{-1} yr^{-1} for the major nutrients N, P, S, Ca, Mg, K and g ha^{-1} yr^{-1} for the minor nutrients Cu and Zn and for Cd) and where Q_{eff1} and Q_{eff2} are the water fluxes at 30 cm and 100 cm depth, respectively (m^3 ha^{-1} yr^{-1}). X_{le1} is the nutrient leaching from the topsoil to the subsoil. For the micronutrients, of which the unit is g ha^{-1} yr^{-1} fluxes are multiplied by 1000 to convert kg to g.

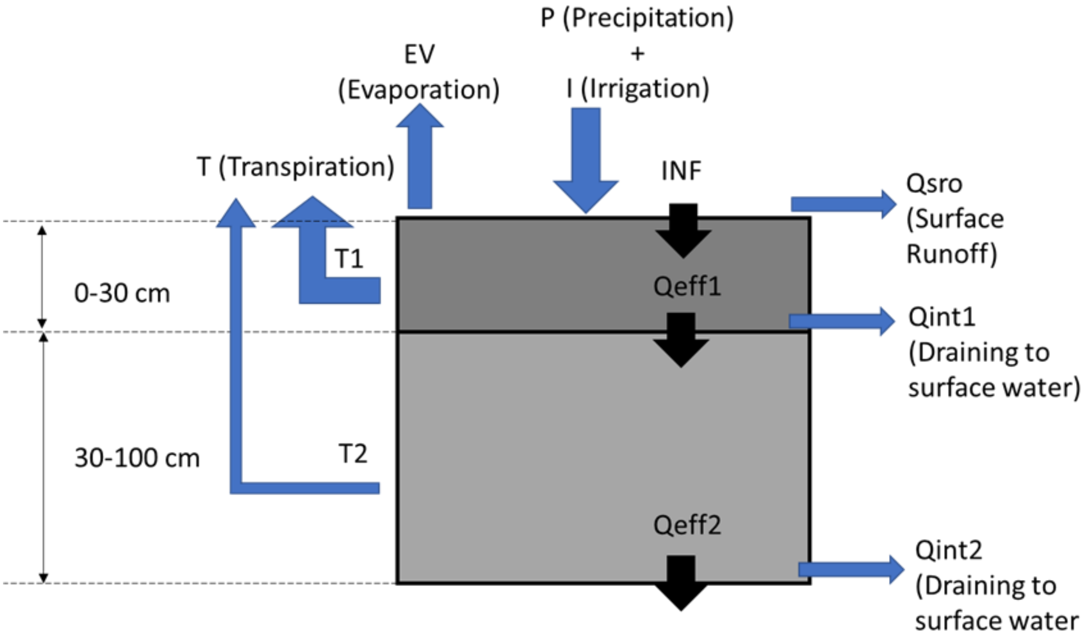


Figure 4. Scheme of the partitioning of the total runoff (Qtot), being equal to water input by precipitation and irrigation minus the evapotranspiration, divided over surface runoff (Qsro), and leaching recharging shallow groundwater (Qeff) in layer 1 (0-30 cm) and layer 2 (30-100cm).

3.1.2 Initialization of NutriFarm

In calculating budgets of C, P, S, base cations, and metals for the baseline year (2020), it is necessary to have a spin-up period to avoid unrealistic changes in the first year. The Idea could be to start in a certain year (e.g. 1960) and then run for 60 years but this requires data for this year and input data over the past period. Since the focus of the data derivation is on the year 2020, both for inputs, crop outputs and soil concentrations/soil properties, the input data for or near 2020 are used to run the model for 10 years and then using those slightly adapted data as the input data for 2020. Below, the arguments for this initialization period are given:

Carbon: Like MITERRA-Europe, NutriFarm also uses the current carbon inputs to assess the fraction of carbon in the different pools.

Phosphorus: Available P Olsen data (near 2020) are used to assess the P content extracted by oxalate (Pox): assuming that Pox is 8 times P Olsen (Steinfurth et al., 2021; De Vries et al., 1994). The input data of 2020 are then used to run the model for 10 years using the same input data for each year. The calculated labile and stable P pools in year 10 are taken as a starting point for 2020. It is checked that the calculated Pox data are close to the original data used (Annex 1).

Sulphur adsorption, pH and base saturation: the sulphur adsorbed by soils ($S_{adsorbed}$) is dependent on pH, and pH is dependent on base cations (BC) accumulation or release. BC accumulation or release follows from input minus uptake (determined by crop yield) and leaching, determined by SO_4, NO_3, Cl and HCO_3 leaching. This BC change leads to a pH change that is affected by CEC. Given the above reasons, the input data of 2020 are used to run the model for S, N, Cl, BC and pH changes for 10 years using the same input data for each year. The amount of $S_{adsorbed}$ in 2020 is set in equilibrium with S inputs and uptake. The calculated $S_{adsorbed,}$ base saturation and pH in year 10 are taken as a starting point to run the model. It is checked that the calculated pH data are relatively close to the original data used (Annex 1).

Cu, Zn and Cd: Current soil content determines: (i) the dissolved concentrations in solution and thereby the leaching and (ii) the concentrations in the crop and thereby the crop uptake, thus determining the budget (at a given input, the accumulation is based on input – crop uptake – leaching). The concentrations of Cu, Zn and Cd in the soil and in crops (Zn and Cd) are dependent on pH and SOM, which need to be initialized as mentioned above. The input data of 2020 are thus used to run the model for Cu, Zn and Cd for 10 years using the same input data for each year. The calculated content of Cu, Zn and Cd in the soil in year 10 are taken as a starting point to run the model. It is checked that the calculated soil content data of Cu, Zn and Cd data is close to the original data used (Annex 1).

3.1.3 Parameterisation of NutriFarm

The input data for NutriFarm were categorised into:

1. General information, including the name and location of the field; crop type, soil type and field general properties, including the field area and slope
2. Livestock properties, including the type and number of animals and housing days (hours)
3. Nutrient (N, P, S, Ca, Mg, K) and heavy metal inputs from atmospheric deposition, fertilizers and manure and irrigation rate
4. Crop yield and nutrient and heavy metal (for Cu) content in the crop. The Zn and Cd content in the crop are estimated based on the initial soil Zn and Cd content and soil properties mentioned above.
5. Soil properties for two layers (0-30cm and 30-100cm), including bulk density, soil pH (in KCl), content of clay, soil organic matter, inorganic N, and initial C:N ratio, cation exchange capacity and base saturation, initial content of soil P (Olsen-P or P extracted by oxalate), and initial heavy metal (Cu, Zn and Cd) content;
6. Annual and monthly climatic data, including precipitation, temperature, evaporation and transpiration.

3.2 CHN

The main objective of the CHN model is to be used during the agricultural season as a decision support tool for farmers to advise them on sustainable carbon and nutrient management options. Arvalis set out to build an agronomically relevant crop model that (1) did not need to be coupled with an external tool; (2) was compatible with 105 field-based measurements and remote sensing data and (3) required less computing time and a smaller number of input parameters. This approach was justified, in particular, by the development, by the Arvalis Institute, of a number of reference systems (including a soil database with more than 500 referenced French soils; a database of varieties including more than 2000 varieties), and a centralized IT environment (Figure 5) in which a crop model could provide added value for our expertise.

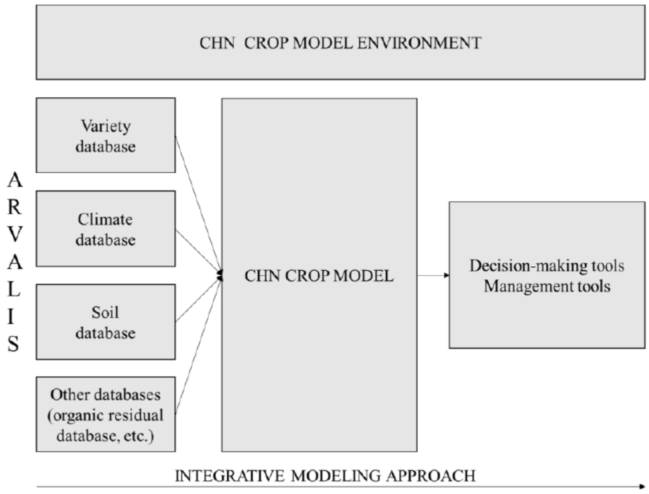


Figure 5. CHN crop model environment with its connections to databases and decision-making tools.

It has been designed as a conceptual and mechanistic model. The main processes simulated are plant development and growth, carbon, water and nitrogen fluxes and stocks in the soil, plant and atmosphere compartments (Figure 6). The model is built around 3 main modules:

The 'carbon' module (C), with, for the soil compartment, the formalisation and parameterisation of the AMG model (Andriulo et al., 1999), and, for the plant compartment, the Monteith's carbon accumulation principle (Monteith and Moss, 1977);

The 'water' module (H), with the water balance model, based on the work of Wery and Lecoeur (2000) and the PILOTE model (Khaledian et al., 2009);

The ‘nitrogen’ (N) module, based on the principle of the nitrogen nutrition index (Justes et al., 1994) for the plant compartment. Four forms of nitrogen are considered: organic nitrogen, urea, ammonia and nitrate.

The initialisation of CHN water fluxes is done at the beginning of August, where we consider that the soil water holding capacity is the lowest of the year. The N balance is initialized on August 1st (before sowing). This is an empirical method based on a key for distributing nitrogen by horizon (0-30, 31-60 and 61-90 cm) according to previous crop and soil type. This soil mineral nitrogen stock, called Post-harvest residue (noted RPR), is considered to be no less than a minimum amount of nitrogen (Nmin), which corresponds to a minimum value of soil nitrogen, non-leachable and non-absorbable. For the different CHN model modules, databases are divided into two distinct sets: one for calibration and the other for evaluation. The CHN parameters were calibrated using the Nelder-Mead optimization algorithm. For example, Crop Growth Monitoring calibration datasets comprises 312 data points collected across 38 sites over a period of 14 years (from 2000 to 2015), covering 35 different varieties. The sowing dates range from October 7th to November 15th, with nitrogen application rates varying between 40 and 265 kg per hectare. The evaluation and validation of models is based on field datasets collected by Arvalis. For example, CGM Evaluation/Validation dataset includes 132 individual plots distributed across 44 sites, involving 10 varieties over 4 years (from 2018 to 2021). Sowing dates range from October 4th to November 5th, with nitrogen fertilization rates varying between 30 and 340 kg per hectare.

Potential changes or refinements to be made for a better alignment between CHN and the NutriModel Framework are listed in Annex 2.

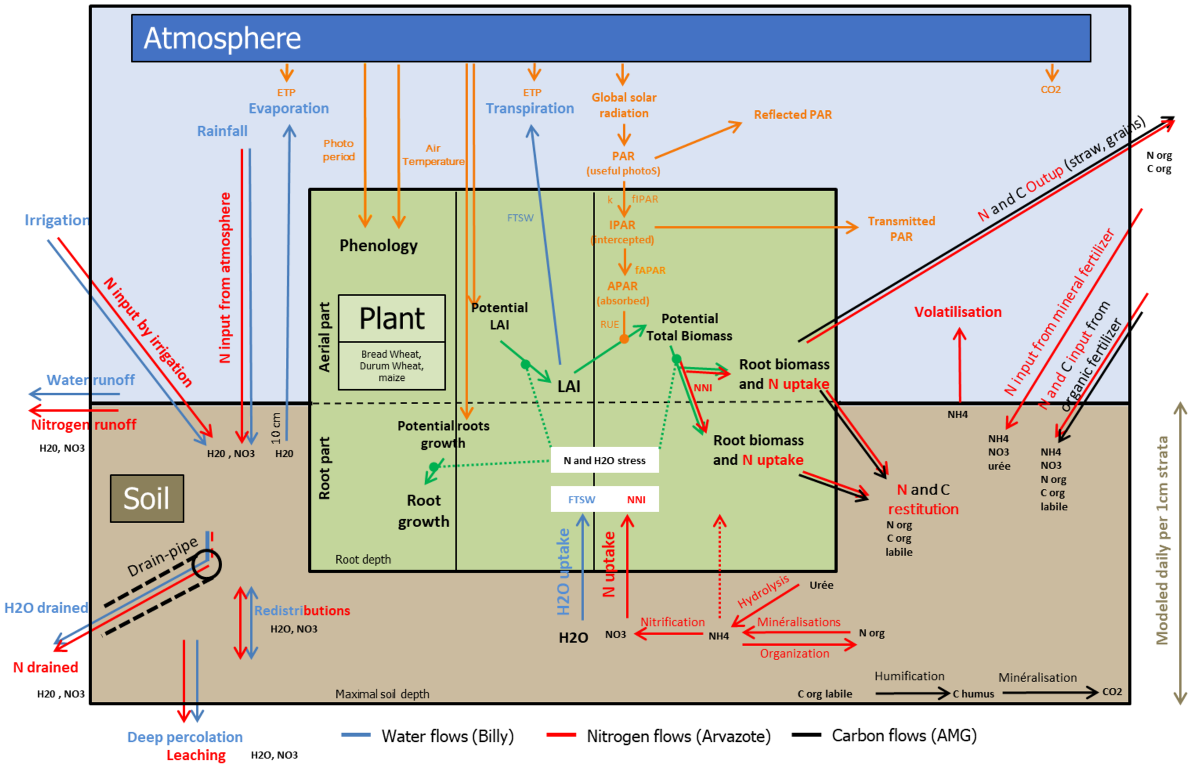


Figure 6. Flowchart of the CHN model.

3.3 FSF

The model FSF is a new, fully mechanistic model that depends on singular causal relationships between any two components (one example being the Arrhenius temperature response function regulating the weathering rate of a given mineral). It is a combination of two existing models, namely ForSafe (Gaudio et al., 2015; Zanchi et al., 2021) and FarmFlow (e.g, Modin-Edman et al., 2007; Stockwell et al., 2012), and it is further elaborated on Cd and C flows. The singular causal relationship structure makes the model less dependent on calibration, but heavily dependent on empirical bases for the causal relationship it is constructed of. It also allows the model to be more responsive to changes in drivers that may have plural impact on the soil (such as moisture and acidity) and, where relevant, able to regulate these drivers in turn through feedback mechanisms. The mechanistic nature of the model also means that it keeps track of interactions between the cycles of different elements, since the rate variables (chemical reaction rates, physical change rates, or biological activity rates) are dependent on the state variables (such as element concentrations and substrate availability), which are in turn regulated by these rates. This implies, for example, that a change in the mineralization rate for nitrogen will have an impact on soil solution pH, which will in turn affect the adsorption of potassium, and thereby the bioavailability of the latter.

This last aspect of the FSF model, the integrated mechanistic architecture, is the added value to the project, since it allows to identify critical thresholds and indirect impacts of agricultural measures meant for one element on the other elements.

At this stage in the project, we have isolated the compartments in FSF that are relevant for the aims of the work package. The modular architecture of the model has allowed us now to isolate the soil compartment and focus on the cycles of elements in the soil, as impacted by agronomic choices involving crops, residue and fertilisation, as well as climatic factors and site conditions. The model is now able recreate changes in the bioavailability of N, P, S and base cations, The adaptation to agricultural application required as number of modifications to the uptake and litterfall algorithms. The model now reads these fluxes as inputs. In the case of nutrient and water uptake, the model receives time series of potential uptake required by a user defined crop and returns values of actual uptake that are regulated by soil water and nutrient bioavailability in the soil. The latter are continuously updated by the model internally.

The model is focused on mass balances in the soil, keeping track of mass conservation as fluxes and chemical transformations affect how much of any element is available under which form. The forms dealt with are in the solid, aqueous and gaseous phases. The solid phase include mineral, exchangeable and organic form. The aqueous phase refers to the soil solution where chemical reactions can occur, both in speciation (such as oxidation and reduction reactions) and precipitation into secondary minerals or adsorption onto the ion exchange receptors on clay, silt and organic particles. The aqueous phase acts as a conduit to allow gaseous elements, such as CO_2, methane and N_2O, to volatilise out of the soil. The rates governing the reactions in the aqueous phase, as well those regulating the exchanges with the solid and aqueous phases, are all controlled by microenvironmental conditions and relative concentrations of the different elements.

FSF will identify conditions within which nutrients are bioavailable while the risk for leaching is kept low. These conditions are dictated by how the different elements interact, affecting ultimately the levels and timing of concentrations of nutrients in the soil solution. In this manner, we intend to create a set of dynamic response curves that describe the boundary beyond which a certain nutrient may become deficient, or when the risk for leaching becomes high. These curves will delimit a space of viable bioavailability within low leaching risk and will inform the other model to back-calculate agricultural measures that are able to keep the elements concentrations withing the said spaces.

4. Input data

4.1 MITERRA-Europe input data for European application

In the previous report (D2.1), the potentially required updates and refinements on the input data of MITERRA-Europe were stated. Now the input data have been updated and refined, the potentially and the realised updates and refinement were described in Annex 3A.

The input data of MITERRA-Europe were updated to baseline year 2020 (Annex 3B). For variables that deviate each year (e.g., crop yield), an average of the years 2019, 2020 and 2021 was taken. For variables that do not have data in 2020 available, most recent data are selected. Weather data were averaged over a time period 1990-2020. And crop, organic fertilizer, and chemical fertilizer composition were compiled from the median of multiple data sources. Further, the input data were elaborated with crop (residue), manure and chemical fertilizer composition data on nutrients P, K, Ca, Mg, S, Zn and Cu.

The data were all updated to the NUTS2 regions of 2021 (Eurostat, 2021). A downscaling to NUTS3 is currently not possible, because a request for NUTS3 data to Eurostat resulted in: 1) individual farm activity data that was only linked to NUTS2 (so not to NUTS 3 or actual locations), 2) data of only a limited number of Member States, and 3) outdated data of 2016. In Annex 3A can be seen that Eurostat data is the main input data source of MITERRA-Europe. As long as the NUTS3 data are not available in the requested format (data of 2020, at NUTS3, and for EU-28), it is not possible to downscale MITERRA-Europe to NUTS3 regions.

For the calculation of nutrients other than N, the soil properties become a dominant factor controlling the fate in soil, crop uptake and losses. Downscaling is implemented by linking land use type (arable, grassland and perennial) and/or soil conditions to a proportion of occurrence within a NUTS2 unit. Another approach is to make directly use of the spatial maps, instead of a proportion within a NUTS2 region. An example of this approach is given by De Vries et al., (2011), where unique combinations of land use, soil type, slope class, and altitude class were created to assess nutrient budgets in so-called Nitrogen Calculation Units (NCUs). This downscaling procedure should be compared to the downscaling procedure MITERRA-Europe uses at the moment (considering soil properties, land use types and livestock categories). However, average soil and climate conditions at NUTS 2 level can be replaced by the initial spatial data to adopt to the calculate-first-interpolate-later approach, as suggested by Addiscott and Tuck (2001) and Leterme et al. (2007). The computational power of gridded input data turned out that MITERRA-Europe can run using spatial input data at the finest resolution of 10x10 km.

The area of agricultural land was selected based on CORINE Land Use Map – 2018 (EEA, 2019). Besides distinction between agricultural versus non-agricultural land, the model is able to assess nutrient and carbon flows specifically for arable land, grassland, and perennial crops. Also, animal-specific emission factors are applied to assess the emissions for each livestock category.

4.2 Approach for default dataset for NutriFarm

The input dataset of MITERRA-Europe will serve as default dataset for the NutriFarm model. At the moment, the input data of MITERRA-Europe is compiled at NUTS2 level. However, these data cannot directly be used as default dataset for the NutriFarm model.

Through the DST, a user will request carbon and nutrient budgets for a single field or a couple of fields. This request is sent to the API, which picks the centre of the field(s) to select a unique identifier for the pixel in which the field is located. This unique identifier is linked to the default dataset, where the required input data are selected to run the NutriFarm model. Difficulties might be faced by rasterizing data that are initially available at administrative level. In collaboration with WP5, the reliability of European input data as default data at field level needs to be tested, and if necessary, addition input data need to be requested in the DST. More background information on the running IT services for the DST are described in D3.4.

In addition, NutriFarm calculates the nutrient and carbon budgets over two soil layers, whereas MTIERRA-Europe calculates these budgets only for one soil layer due to lack in input data at European level. In NutriFarm, the soil properties of the second soil layer (30-100cm) were derived from the LUCAS topsoil data that was used in MITERRA-Europe using a topsoil:subsoil ratio per element. The ratios were derived from:

(1) raster data of world soil grid (1x1km) for soil bulk density, cation exchange capacity (CEC), soil texture (sand, silt and clay content), soil pH (in H_2O) and soil organic carbon content (SOC);

(2) the measurement-based Cu, Zn and Cd contents in topsoil and subsoil in the Netherlands up to 1m (http://weppi.gtk.fi/publ/foregsatlas/maps_table.php);

(2) the Digital Soil Maps published by Doorn et al. (2023) (https://data.4tu.nl/datasets/96c54816-4e36-4285-89fd-a63e478f9acd) for soil Alox and Fe_{ox} content in the Netherlands up to 1m for related soil types;

(3) the Harmonized World Soil Dataset (HWSD) dataset for soil calcium carbonate ($CaCO_3$) content.

4.3 Test datasets for field scale models

The field scale models run for a consistent dataset based on a long-term field experiment in Sweden. This consistent model run helps comparing modelling processes and results. A single field (spring barley) and year (2020) was selected to ease the comparison. The input data of the test dataset are summarized in Annex 4.

The datasets were provided in a way that they could directly be used by NutriFarm. Additional data required by FSF and CHN are listed in subchapters 4.3.1 and 4.3.2 respectively.

4.3.1 Additional input data required by CHN

The CHN model relies on a range of input data to accurately simulate crop growth and nutrient dynamics. Key inputs include crop type, cultivar, drilling density, and sowing date. Climate conditions and trial location are also essential, along with detailed soil information, such as soil type, analysis results, and the stock of soil mineral nitrogen. Additional data inputs encompass water sensor readings, mineral nitrogen fertilization, irrigation practices, soil tillage, organic fertilization, and information on the previous crop (type, harvest date, yield, residues, nitrogen content, etc.). The model also considers the impact of cover crops and incorporates observed phenological stage dates, as well as measurements of biomass, nitrogen percentage, and Leaf Area Index (LAI). Among these inputs, the most sensitive data include soil type and parameters (such as soil Water Holding Capacity, soil depth, C/N ratio, and CaCO3 content), the soil mineral nitrogen stock, cultivar selection, and the observed development stage dates (e.g., Z31 and Z55).

The mandatory climate dataset required for the CHN model consists of daily data for the following parameters:

- Minimum temperature
- Maximum temperature
- Total precipitation
- Global radiation
- Minimum relative humidity
- Maximum relative humidity
- Wind speed measured at 2 meters above ground level

These climate variables are critical for simulating crop growth and environmental interactions accurately.

For accurate simulation with the CHN crop model, a comprehensive soil data set is crucial. The mandatory soil data includes information on soil total depth, row growth maximum depth, and specific soil horizon depths. Essential properties for each horizon include water holding capacity, texture without CaCO3 (analysed through 5 fractions as per NF X 31-107 and ISO 11277), gravel and stone percentage with their geological nature, CaCO3 content (measured by NF ISO 10693), pH in water (NF ISO 10390), and dry bulk density calculated from the mass and volume of a soil sample according to the specified ISO standard. Additional data required comprises soil horizon sequence, soil classification based on WRB, field capacity, wilting point (pF 4.2), and other chemical analyses. These include phosphorus content (Olsen method, NF ISO 11263), potassium and magnesium levels (NF X 31-108), cation exchange capacity (CEC) using Metson's method (NF X 31-130), organic carbon content (NF ISO 14235), nitrate, nitrite, and ammonium concentrations (extracted with potassium chloride solution, ISO/TS 14256), and total nitrogen content (NF ISO 13878). Accurate measurements of these parameters are essential for the model's predictions and effectiveness.

For effective calibration and simulation with the CHN crop model, detailed crop and farm management practices data are essential. The mandatory data includes information on the main crop, such as growth stage dates, sowing date, harvest date, and yield. For irrigation, details on the date, amount (in mm), and NO3- concentration in the irrigation water are required. Fertilizer application data should include the date, amount (kg/ha), type of fertilizer, and its elemental composition. Additionally, information on the previous crop is crucial, including the sowing and harvest dates, as well as any residues remaining. Additional data that would enhance the model's accuracy includes drilling density and tillage practices, with specifics on the date, soil depth, description, and any relevant comments. Collecting and providing these data will ensure robust model predictions and support effective crop management strategies.

For precise calibration and validation of the CHN crop model, specific observations and measurements are required. Very useful observations in unknown environments include the growth stage date for Z30 (pseudo-stem erection), Z55 (emergence of inflorescence completed), and Z65 (anthesis completed). For Z65, additional data on biomass and %N at the growth stage date are necessary. Sensor data should include soil moisture dynamics measured using tensiometers and Leaf Area Index (LAI) readings. To assess nitrogen nutrition, additional data should include measurements of nitrogen concentration, or any other sensor correlated with nitrogen concentration, such as chlorophyll meter to determine the nitrogen nutrition index throughout the growth cycle in winter wheat. Collecting these observations and sensor data will enhance the accuracy of the model’s predictions and provide a clearer understanding of crop performance.

In conclusion, to extend the applicability of the CHN model to various land uses and across all of Europe, a comprehensive collation of environmental data from field platforms situated in different agroclimatic regions is essential. This data includes detailed soil information, climate and weather records, as well as manual observations or data gathered from sensors installed in each field platform. By collecting this wide range of environmental inputs, the CHN model can be fine-tuned to account for the diverse conditions found across Europe. The next step involves the assimilation of sensor data or manual observations, ensuring that the model accurately reflects real-world conditions. This process allows the model to be calibrated and validated against field-specific data, making it robust and adaptable for different land uses and regional variations.

4.3.2 Additional input data required by FSF

FSF requires a set of site-specific data that determine the biogeochemical conditions of the soil, as well as climatic and background atmospheric deposition conditions. The model calculates the release of elements from the weathering of minerals and requires therefore an estimate of the mineralogy of the soil. This information can be obtained from existing databases of soil mineralogy compiled through the UU convention on long range transboundary air pollution (LRTAP), which were compiled to calculate critical loads of acid deposition on European terrestrial ecosystems. In case this information is missing, the weathering calculations can be entirely substituted with estimate of weathering fluxes. The model also requires texture (sand, silt clay) as well as original carbon and coarse material content (stoniness). From these, the model calculates internal physical (density), hydrological and stoichiometric parameters. Data for climate and background atmospheric deposition is required in coordination with the other models in the work package and available from European databases. Climate data is required daily, while deposition can be given in annual values that are scaled to daily values depending on the daily fraction of annual rainfall.

The model requires a range of parameters to regulate the response functions describing all the reactions and fluxes in the soil. These include chemical rate parameters, exchange velocities, and decomposition rates. All these parameters are available from earlier developments of the model and have been extensively tested and revised for a range of soil types and climatic conditions and are provided as part of the model package (Belyazid et al., 2022; Zanchi et al., 2021; Belyazid et al., 2019; Erlandsson-Lampa et al., 2019; Yu et al., 2018; Belyazid and Zanchi, 2019; Gaudio et al., 2015; Belyazid et al., 2011).

For initialisation, the model first creates hypothetical starting conditions by running a simplified simulation with mundane changes until approaching steady state in soil state variables. The model has an algorithm to back cast starting base saturation based on present observed values, and one to recreate observed values of soil organic carbon stocks. These steps provide a starting seed for the model at a given site that only needs to be estimated once and is saved for future simulations. Because of the relatively high number of feedbacks regulating the calculations of the model, it is important to carry out the initialisation step to approach a steady state, otherwise responses to external signals can cause large fluctuations in state variables.

5. Results

5.1. Preliminary baseline results

Nutrient and carbon budgets and surpluses were assessed at NUTS2 level for EU-25. Malta and Cyprus, as well as the UK and Switzerland are not (yet) included due to inconsistencies in the input data. Inputs, outputs, balances and surpluses were assessed:

- Inputs include: atmospheric deposition, mineral fertilizer, manure and organic fertilizers, inputs through grazing livestock, and biological fixation in case of N.
- Outputs include: plant uptake, leaching to groundwater, runoff to surface water, and atmospheric emissions in case of C and N.
- The balance is the difference between the input and the output, being soil accumulation or release.
- The surplus is the difference between the input and the plant uptake.

The results provide national average inputs (country codes are provided in Annex 5), outputs and balances and spatial surpluses at NUTS2 level. The proportion of cropland, arable land and perennials within a NUTS2 region are used to assess this average.

The published results are preliminary and should be used with caution. In the next sections we explain what additional attention is needed before the final baseline can be published.

5.2.1 Soil N, P and C

Figure 7 shows the region-averaged input, output, and balance of N and P for EU-25 countries, and the spatial surplus of N and P. For N and P, input includes deposition, bio-fixation (N only), mineral and manure fertilization, grazing excretion, and compost and sludge, whereas output accounts for removal by harvest and residues. The nitrogen budget shows that inputs and outputs are highest in the Netherlands (NL), 330 kg N/ha and 240 kg N/ha, and Belgium (BE), 272 kg N/ha and 203 kg N/ha respectively for inputs and outputs. These countries also show highest surplus. Comparable results were found in the literature (Duan et al., 2020). A more in depth look at the N and P balance is required, as especially the positive balances seem to be odd due to the balanced P fertilization in some countries (e.g., Netherlands), which should result in a P balance near 0 kg/ha.

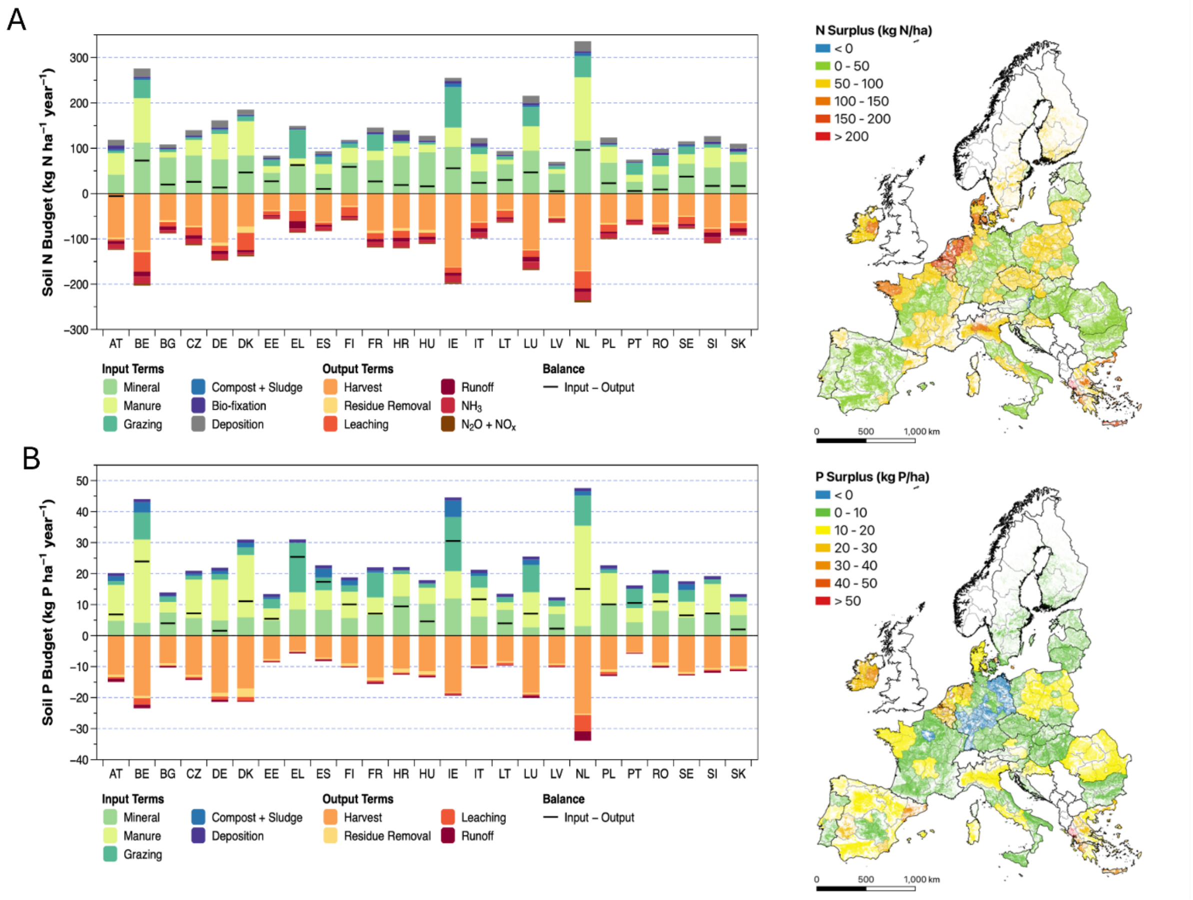


Figure 7. Budgets of nitrogen (N), and phosphorus (P) with national-averaged soil inputs (mineral fertilizer, organic manure, compost and sludge fertilizers, manure input from grazing livestock, atmospheric deposition, and biological fixation (for N)) and outputs (harvested product, crop residue removal, nutrient leaching and runoff, and atmospheric emissions) *per county for EU-25*, together with maps of the N and P *surpluses at NUTS2 level for EU-25. Cyprus (CY) and Malta (MT) are excluded due to inconsistencies in the input data.*

Leaching is the largest loss of N and P to the environment in western Europe, particularly in the Benelux region (Fig.8). In this region, the livestock density and grassland productivity is also highest (Neumann et al., 2009; Chang et al., 2015).

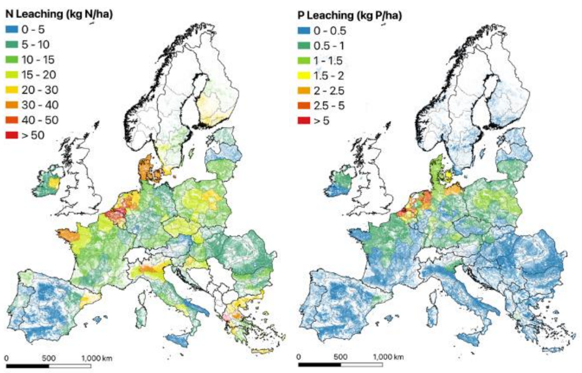


Figure 8. N and P leaching to groundwater (kg/ha) at NUTS2 level for EU-25.

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 (Fig. 9; Duan et al., 2020).

The SOC balance and surplus results of the renewed MITERRA-Europe model require some additional attention. The new soil input data from the LUCAS dataset (Fernandez-Ugalde et al., 2022) show some inconsistencies compared to the previously used soil carbon data. This should be solved before the SOC balance resulting from the NutriBudget project can be published.

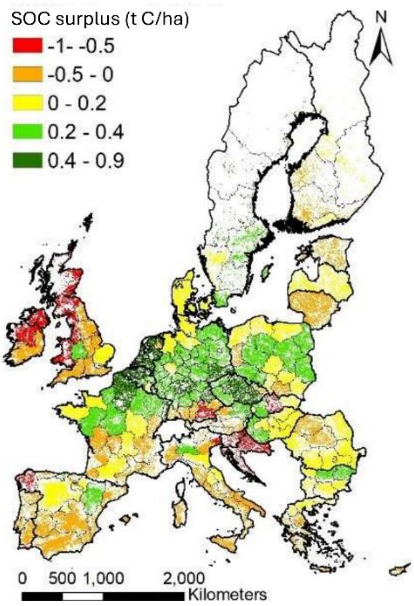


Figure 9. Soil organic carbon (SOC) surpluses (t C/ha) in Europe (Duan et al., 2020).

5.2.2 Other nutrients (K, S, Ca, and Mg)

The K and S balances are around 0 (Fig. 10). These maps are one-of-its-kind and have not been published before. Literature and expert judgement is therefore required to test the range of the different inputs and outputs. Although the balances look reasonable, some additional attention still needs to be paid to the K content in the inputs, because this should be comparable to N inputs, but currently is this deviates.

The Ca and Mg budgets and surpluses still seem to deviate from the expectations, and therefore these nutrients are not yet published. Currently, no Mg leaching occurs while this is expected, even more than Ca, and the losses of Ca are too high.

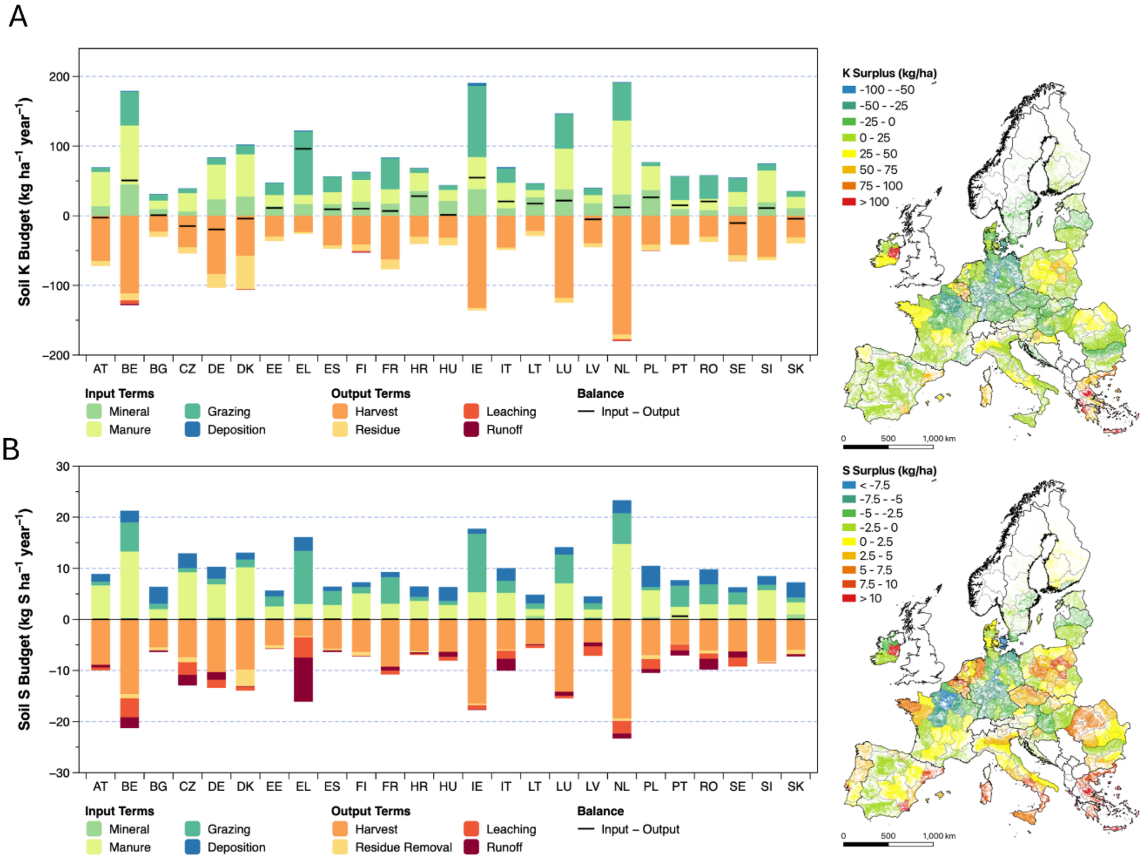


Figure 10. Budgets of potassium (K), and sulphur (S) with national-averaged soil inputs and outputs (kg/ha/yr) per county for EU-25, together with maps of the K and S surpluses at NUTS2 level for EU-25. Cyprus (CY) and Malta (MT) are excluded due to inconsistencies in the input data.

5.2.3 Heavy metals (Cd, Cu, Zn)

An exhaustive study on the heavy metal budgets was carried out by De Vries et al. (2022) using the INTEGRATOR model. The integration of the model INTEGRATOR into the MITERRA-Europe model resulted in some deviating results, and therefore the results of De Vries et al. (2022) are picture in Fig.11.

In Europe, dominantly Cd accumulation takes place. This implies that cadmium levels in soil, on the long term, will increase which is an unwanted development in view of potential effects on food quality and leaching to ground- and surface waters. The fact that current cadmium inputs result in low accumulation rates, or even a net decrease of soil Cd concentrations reflects the substantial decrease in cadmium inputs during the last decades. These are mostly due to lower application rates of inorganic P fertilizers and policy induced reductions of atmospheric inputs. Such lower inputs to soil in combination with ongoing leaching of cadmium from the topsoil leads to a net decrease of Cd in the soil at European level.

Cu inputs are highest in areas with intensive animal husbandry including the Netherlands, Belgium and parts of France and Denmark. Calculated ranges of copper accumulation are directly related to regional differences in Cu inputs, which are also highest in areas with animal husbandry.

The cause of Zn surpluses is comparable to Cu surpluses. Manure is the most dominant source of Zn input. For Zn, however, leaching losses, are quantitatively more important due to the higher relative mobility of Zn compared to Cu. High leaching losses in combination with high uptake fluxes even can result in a negative balance for Zn. Examples of such regions include central parts of Germany, Portugal, Belgium and Luxemburg, where a net accumulation is observed at country level while depletion occurs regionally. This illustrates the added value of a regional balance approach in addition to a country balance approach, as Zn depletion is unwanted in view of sustainable crop quality and production.

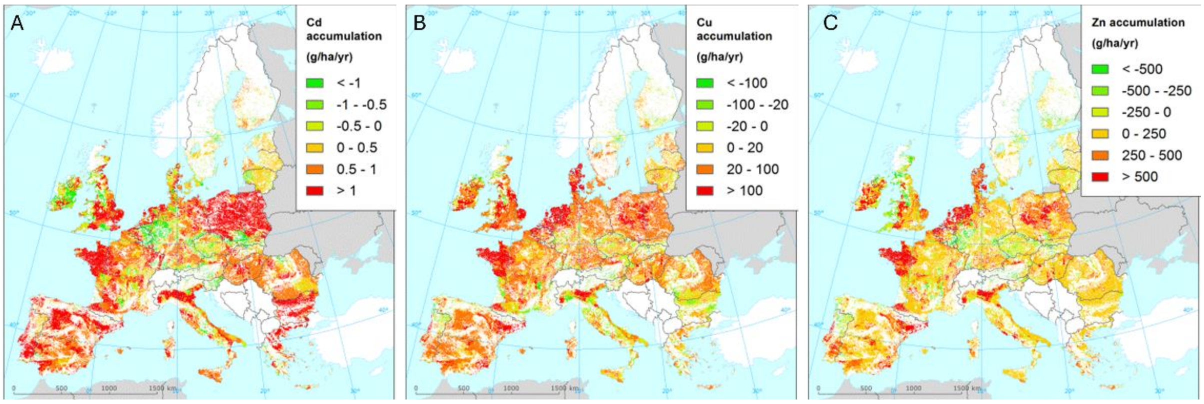


Figure 11. Accumulation rates (in g/ha/yr) of Cd (A), Cu (B), and Zn (C) assessed by the INTEGRATOR model (De Vries et al., 2022).

5.2 Results of field scale models with test datasets

The field-level models all run for the test-dataset based on a long-term field experiment in Sweden (Annex 4). The preliminary results of the three farm-level models are published here. In Chapter 6, the next steps of the farm-level models are explained.

5.2.1 NutriFarm

Results presented here include budgets (inputs and outputs) of C and nutrients N, P, K, S, Mg, Ca, Cu and Zn for the year 2020 using input data from a long-term experimental (LTE) test site of Sweden. For C the inputs are crop residues, manure and soil carbon release (in this test site an input) while the outputs are CO_2 emissions. For the nutrients, the inputs include chemical fertilizer, manure and deposition and outputs include removal by crop harvest and crop residues, soil accumulation, leaching and runoff. In case of N, inputs also and outputs also include losses through emissions of ammonia (NH_3), nitrous oxide (N_2O), nitrogen oxides (NO_x) and di-nitrogen (N_2) by denitrification.

For C, most input was from manure (1144 kg/ha), followed by crop residue (637 kg/ha) and organic pool change (485 kg/ha). CO_2 emission (2265 kg/ha) was the only output (Fig.12).

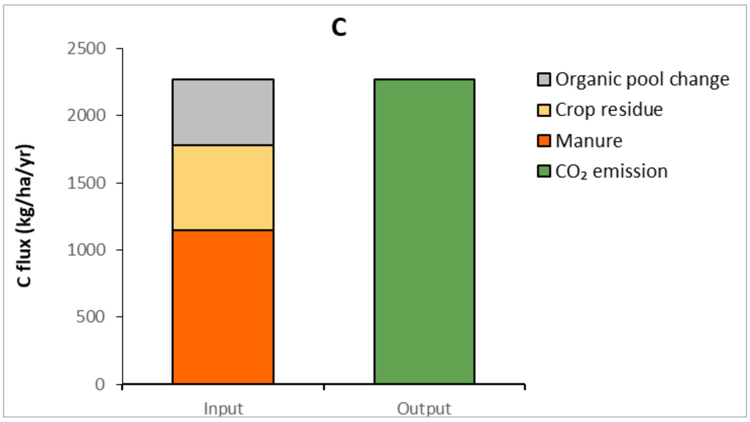


Figure 12. Inputs and output of carbon (C) (kg/ha/yr) in the LTE test site of Sweden. C inputs include crop residue, manure, and C release from the soil C pool. Output includes CO2 decomposition from the soil organic pool.

For N input, fertilizer and manure were the main input sources (both 80 kg/ha), while inputs by deposition and fixation were low, i.e. 3.4 and 2.0 kg/ha, respectively (Fig.13). The crop removal by harvest (grain) was the major output (76 kg/ha), with a nitrogen use efficiency (NUE) of 46%. The crop residue removal was 26 kg N/ha. NH_3 was the major gas emitted (25 kg N/ha), followed by N_2, N_2O and NO_x emissions (16 kg N/ha). Surface and subsurface runoff of N were in total 21 kg/ha, and leaching to ground water contributed the least output (2.0 kg/ha).

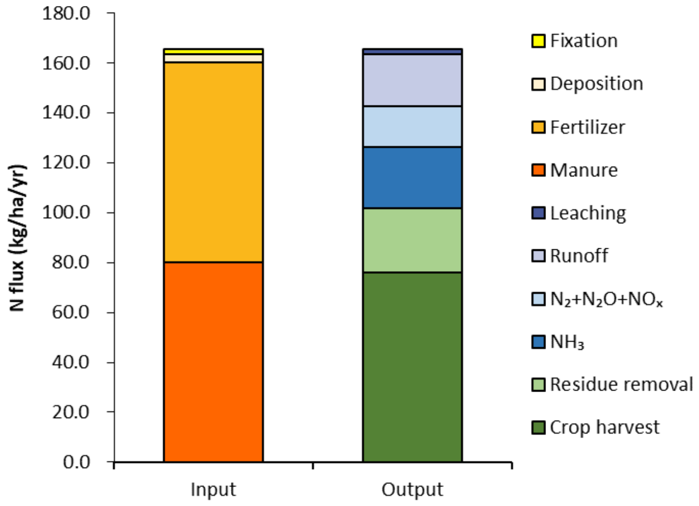


Figure 13. Inputs and outputs of nitrogen (N) (kg/ha/yr) in the LTE test site of Sweden.

For P input, manure was the major source (14 kg/ha), followed by chemical fertilizer input (5.8 kg/ha). Due to minor atmospheric deposition (0.2 kg/ha) but higher crop removal (18 and 5.9 kg/ha for crop harvest and crop residue removal, respectively), soil released 6.0 kg P/ha. For P output, surface and subsurface runoff contributed 0.67 kg/ha, and leaching to groundwater was 1.9 kg/ha (Fig. 14).

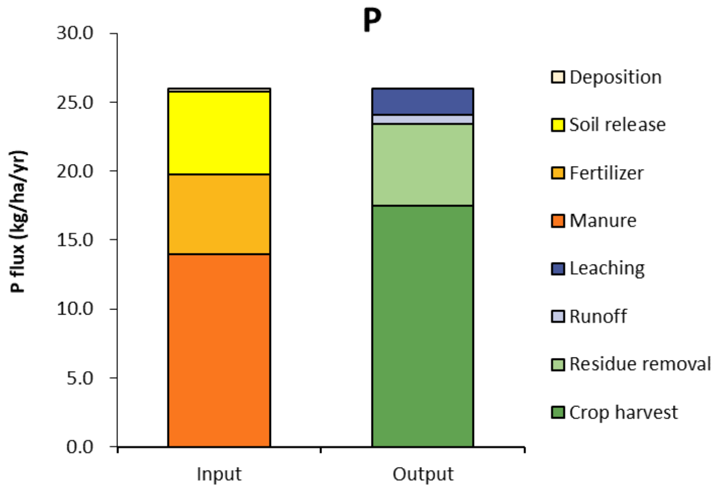


Figure 14. Inputs and outputs of phosphorus (P) (kg/ha/yr) in the LTE test site of Sweden.

For S, chemical fertilizer was the main input source (12 kg/ha), followed by manure input (8.8 kg/ha) and atmospheric deposition (0.72 kg/ha); crop uptake by crop harvest and residue removal was the major output (9.1 kg/ha), followed by leaching (8.7 kg/ha) and runoff (5.1 kg/ha). This led to the soil release of S by 1.5 kg/ha (Fig.15).

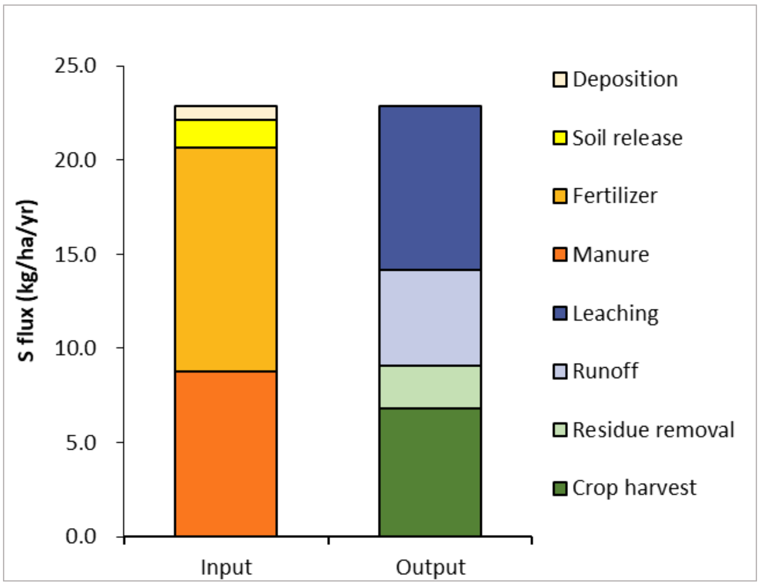


Figure 15. Inputs and outputs of sulphur (S) (kg/ha/yr) in the LTE test site of Sweden.

For K, manure was the main input source (84 kg/ha), followed by chemical fertilizer (1.5 kg/ha) and atmospheric deposition (0.46 kg/ha); for output, crop uptake contributed to 34 kg/ha, with crop harvest and residue removal being 26 and 8.6 kg/ha, respectively. Leaching was the most important loss of K (13 kg/ha), followed by runoff (8.8 kg/ha). The higher input than output led to the K accumulation of 30 kg/ha (Fig.16).

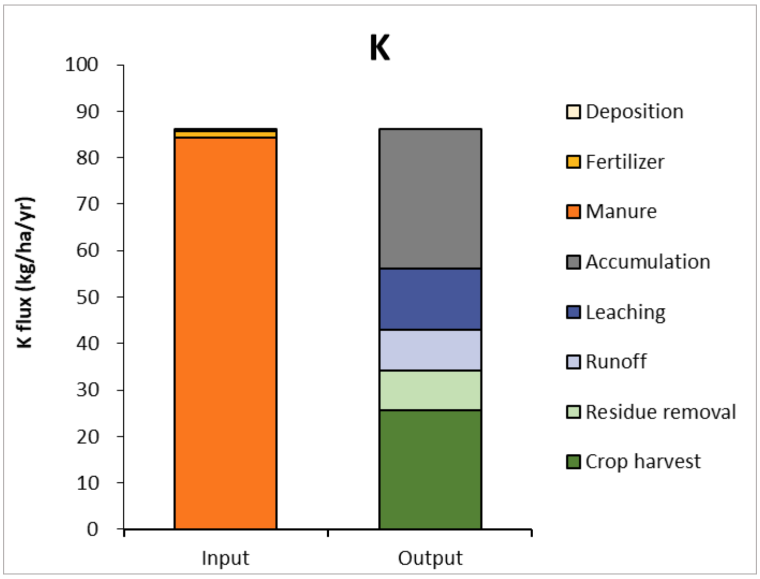


Figure 16. Inputs and outputs of potassium (K) (kg/ha/yr) in the LTE test site of Sweden.

For Mg, manure was the main input source (11 kg/ha), followed by chemical fertilizer (5.1 kg/ha) and atmospheric deposition (1.7 kg/ha); crop uptake was the major output (7.4 kg/ha, in which 5.5 kg/ha from crop harvest and 1.9 kg/ha from residue removal), followed by leaching (8.1 kg/ha) and runoff (5.4 kg/ha). The soil released Mg of 3.4 kg/ha (Fig.17).

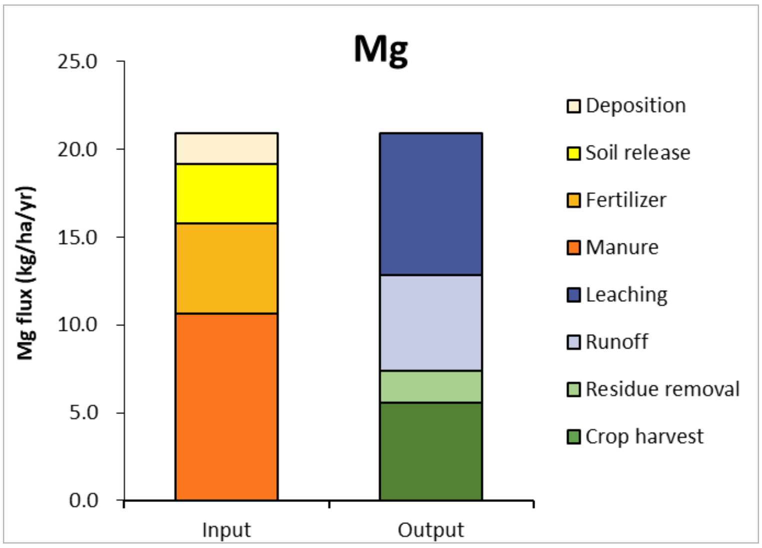


Figure 17. Inputs and outputs of magnesium (Mg) (kg/ha/yr) in the LTE test site of Sweden.

For Ca, manure contributed the most input (32 kg/ha), followed by chemical fertilizer (14 kg/ha) and atmospheric deposition (11 kg/ha); crop uptake was the major output (3.6 kg/ha, in which 2.7 kg/ha from crop harvest and 0.92 kg/ha from residue removal). The most of Ca was leached (47 kg/ha) and lost via runoff (32 kg/ha), leading to a soil release of 27 kg/ha (Fig.18).

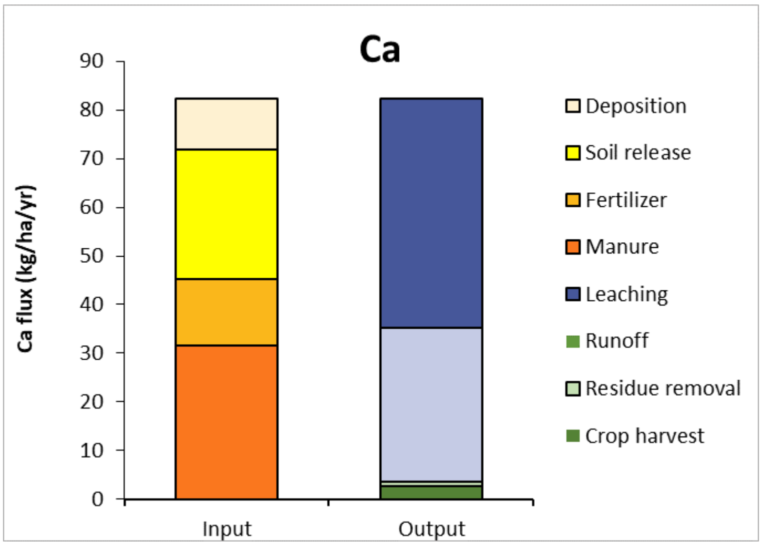


Figure 18. Inputs and outputs of calcium (Ca) (kg/ha/yr) in the LTE test site of Sweden.

For Cu, manure contributed the most input (79 g/ha), followed by chemical fertilizer (41 g/ha) and atmospheric deposition (3.7 g/ha); crop uptake was the major output (22 g/ha), mostly from crop harvesting (16 g/ha). The Cu losses via leaching and runoff were minor (0.61 and 0.39 g/ha, respectively), leading to a considerable accumulation in the soil (101 g/ha) (Fig.19).

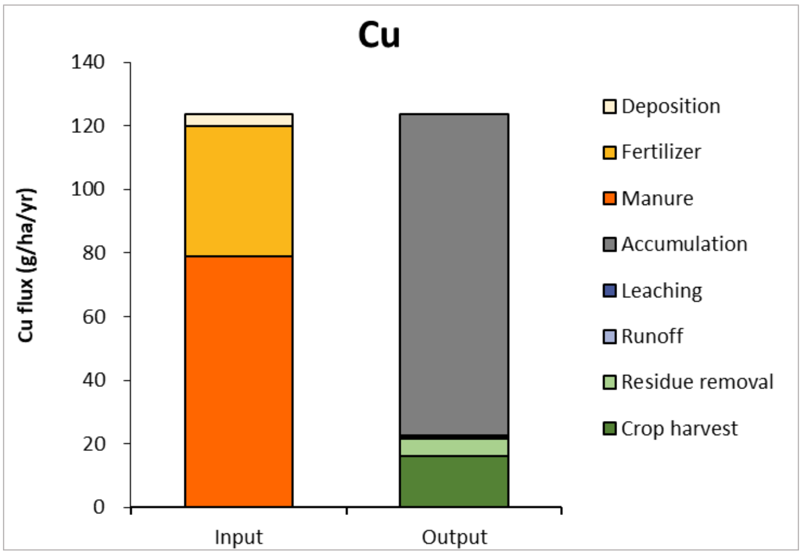


Figure 19. Inputs and outputs of copper (Cu) (g/ha/yr) in the LTE test site of Sweden.

For Zn, manure contributed 351 g/ha to the soil inputs, followed by chemical fertilizer (71 g/ha) and atmospheric deposition (18 g/ha); crop uptake was the major output (139 g/ha). Similar to Cu, Zn losses via leaching and runoff were minor (2.8 and 1.7 g/ha, respectively), leading to a considerable accumulation in the soil (296 g/ha) (Fig.20).

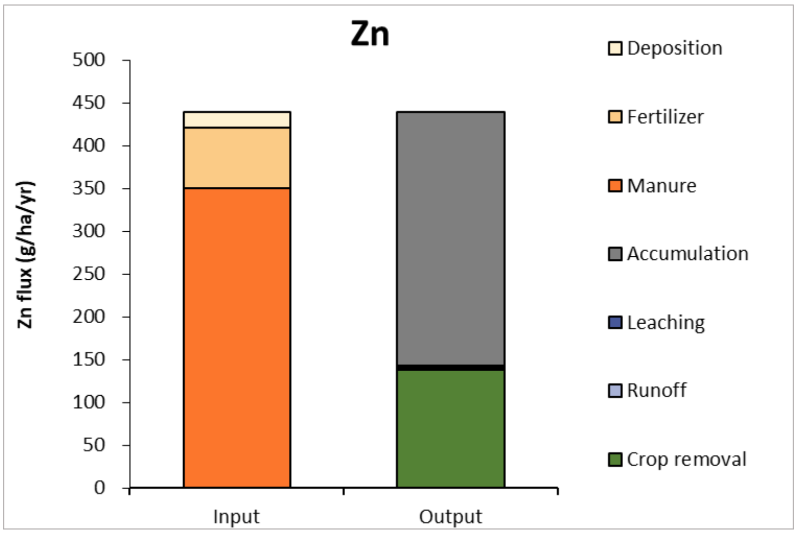


Figure 20. Inputs and outputs of zinc (Zn) (g/ha/yr) in the LTE test site of Sweden.

For Cd input, chemical fertilizer contributed 0.75 g/ha to the soil inputs, followed by manure (0.47 g/ha) and atmospheric deposition (0.19 g/ha); crop uptake was 0.23 g/ha. The Cd losses via leaching and runoff were minor (0.03 and 0.02 g/ha, respectively), leading to a considerable accumulation in the soil (1.1 g/ha) (Fig.21).

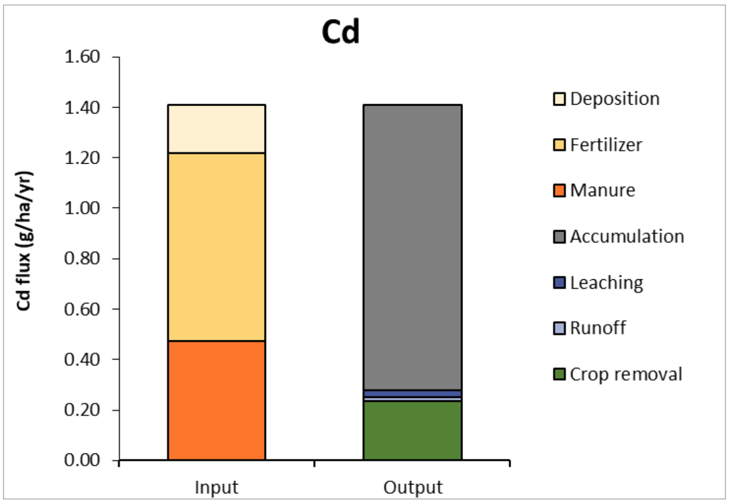


Figure 21. Inputs and outputs of cadmium (Cd) (g/ha/yr) in the LTE test site of Sweden.

5.2.2 CHN

The additional value of CHN is that the model includes a crop-growth model to assess the yield, whereas NutriFarm relies on static crop yields. The model assesses the daily Leaf Area Index and the daily cumulative plant and root biomass, which provides much more temporal detail on N fluxes compared to NutriFarm. Also, hydrology in the soil system is assessed differently and in more detail, and therefore the model can also complement the NutriBudget results with information on the daily water soil stock and the cumulative runoff, infiltration and drainage rate that is assessed by the model.

The model focused on the N fluxes over one growing period. Within this period changes in C fluxes were not significant and are therefore not included in the results. The results of the CHN model are provided in Figure 22.

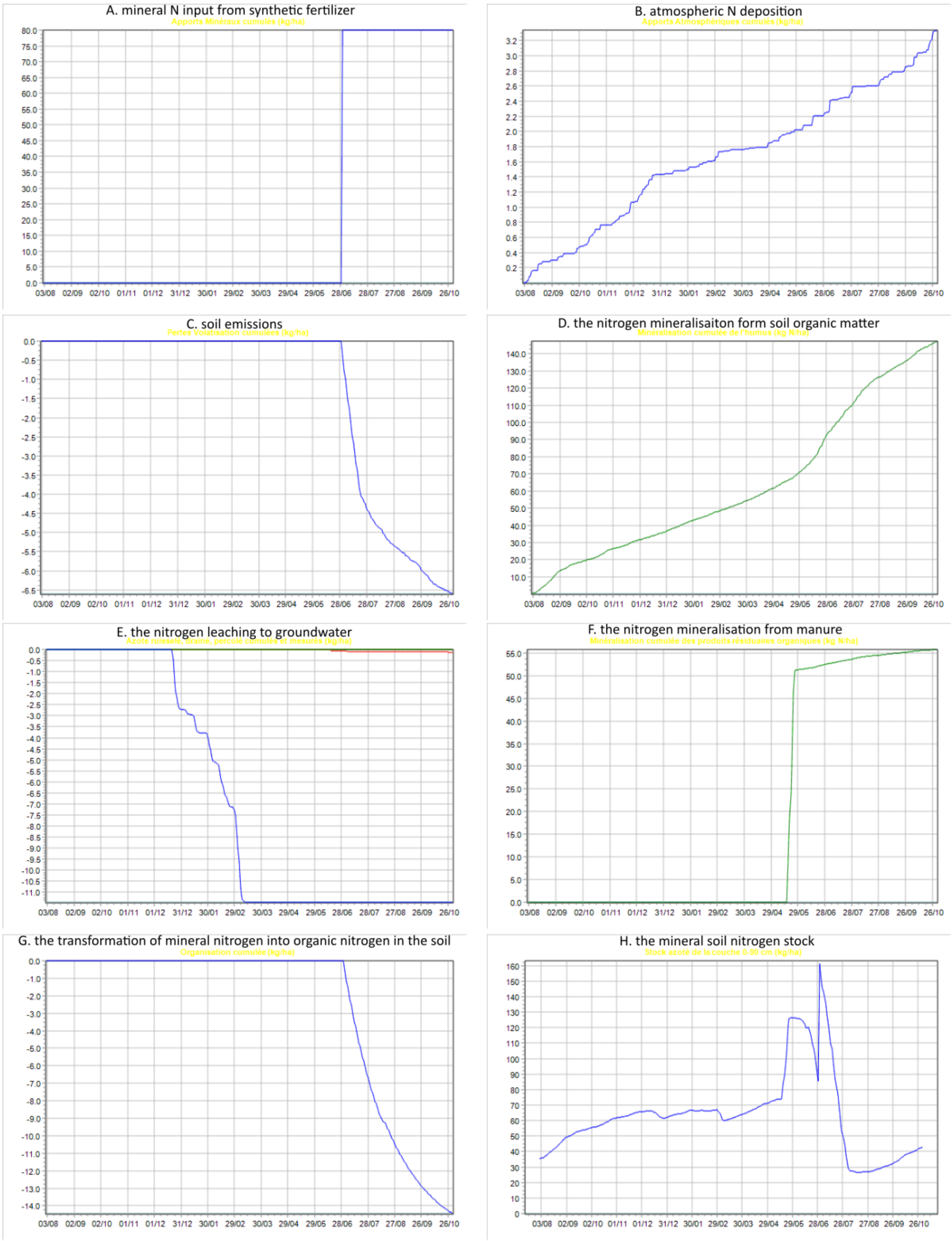


Figure 22. The trends over one cropping period (x-axis) show: (A) mineral N input from synthetic fertilizer (kg/ha), (B) atmospheric N deposition (kg/ha), (C) soil emissions (kg/ha), (D) the nitrogen mineralisation from soil organic matter (kg N/ha), (E) the nitrogen leaching to groundwater (kg/ha), (F) the nitrogen mineralisation from manure (kg N/ha), (G) the transformation of mineral nitrogen into organic nitrogen in the soil (kg/ha), and (H) the mineral soil nitrogen stock (kg/ha).

5.2.3 FSF

The model ForSAFE was adapted to accept input based on agricultural scenarios. Fertiliser and manure were added into the deposition. Since the model focuses on soil chemistry dynamics, here the output is described with leaching, soil organic matter and crop nutrient uptake. The inputs provided by the LTE test site of Sweden were converted into the format accepted by the ForSAFE model. The FSF model assesses the same nutrient budgets as NutriFarm, but the soil processes are described in more detail and therefore FSF can complement the NutriBudget project.

An important detail is that the ForSAFE model requires initialisation to have a stable start for the simulations. For this run, it was initialised from the 1950, which is the approximate time cultivation and management of the site started. Since the results in this document focus on the timespan from 2020, the simulation of the system has stabilised, and the early fluctuations are smaller than if the management was introduced recently.

The balances of nitrogen and phosphorus were stable around 0 to –1 g/m², whereas the balance of SOM carbon varied significantly from year to year and was almost always negative, up to –20 g/m² per year (Fig.23). That can be associated with the intense fertilisation provided with the inputs. The cycling of carbon, especially DOC, is faster with more macronutrients in the soil.

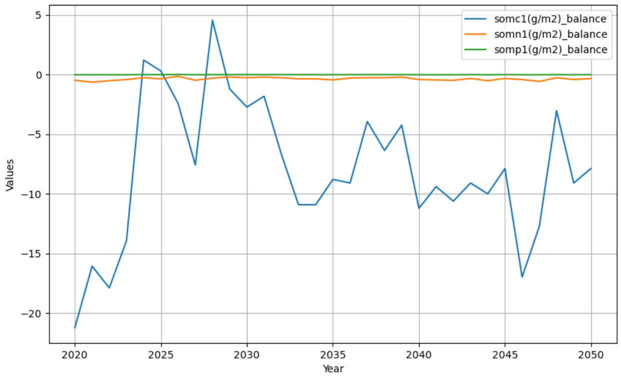


Figure 23. Balances of C (somc1), N (somn1) and P (somp1).

Leaching of dissolved organic carbon was estimated at 5 – 10 g/m² per year (Fig.24). That is the most labile fraction of the SOM and is very susceptible to leaching. That is further reinforced by the management of the site.

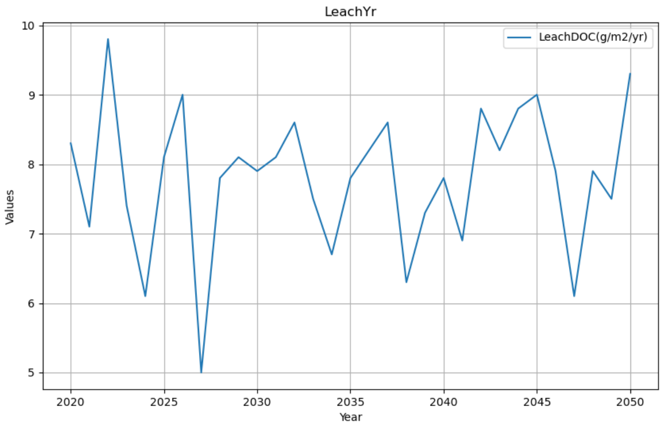


Figure 24. Yearly leaching of dissolved organic carbon.

Leaching of nitrogen and phosphorus was estimated in small amounts up to 0,1 g/m² per year (Fig.25). That suggests that the SOM has reached an equilibrium of macronutrients and N and P are stabilised in the soil. The variation in the magnitude of leaching is caused by the yearly and seasonal variations in precipitation.

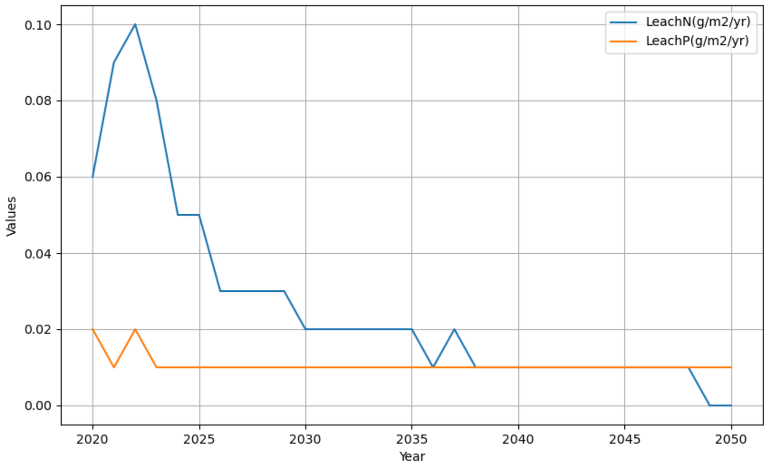


Figure 25. Yearly leaching of nitrogen and phosphorus.

Contents of soil organic matter were relatively stable with carbon decreasing due to the leaching described earlier (Fig.26). This shows that the model correctly accounts for the changes in SOM.

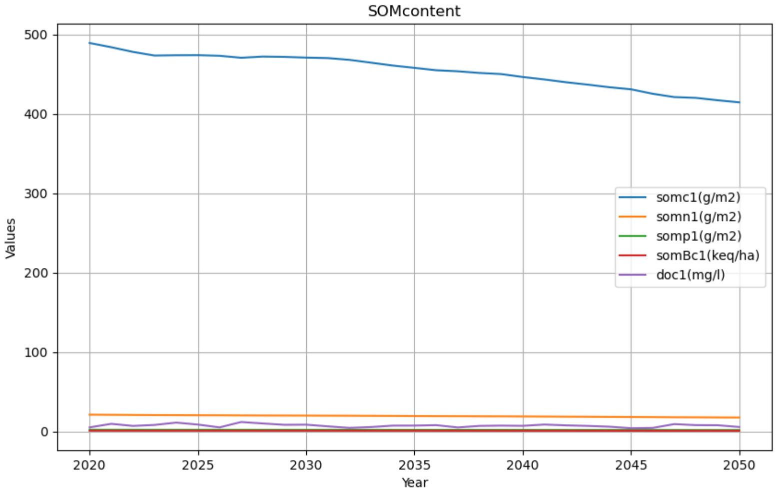


Figure 26. Contents of Soil Organic Matter.

The uptake is simulated as Potential against Actual (Fig.27), with potential uptake being the total amount the plant would need and take up and the actual being that limited by the given soil conditions. Since the plot was heavily fertilised and the macronutrients are in a surplus, the actual uptake equalled the potential uptake, suggesting that the needs of the crop were met. The shape of the graph shows the growing periods of the crop when uptake is occurring and the periods after harvest when the soil is bare.

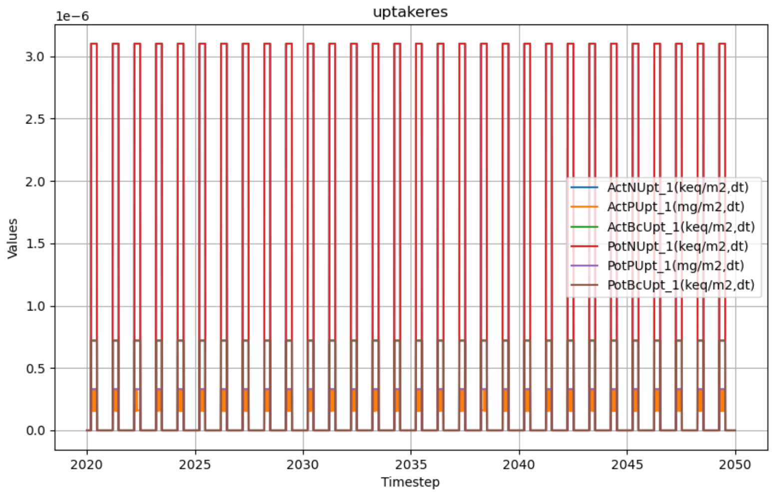


Figure 27. Actual and Potential Uptakes of nutrients.

Overall, the ForSAFE model has showed its capability to simulate soil chemistry dynamics and predict leaching rates, which can contribute to the Nutrimodel framework.

5.2.4 Comparison of the farm-level models

NutriFarm run at annual time step, whereas CHN provided interannual variation in the nitrogen fluxes. This interannual variation provides additional insight in the environmental conditions or management actions that cause emissions to the atmosphere or leaching to ground or surface water. This can help making recommendations on the timing of implementing nutrient mitigation measures.

The FSF model is designed for runs on the long-term. It illustrated the effect on nutrient and carbon budgets in the soil when current management (2020) is continued until 2050. Where the nutrient balances were quite stable over time, the C balance was fluctuating for each year and resulted in a decline in SOC stock. The model includes the soil organic matter mineralization processes in more detail compared to NutriFarm (which uses the RothC model) and the results of FSF can complement the results of NutriFarm.

How strongly CHN and FSF influence the results of the NutriFarm model still needs to be determined, based on a sensitivity analysis of the three farm-level models and the capacity of the models. For example, not all models run for all nutrients and regions in Europe, or the accuracy of the model output differs spatially.

6. Next steps

Now the NutriModel framework and the baseline is set, we can start testing the effect of measures (WP1 and WP4) that help moving towards the desired state (D3.2), but also a start can be made with the Decision Support Tool (WP5). Besides these connections to the other work packages, MITERRA-Europe as well as the farm-level models still have some issues to solve. An insight in the next steps that are necessary for a solid modelling approach are given in subchapters 6.1 and 6.2.

6.1 MITERRA-Europe

- Test and publish the final nutrient and carbon budgets for EU-27 and Switzerland.
- Create the default dataset for NutriFarm from the input data MITERRA-Europe currently uses.
- Implement a calculate-first-interpolate-later approach to the spatial input data of MITERRA-Europe

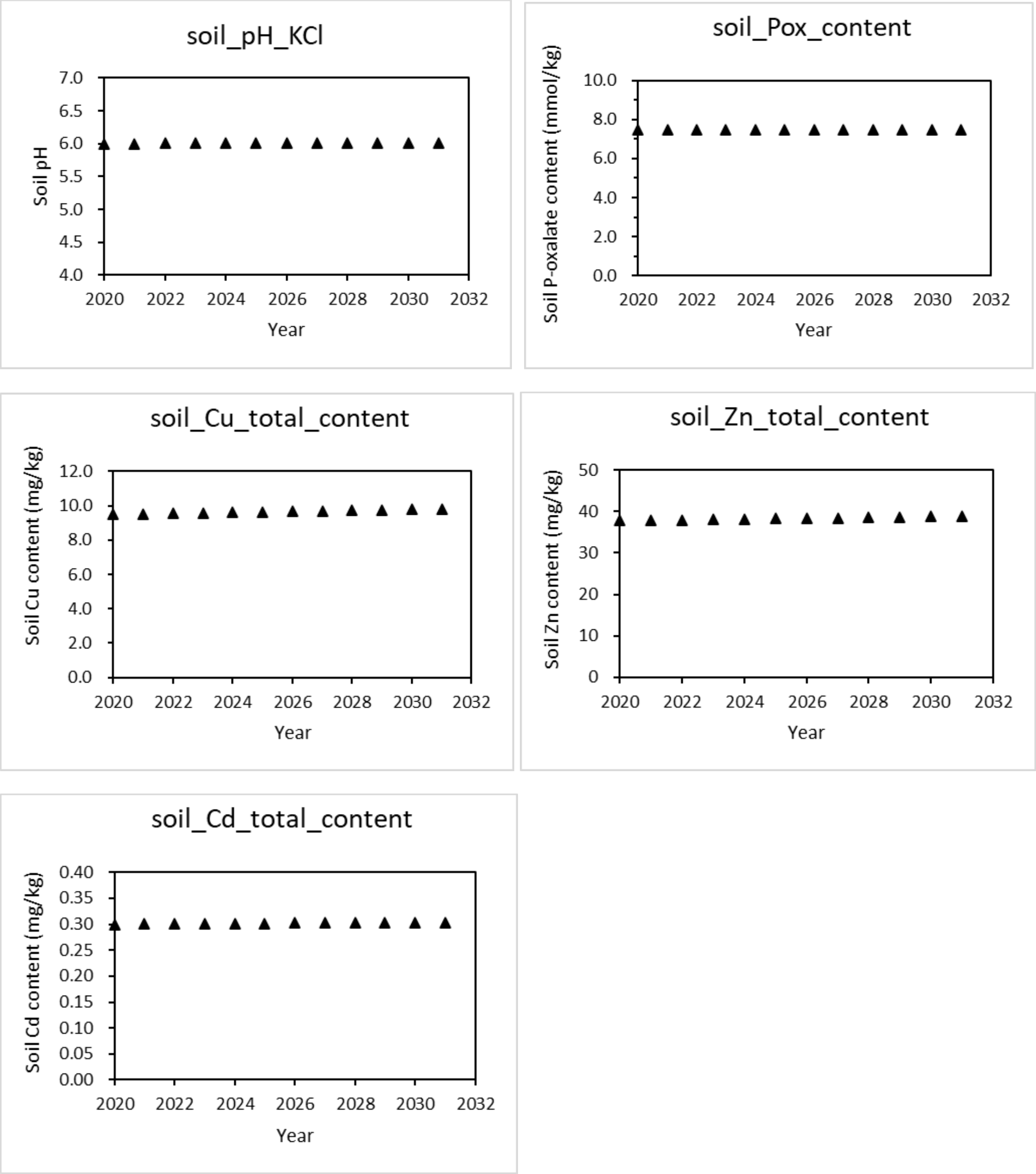
- Test whether the excretion rates given by the NIR-CRF are in line with the Eurostat animal numbers. If not, apply a correction factor.
- Implement interactions between nutrients and carbon
- Update and elaborate the input data that is required to run nutrient management mitigation measures.
- Carry out a sensitivity analysis on the input variables.
- Retrieve the missing data for Switzerland from local authorities.

6.2 Farm-level models

- Run the farm-level models on five additional test-datasets (one for each climatic zone) to assess the functioning of the different models under different climatic conditions.
- Compare the results of the farm-level models in a consistent manner, so an approach on how FSF and CHN can complement NutriFarm can be designed and implemented.
- Carry out a sensitivity analysis on the different farm-level models in a consistent manner.
- Test whether other input data besides spatial datasets, e.g., farm activity data, can be gridded and used in the default database, and which input data a user should be requested to a user or should be downscaled otherwise (e.g., Schulte-Uebbing et al., 2021; De Vries et al., 2020).
- Build the computational framework and an API, so requests can be sent from the DST to the API and results can flow back to the DST.

Annexes

Annex 1. Changes in soil pH (in KCl), soil P-oxalate content and soil heavy metal (Cu, Zn and Cd) content during the initialization of NutriFarm.



Annex 2 Updates and refinements on the input data of CHN crop model.

Dataset	Parameter	Potential changes to be made or explore:
Local soil analysis (if LTE), or LUCAS – European Soil Data Centre	SOC content, pH, C/N, soil texture, soil depth, root depth, availability of CaCO3, soil mineral nitrogen stock at the end of winter, water holding capacity, stoniness percentage and types	- Include soil property based on the LUCAS database. - need to have measurements of soil mineral nitrogen stock and an accurate estimation of soil water holding capacity (especially in shallow soils) to evaluate model performances
ESDB v2.0 and soil erosion maps (JRC)	Soil type, soil depth, soil erosion	- Refine to NUTS3 level.
LTE datasets and national and regional public survey on agricultural practices (EUROSTAT).	Precise total nitrogen dose, the amounts and dates of splitting application	- Calculate averages over 2019-2021.
European climate data and Germany Open Data (National Weather Service)	Global Summary of the Day TN, TX, RR, HR, Wind speed, Global radiation	Missing data NASAPOWER (reanalysis data at 50 km grid, all parameters available) One of the key advantages of utilizing free data and existing processing chains for the CHN model is the cost efficiency, as this approach allows for the integration of readily available data without incurring additional expenses. Moreover, the existing processing infrastructure provides a seamless and efficient means to handle and analyze the data, streamlining the workflow. However, there are notable disadvantages, such as reliance on the nearest available weather station, which may not accurately reflect microclimatic conditions at specific field sites. Additionally, the density of weather stations can vary significantly from country to country, potentially leading to gaps in data coverage and reducing the precision of climate inputs in certain regions.

Annex 3A. Updates and refinements on the input data of MITERRA-Europe.

Dataset	Parameter	Potential changes to be made or explore:	Outcomes of the changes or explorations:
LUCAS – European Soil Data Centre	SOC content, pH, CEC, soil texture, bulk density, depth to bedrock, availability of CaCO3, NPK content, perennial grass cover (used for C balance)	- Include soil property maps (S, Ca, Mg, Cu, and Zn) based on the LUCAS database. - Explore the use of the soil property maps of SoilGrids (1km resolution) and compare these maps with the soil property maps of LUCAS.	- Soil property maps (S, Ca, Mg, Cu, and Zn) based on the LUCAS database are included - SoilGrids lacks some soil properties LUCAS includes. The application of the methodology of SoilGrids on the LUCAS point data will be explored.
FAOSTAT	Fertilizer use and type, livestock production	- Calculate averages over 2019-2021.	- Averages over 2019-2021 were calculated
EUROSTAT (FSS, Agricultural Production Database, and SAPM)	Fat and protein content of milk, percentage and area of natural grassland (not fertilized land), animal numbers, crop areas, and crop yields, arable farm size, farming system, crop rotation, livestock units, areas with organic farming, irrigation, crop cover (arable land).	- Refine to NUTS3 level. - Update data to 2020.	- No refinement to NUTS3 level possible. - Data were updated to 2020.
NIR - CRF	N excretion of animals, CH4 emissions from manure management and enteric fermentation	- Keep using these national data. - Update data to 2020	- National data were used. - Data were updated to 2020.
GAINS	NH3 emission factors, NH3 mitigation measures.	- Explore using the EMEP calculation rules including some additional data of EUROSTAT instead of using the GAINS data.	- This will be explored when analysing the effect of measures (D2.5).
WoldClim	Precipitation, evapotranspiration, temperature	- Switch to ERA5 and update the climate data to the average 1990-2020 data.	- Average 1990-2020 data of ERA5 were used
Keuskamp et al. (2012)	Precipitation surplus, surface runoff and groundwater leaching fractions	- Explore the potential use of the more detailed Variable Infiltration Capacity (VIC) model (Liang et al., 1994) instead of Keuskamp (2012).	- The VIC model is not yet sufficiently developed for these kind of applications. However, this can change in the near future.
ESDB v2.0 and soil erosion maps (JRC)	Soil type, soil depth, soil erosion	- Refine to NUTS3 level.	- The data were not refined to NUTS3 level, because of the lack in NUTS3 level data from Eurostat.

Annex 3B. Input data required by MITERRA-Europe and the datasets and sources that were used to retrieve these data.

Parameter	Datasets	Source
Soil pH, CEC, availability of CaCO3, NPK content	Soil Chemical properties at European scale based on LUCAS 2009/2012 topsoil data	Ballabio, C., Lugato, E., Fernández-Ugalde, O., Orgiazzi, A., Jones, A., Borrelli, P., Montanarella, L. and Panagos, P., 2019. Mapping LUCAS topsoil chemical properties at European scale using Gaussian process regression. Geoderma, 355: 113912.
Soil organic carbon (SOC) content	LUCAS 2018 TOPSOIL data	Fernandez-Ugalde, O; Scarpa, S; Orgiazzi, A.; Panagos, P.; Van Liedekerke, M; Marechal A. & Jones, A. LUCAS 2018 Soil Module. Presentation of dataset and results, EUR 31144 EN, Publications Office of the European Union, Luxembourg. 2022, ISBN 978-92-76-54832-4, doi:10.2760/215013, JRC129926. Orgiazzi, A., Ballabio, C., Panagos, P., Jones, A., Fernández-Ugalde, O. 2018. LUCAS Soil, the largest expandable soil dataset for Europe: A review. European Journal of Soil Science, 69(1): 140-153. https://doi.org/10.1111/ejss.12499.
Soil texture, coarse fractions, bulk density, rooting depth	Topsoil physical properties for Europe (based on LUCAS topsoil data)	Ballabio C., Panagos P., Montanarella L. Mapping topsoil physical properties at European scale using the LUCAS database (2016) Geoderma, 261 , pp. 110-123.
Fertilizer use and type	FAOSTAT and IFASTAT	Food and Agriculture Organization of the United Nations, 1997. FAOSTAT statistical database. Rome: FAO. International Fertilizer Association, 2024, https://www.ifastat.org/.
Percentage and area of natural grassland (not fertilized land) and rough grazing, animal numbers, crop areas, crop yields, arable farm size, farming system, crop rotation, livestock units, areas with organic farming, irrigation, crop cover (arable land), perennial grass cover (used for C balance)	EUROSTAT and Agrarstrukturerhebung (2020) for Germany	European Commission, 2020. Eurostat statistical database. Brussels: European Commission. Agrarstrukturerhebung, 2024, https://www.regionalstatistik.de/genesis/online?operation=previous&levelindex=0&step=0&titel=Statistik+%28Tabellen%29&levelid=1727099952945&acceptscookies=false.

N excretion of animals, CH_4 emissions from manure management and enteric fermentation	National GHG inventory submissions	United Nations Framework Convention on Climate Change, 2020. National Inventory Submissions 2020. Bonn: United Nations Climate Change.
Precipitation, evapotranspiration, temperature	ERA5	Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J-N. (2023): ERA5 hourly data on single levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS), DOI: 10.24381/cds.adbb2d47 (Accessed on 10-09-2024).
Precipitation surplus, surface runoff and groundwater leaching fractions	Keuskamp et al. (2012)	J. A. Keuskamp, G. Van Drecht, A. F. Bouwman (2012). European-scale modelling of groundwater denitrification and associated N 2O production. Environmental Pollution, 165, pp. 67-76, doi: http://dx.doi.org/10.1016/j.envpol.2012.02.008.
Soil type, soil texture class, soil depth, rooting depth, soil erosion, organic carbon class, parent material, peat fraction.	ESDB v2.0 and soil erosion maps (JRC)	International Institute for Applied Systems Analysis, 2018. The GAINS model. Laxenburg: IIASA
Slope	EU-DEM	European Environmental Agency, 2024. European Digital Elevation Model (EU-DEM). DOI: https://ec.europa.eu/eurostat/web/gisco/geodata/digital-elevation-model/eu-dem#Slope (Accessed on 01-08-2024).
C-factor, erosion	USLE model	Panagos, P., Borrelli, P., Meusburger, C., Alewell, C., Lugato, E., Montanarella, L., 2015. Estimating the soil erosion cover-management factor at European scale. Land Use policy journal. 48C, 38-50.
N_2O, CO_2 (peatland) emission factors, global warming potentials,	IPCC	PCC, 2019. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4, Agriculture, Forestry and Other Land Use. IPCC National Greenhouse Gas Inventories Programme. Institute for Globa
NH3 emission factors, NH3 mitigation measures	GAINS	International Institute for Applied Systems Analysis, 2018. The GAINS model. Laxenburg: IIASA.
Soil cover and Tillage practice	FSS	European Commission, download September 2009 URL:https://ec.europa.eu/eurostat/web/microdata/farm-structure-survey

Areas under derogation	EC	European Commission, downloaded May 2019. URL: https://ec.europa.eu/environment/water/water-nitrates/index_en.html
Composition of organic fertilizers	(-)	Multiple sources based on literature and database study
Composition of crop (residues)	(-)	Multiple sources based on literature and database study
Composition of chemical fertilizers	(-)	Multiple sources based on literature and database study, including expert judgement of Römkens (2024)
Ca, Cd, Cu, K, Mg, Na, NH_3, NO_x, SO_x, Zn deposition	EMEP	Van Loon, M., Tarrasón, L., Posch, M., 2005. Modelling Base Cations in Europe. EMEP/MSC-W&CCE Note2/2005. ISSN 0804-2446.
Land use	CORINE Land Cover - 2018	European Union, Copernicus Land Monitoring Service 2021, European Environment Agency (EEA). Corine Land Cover. DOI: CORINE Land Cover 2018 (vector/raster 100 m), Europe, 6-yearly — Copernicus Land Monitoring Service (Accessed on 01-08-2024).
Base cation weathering	ESDB v2.0 and De Vries (1991)	De Vries, W.: 1991, Methodologies for the assessment and mapping of critical loads and of the impact of abatement strategies on forest soils, DLO Winand Staring Centre, Wageningen, the Netherlands, Report 46, 109 pp. International Institute for Applied Systems Analysis, 2018. The GAINS model. Laxenburg: IIASA

Annex 4 Test dataset to run the farm-level models

Annex 3A. Custom input data required by NutriFarm based on a long-term experiment in Sweden

Variable	Value	Unit	Definition
farm_id	LTE_Saby		Farm ID (name)
year	2020		Initial year for modelling
Longitude	17.42		Longitude of farm, as positive value with E while negative value with W
Latitude	59.49		Latitude of farm, as positive value with N while negative value with S
precipitation[location]	750	mm/year	Precipitation (rainfall) at the farm location
mean_air_temperature	6.3	Celsius degree	Mean air temperature at the farm location
evaporation[maize]	539	mm/year	Evaporation at the farm location
transpiration[maize]	0	mm/year	Transpiration of the crop
animal_type			The type of livestock in the farm; If no livestock, leave it blank
animal_number	0	head	Number of livestock
housing_days	0	d	housing days of the livestock
extra_stable_time	0		extra stable time during grazing days of the livestock
field_area	1	ha	area of the field
slope_percent	10	%	calculated based on the slope degree of the field, the value equals to tan(slope degree) * 100
soil_type	clay		classification based on soil texture
SOM	4	%	Soil organic matter content
clay_content	24	%	Soil clay content
initial_CN_ratio	11		Ratio of the initial soil carbon and nitrogen content
cation_exchange_capacity	151	mmolc/kg	initial soil cation exchange capacity
initial soil base saturation		%	initial soil base saturation
depth_to_rock	2000	cm	depth to rock
ESDB_texture	Loam		["Sand", "Loam", "Clay", Heavy clay", "Peat"]
ESDB_root_depth	Moderate		Rooting depth data are based on ESDB “Depth class of an obstacle to roots” (database field ROO).
atmospheric_NH3_deposition	1.5	kg/ha/yr	atmospheric NH3 deposition
atmospheric_NOx_deposition	1.9	kg/ha/yr	atmospheric Nox deposition
atmospheric_P_deposition	0.2	kg/ha/yr	atmospheric P deposition
atmospheric_K_deposition	0.5	kg/ha/yr	atmospheric K deposition
atmospheric_Ca_deposition	10.5	kg/ha/yr	atmospheric Ca deposition
atmospheric_Mg_deposition	1.7	kg/ha/yr	atmospheric Mg deposition
atmospheric Na deposition	4.0	kg/ha/yr	atmospheric Na deposition
atmospheric_S_deposition	0.7	kg/ha/yr	atmospheric S deposition
atmospheric_Cl_deposition	6.7	kg/ha/yr	atmospheric Cl deposition
atmospheric_Cu_deposition	3.7	g/ha/yr	atmospheric Cu deposition
atmospheric_Zn_deposition	17.6	g/ha/yr	atmospheric Zn deposition
atmospheric_Cd_deposition	0.2	g/ha/yr	atmospheric Cd deposition
crop_type	Spring barley		crop type
crop_category	cereal crops		based on crop type, give [grass, cereal crops or legumes]
crop_yield	6.38	t FW /ha/year	yield of crop

crop_DM	0.85		fraction of dry matter in the yield (values varying from 0 to 1)
N_content	14	g/kg	N content of crop harvested part dry weight, same for elements below
P_content	3.23	g/kg	P content of crop harvested part
K_content	4.71	g/kg	K content of crop harvested part
Ca_content	0.5	g/kg	Ca content of crop harvested part
Mg_content	1.02	g/kg	Mg content of crop harvested part
Na_content	0.1	g/kg	Na content of crop harvested part
S_content	1.26	g/kg	S content of crop harvested part
Cl_content	1.07	g/kg	Cl content of crop harvested part
Cu_content	0	g/kg	Cu content of crop harvested part
Zn_content	0.03	g/kg	Zn content of crop harvested part
Cd_content	no data	g/kg	Cd content of crop harvested part
GSratio	0.86		Grain:straw ratio of crop
RSratio	0.25		Straw:root ratio
harvest_index	0.46		proportion of plant dry biomass allocated into grains
residue_removal_index	0.8		ratio of crop residue removal, varying between 0 to 1
irrigation	0	mm/year	annual irrigation rate of the crop
fertilizer_type	Urea		type of applied mineral N fertilizer
fertilizer_N_input	80	kg/ha/yr	annual N input rate of mineral fertilizer
fertilizer_P_input	5.8	kg/ha/yr	annual P input rate of mineral fertilizer
fertilizer_K_input	1.5	kg/ha/yr	annual K input rate of mineral fertilizer
fertilizer_Ca_input	13.64	kg/ha/yr	annual Ca input rate of mineral fertilizer
fertilizer_Mg_input	5.1	kg/ha/yr	annual Mg input rate of mineral fertilizer
fertilizer_Na_input	28.08	kg/ha/yr	annual Na input rate of mineral fertilizer
fertilizer_S_input	11.89	kg/ha/yr	annual S input rate of mineral fertilizer
fertilizer_Cl_input	50.5	kg/ha/yr	annual Cl input rate of mineral fertilizer
fertilizer_Zn_input	70.5	g/ha/yr	annual Zn input rate of mineral fertilizer
fertilizer_Cu_input	40.8	g/ha/yr	annual Cu input rate of mineral fertilizer
fertilizer_Cd_Input	0.745	g/ha/yr	annual Cd input rate of mineral fertilizer
liquid_manure_type	Solid cattle manure		the type of applied liquid manure
liquid_manure_N_input	80	kg/ha/yr	annual N input rate of liquid manure
solid_manure_type	0		the type of applied solid manure
solid_manure_N_input	0	kg/ha/yr	annual N input rate of solid manure
manure_application_fraction	0.8		fration of livestock manure in the farm that applied to the field (if applicable)
manure_NPratio	5.74		N:P ratio in manure
manure_NKratio	0.95		N:K ratio in manure
manure_NCaratio	2.54		N:Ca ratio in manure
manure_NMgratio	7.5		N:Mg ratio in manure
manure_NNaratio	7.16		N:Na ratio in manure
manure_NSratio	9.13		N:S ratio in manure
manure_NClratio	5.81		N:Cl ratio in manure
manure_NZnratio	228		N:Zn ratio in manure
manure_NCuratio	1012		N:Cu ratio in manure

manure_NCdratio	169404		N:Cd ratio in manure
bulk_density_topsoil[location]	1118	kg/m3	soil bulk density of topsoil (0-30cm)
bulk_density_subsoil[location]	1309	kg/m3	soil bulk density of subsoil (30-100cm)
init_pH_KCl_topsoil	6		initial soil pH extracted by KCl of topsoil
init_pH_KCl_subsoil	6		initial soil pH extracted by KCl of subsoil
init_Pox_topsoil	7.5	mmol/kg	initial content of soil P extracted by oxalate of topsoil
init_Pox_subsoil	7.5	mmol/kg	initial content of soil P extracted by oxalate of subsoil
AlFeox_pool_topsoil	30	mmol/kg	initial content of soil Al and Fe extracted by oxalate of topsoil
AlFeox_pool_subsoil	20	mmol/kg	initial content of soil Al and Fe extracted by oxalate of subsoil
KL	2000	m3/kg	Langmuir adsorption constant for soil P
KF_topsoil	0	mmol. kg(soil)$^{-1}$ (mg.l (water)$^{-1}$)$^{-n}$	Freundlich constant of the stable soil P pool in the topsoil
KF_subsoil	0	mmol. kg(soil)$^{-1}$ (mg.l (water)$^{-1}$)$^{-n}$	Freundlich constant of the stable soil P pool in the subsoil
nP	0.26		Code from Jan Cees
init_cu_total_content_topsoil	9.48	mg/kg	initial content of soil Cu of topsoil
init_cu_total_content_subsoil	9.48	mg/kg	initial content of soil Cu of subsoil
init_Zn_total_content_topsoil	37.81	mg/kg	initial content of soil Zn of topsoil
init_Zn_total_content_subsoil	37.81	mg/kg	initial content of soil Zn of subsoil
init_Cd_total_content_topsoil	0.3	mg/kg	initial content of soil Cd of topsoil
init_Cd_total_content_subsoil	0.3	mg/kg	initial content of soil Cd of subsoil
init_pH_H2O_topsoil	6.9		initial soil pH extracted by H2O of topsoil, if missing, calculated based on KCl_pH
init_pH_H2O_subsoil	6.9		initial soil pH extracted by H2O of subsoil, if missing, calculated based on KCl_pH
init_pH_CaCl2_topsoil	6.1		initial soil pH extracted by CaCl2 of topsoil, if missing, calculated based on KCl_pH
init_pH_CaCl2_subsoil	6.1		initial soil pH extracted by CaCl2 of subsoil, if missing, calculated based on KCl_pH
init_pH_ss_topsoil	6.7		pH in soil solution, equal to pH_H2O (?)
init_pH_ss_subsoil	6.7		pH in soil solution, equal to pH_H3O (?)
init_OlsenP_topsoil	28.9	mg/kg	
init_OlsenP_subsoil	28.9	mg/kg	
sowing date	151	day	
harvesting date	273	day	
crop residue management	0.85	(-)	
N application from manure	137	day	
N application from mineral fertilizer	181	day	

Annex 3B. Average monthly climate data retrieved from MITERRA-Europe.

	Evapotranspiration (mm)	Precipitation (mm)	Temperature (°C)	Irrigation
Total	539	750	6.3	0
M1	10.1	52.1	-2.9	0
M2	11.2	43.9	-3.1	0
M3	21.3	41.3	0	0
M4	44.8	43.1	4.7	0
M5	76.2	54.1	10.6	0
M6	94.1	80.2	15	0
M7	94.1	87.1	17.3	0
M8	78.4	86.9	16	0
M9	49.3	67.9	11.3	0
M10	29.1	66.9	6.4	0
M11	16.8	64.9	2	0
M12	12.3	61.5	-1.6	0

Annex 3C. Crop input data.

Crop type	spring barley
Dry weight fraction	0.85
Harvest Index	0.46
N content	14
P content	3.23
K content	4.714
Ca content	0.5
Mg content	1.022
Na content	0.1
S content	1.255
Cl content	1.074
Cu content	0.25
Fraction uptake topsoil	0.8
Crop C fraction	0.54
Residue N index	1.53

Annex 3D. Livestock input data

animal_type	dairy cow
N_excre_rate (kg/head/yr)	144
liquid_manure_fraction	0.9
urine_fraction	0.6
liquid_manure_CNratio	7.8
solid_manure_CNratio	14.3
liquid_manure_NPratio	7.46
solid_manure_NPratio	7.46
CH4_enteric_factor	134.59
CH4_grazing_factor	3
CH4_housing_factor	37.85
slurry_housing_NH3_EF	0.1396
slurry_housing_N2O_EF	0.00225
slurry_housing_NOx_EF	0.003
solid_housing_NH3_EF	0.1396
solid_housing_N2O_EF	0.005
solid_housing_NOx_EF	0.003
slurry_storage_NH3_EF	0.052
slurry_storage_N2O_EF	0.00475
slurry_storage_NOx_EF	0.0000475
slurry_storage_N2_EF	0.01
solid_storage_NH3_EF	0.045
solid_storage_N2O_EF	0.00286
solid_storage_NOx_EF	0.00143
solid_storage_N2_EF	0.1

Annex 5 Country codes from Eurostat

Country code	Country	Remark
AT	Austria	
BE	Belgium	
BG	Bulgaria	
CH	Switzerland	To be included
CY	Cyprus	To be included
CZ	Czech	
DE	Germany	
DK	Denmark	
EE	Estonia	
EL	Greece	
ES	Spain	
FI	Finland	
FR	France	
HR	Croatia	
HU	Hungaria	
IE	Ireland	
IT	Italy	
LT	Lithuania	
LU	Luxembourg	
LV	Latvia	
MT	Malta	To be included
NL	Netherlands	
PL	Polland	
PT	Portugal	
RO	Romania	
SE	Sweden	
SI	Slovenia	
SK	Slovakia	
UK	United Kingdom	To be included

List of References

Addiscott, T.M. and Tuck, G. (2001), Non-linearity and error in modelling soil processes. European Journal of Soil Science, 52: 129-138. https://doi.org/10.1046/j.1365-2389.2001.t01-1-00366.x.

Andriulo, A., Mary, B., Guerif, J., 1999. Modelling soil carbon dynamics with various cropping sequences on the rolling pampas. Agronomie 19: 365-377. DOI:10.1051/agro:19990504.

Baddeley, J.A., Jones, S., Topp, C.F.E., Watson, C.A., Helming, J., Stoddard, F.L., 2014. Biological nitrogen fixation (BNF) by legume crops in Europe. Legume Futures Report 1.5. Available from www.legumehub.eu.

Belyazid, S., Akselsson, C., Zanchi, G., 2022. Water limitation may restrict the positive effect of higher temperatures on weathering rates in forest soils. Forests 13, 310. https://doi.org/10.3390/f13020310.

Belyazid, S., Phelan, J., Nihlgård, B., Sverdrup, H., Driscoll, C., Fernandez, I., Aherne, J., Teeling-Adams, L., Bailey, S., Arsenault, M., Cleavitt, N., Engstrom, B., Dennis, R., Sperduto, D., Werier, D., Clark, C., 2019. Assessing the Effects of Climate Change and Air Pollution on Soil Properties and Plant Diversity in Northeastern U.S. hardwood forests: Model Setup and Evaluation. Water, Air and Soil Pollution 230:106.

Belyazid, S., Zanchi, G., 2019. Water limitation can negate the effect of higher temperatures on forest carbon sequestration. European Journal of Forest Research, 138(2): 287-297. https://doi.org/10.1007/s10342-019-01168-4.

Belyazid S, Kurz D, Braun S, Sverdrup H, Rihm B, Hettelingh JP., 2011. A dynamic modelling approach for estimating critical loads of nitrogen based on plant community changes under a changing climate. Environmental Pollution 159: 789-801.

Bonten, L.T.C., Reinds, G.J., Posch, M., 2016. A model to calculate effects of atmospheric deposition on soil acidification, eutrophication and carbon sequestration. Environmental Modelling & Software 79: 75-84. DOI: 10.1016/j.envsoft.2016.01.009.

Chang J, Viovy N, Vuichard N, Ciais P, Campioli M, et al. (2015) Modeled Changes in Potential Grassland Productivity and in Grass-Fed Ruminant Livestock Density in Europe over 1961–2010. PLOS ONE 10(5): e0127554. https://doi.org/10.1371/journal.pone.0127554.

Coleman, K., Jenkinson, D.S., 2014. RothC-26.3 - A Model for the turnover of carbon in soil. In: Powlson, D.S., Smith, P., Smith, J.U. (eds). Evaluation of Soil Organic Matter Models. NATO ASI Series 38. Springer, Berlin, Heidelberg. DOI: 10.1007/978-3-642-61094-3_17.

De Vries, W., 1994. Soil response to acid deposition at different regional scales: field and laboratory data, critical loads and model predictions. PhD thesis Landbouwuniversiteit Wageningen. Wageningen, 487 p.

De Vries, W., Kros, J., Voogd, J.C., Ros, G.H., 2023. Integrated assessment of agricultural practices on large scale losses of ammonia, greenhouse gases, nutrients and heavy metals to air and water. Science of The Total Environment 857: 159220. DOI: 10.1016/j.scitotenv.2022.159220.

De Vries, W., Römkens, P.F.A.M., Kros, J., Voogd, J.C., Schulte-Uebbing, L.F., 2022. Impacts of nutrients and heavy metals in European agriculture. Current and critical inputs in relation to air, soil and water quality. European Topic Centre on Data Integration and Digitalisation. ETC-DI Report 2022/01. 72 pages.

Duan, Y.-F., Bruun, S., Stoumann Jensen, L., Van Gerven, L., Hendriks, C., Stokkermans, L., Groenedijk, P., Lesschen, J.P., Prado, J., Fangueiro, D., 2020. D1.5 Mapping and characterization of CNP flows and their stoichiometry in main farming systems in Europe. Retrieved on 11 December 2023: https://www.nutri2cycle.eu/wp-content/uploads/2021/05/D1.5-Nutri2Cycle_Report-on-the-mapping-and-charcaterization-of-CNP-flows.pdf.

EEA, 2019. CORINE Land Cover 2018 (raster 100 m), Europe, 6-yearly - version 2020_20u1, May 2020

Erlandsson Lampa, M., Belyazid, S., Zanchi, G., Akselsson, C. (2019). Effects of whole-tree harvesting on soil, soil water and tree growth – A dynamic modelling exercise in four long-term experiments. Ecological Modelleing 414. doi: 10.1016/j.ecolmodel.2019.108832.

Fetting, C., 2020. The European Green Dela, ESDN Report, December 2020, ESDN Office, Vienna.

Gaudio, N., Belyazid, S., Gendre, X., Mansat, A., Nicolas, M., Rizzetto, S., Sverdrup, H., Probst, A., 2015. Combined effect of atmospheric nitrogen deposition and climate change on temperate forest soil biogeochemistry: A modeling approach. Ecological Modelling 306: 24 – 34. DOI: 10.1016/j.ecolmodel.2014.10.002.

Gustafsson, J.P., Akram, M., Tiberg,C., 2015. Predicting sulphate adsorption/desorption in forest soils: Evaluation of an extended Freundlich equation. Chemosphere 119: 83-89. DOI: 10.1016/j.chemosphere.2014.05.067.

Heckelei, T., Britz, W., 2001. Concept and explorative application of an EU-wide regional agricultural sector model (CAPRI-Project). 281-290

Hendriks, C.M.J., Lesschen, J.P., Duan, K., Adriani, A., Ros, G., De Vries, W., Wang, M., Xu, D., Tan, M., Belyazid, S., Strekalovskaya, A., Degan, F., Bonnard, A., Maradeix, M.S., Sverdrup, H., 2024. Initial report on the design of the Nutrimodel Framework. NutriBudget Deliverable 2.1.

Justes, E., Mary, B., Meynard, J.-M, Machet, J.-M., Thelier-Huche, L., 1994. Determination of a Critical Nitrogen Dilution Curve for Winter Wheat Crops. Annals of Botany 74: 397-407. DOI: 10.1006/anbo.1994.1133.

Keuskamp, J.A., Van Drecht, G., Bouwman, A.F., 2012. European-scale modelling of groundwater denitrification and associated N2O production. Environmental Pollution 165: 67-76. DOI: 10.1016/j.envpol.2012.02.008.

Khaledian, M.R., Mailhol, J.C., Ruelle, P., Rosique, P., 2009. Adapting PILOTE model for water and yield management under direct seeding system: The case of corn and durum wheat in a Mediterranean context. Agricultural Water Management 96: 757-770. DOI: 10.1016/j.agwat.2008.10.011.

Kros, J., Hutchings, N.J., Kristensen, I.T., Kristensen, I.S., Børgesen, C.D., Voogd, J.C., Dalgaard, T., De Vries, W., 2018. A comparison of disaggregated nitrogen budgets for Danish agriculture using Europe-wide and national approaches. Science of The Total Environment 643: 890-901. DOI: 10.1016/j.scitotenv.2018.06.267.

Laberdesque, M., Bessard Duparc, P., Soenen, B., Metais, P., Trochard, R., Le Bris, X., 2017. CHN: practical case of valorization of a dynamic crop model to estimate the number of available days for cultivation works. Conference Paper. EFITA WCCA Montpellier 2017.

Lesschen, J.P., Van den Berg, M., Westhoek, H.J., Witzke, H.P., Oenema, O., 2011. Greenhouse gas emission profiles of European livestock sectors. Animal Feed Science and Technology 166–167: 16-28. DOI: 10.1016/j.anifeedsci.2011.04.058.

Leterme, B., Vanclooster, M., Van der Linden, A.M.A., Tiktak, A., Rounsevell, M.D.A., 2007. The consequences of interpolating or calculating first on the simulation of pesticide leaching at the regional scale. Geoderma 137: 414-425. DOI: 10.1016/j.geoderma.2006.09.004.

Mahowald, N., Jickells, T.D., Baker, A.R., Artaxo, P., Benitez-Nelson, C.R., et al., 2008. Global distribution of atmospheric phosphorus sources, concentrations and deposition rates, and anthropogenic impacts. Global Biogeochem. Cycles 22: GB4026. DOI: 10.1029/2008GB003240.

McCartney, D.H., Block, H.C., Dubeski, P.L., Ohama, A.J., 2006. Review: The composition and availability of straw and chaff from small grain cereals for beef cattle in western Canada. Can. J. Anim. Sci. 86: 443–455.

Modin-Edman, A.-K, Öborn, I., Sverdrup, H., 2007. FARMFLOW—A dynamic model for phosphorus mass flow, simulating conventional and organic management of a Swedish dairy farm. Agricultural Systems: 94: 431-444. DOI: 10.1016/j.agsy.2006.11.007.

Monteith, J.L. and Moss, C.J., 1977. Climate and the Efficiency of Crop Production in Britain. Philosophical Transactions of Royal Society B, 281, 277-294. https://doi.org/10.1098/rstb.1977.0140.

Neumann, K., Elbersen, B.S., Verburg, P.H. et al. 2009. Modelling the spatial distribution of livestock in Europe. Landscape Ecol 24, 1207–1222. https://doi.org/10.1007/s10980-009-9357-5.

Oenema, O., Witzke, H.P., Klimont, Z., Lesschen, J.P., Velthof, G.L., 2009. Integrated assessment of promising measures to decrease nitrogen losses from agriculture in EU-27. Agriculture, Ecosystems & Environment 133: 280-288. DOI: 10.1016/j.agee.2009.04.025.

Panagos, P., Köningner, J., Ballabio, C., Liakos, L., Muntwyler, A., Borrelli, P., Lugato, E., 2022. Improving the phosphorus budget of European agricultural soils. Science of The Total Environment: 853. DOI: 10.1016/j.scitotenv.2022.158706.

Reinds, G.J., Heuvelink, G.B.M., Hoogland, T., Kros, J., De Vries, W., 2012. Estimating nitrogen fluxes at the European scale by upscaling INTEGRATOR model outputs from selected sites. Biogeosciences, 9: 4527 – 4536. DOI: 10.5194/bg-9-4527-2012.

Saveyn H, Eder P. 2013. End-of-waste criteria for biodegradable waste subjected to biological treatment (compost and digestate): Technical proposals . EUR 26425. Luxembourg (Luxembourg): Publications Office of the European Union. JRC87124.

Scarlat, N., Martinov, M., Dallemand, J.-F., 2010. Assessment of the availability of agricultural crop residues in the European Union: Potential and limitations for bioenergy use. Waste Management 30. 1889-1897. DOI: 10.1016/j.wasman.2010.04.016.

Schröder, J.J., Ten Holte, L., Janssen, B.H., 1997. Non-overwintering cover crops: a significant source of N. Netherlands Journal of Agricultural Science 45: 231-248.

Schulte-Uebbing, L., De Vries, W., 2021. Reconciling food production and environmental boundaries for nitrogen in the European Union. Science of The Total Environment 786: 147427. DOI: 10.1016/j.scitotenv.2021.147427.

Shah F, Wu W., 2019. Soil and Crop Management Strategies to Ensure Higher Crop Productivity within Sustainable Environments. *Sustainability* 11:1485. DOI: 10.3390/su11051485.

Smaling, E.M.A., Roscoe, R., Lesschen, J.P., Bouwman, A.F., Comunello, E., 2008. From forest to waste: Assessment of the Brazilian soybean chain, using nitrogen as a marker. Agriculture, Ecosystems & Environment 128: 185-197. DOI: 10.1016/j.agee.2008.06.005.

Steinfurth, K., Hirte, J., Morel, C., Buczko, U., 2021. Conversion equations between Olsen-P and other methods used to assess plant available soil phosphorus in Europe – A review. Geoderma 401: 115339. DOI: 10.1016/j.geoderma.2021.115339.

Stockwell, B., Layden, I., Nicholls, Z., Carter, J., 2012. Addressing rural diffuse pollution in peri-urban agricultural catchments using the FarmFLOW framework: a study in the Pumicestone catchment. Australasian Journal of Environmental Management 19: 182-199. DOI: 10.1080/14486563.2012.701813.

Taghizadeh-Toosi, A., Olesen, J.E., Kristensen, K., Elsgaard, L., Østergaard, H.S., Lægdsmand, M., Greve, M.H. and Christensen, B.T. (2014), Changes in carbon stocks of Danish agricultural mineral soils between 1986 and 2009. Eur J Soil Sci, 65: 730-740. https://doi.org/10.1111/ejss.12169.

Van Doorn, M., Helfenstein, A., Ros, G.H., Heuvelink, G.B.M., Van Rotterdam-Los, D.A.M.D., Verweij, S.E., De Vries, W., 2024. High-resolution digital soil mapping of amorphous iron- and aluminium-(hydr)oxides to guide sustainable phosphorus and carbon management. Geoderma 443: 116838. DOI: 10.1016/j.geoderma.2024.116838.

Velthof, G.L., Lesschen, J.P., Webb, J., Pietrzak, S., Miatkowski, Z., Pinto, M., Kros, J., Oenema, O., 2014. The impact of the Nitrates Directive on nitrogen emissions from agriculture in the EU-27 during 2000–2008. Science of The Total Environment 468–469: 1225-1233. DOI: 10.1016/j.scitotenv.2013.04.058.

Velthof, G.L., Oudendag, D., Witzke, H.P., Asman, W.A., Klimont, Z., Oenema, O., 2009. Integrated assessment of nitrogen losses from agriculture in EU-27 using MITERRA-EUROPE. J Environ Qual. 38: 402-17. DOI: 10.2134/jeq2008.0108. PMID: 19202011.

Wery, J., Lecoeur, J., 2000. Learning Crop Physiology from the Development of a Crop Simulation Model. J. Nat. Resour. Life Sci. Educ. 29: 1-7. DOI: **10.2134/jnrlse.2000.0001**.

Winiwarter, W., 2005. The GAINS Model for Greenhouse Gases - Version 1.0: Nitrous Oxide (N2O). IIASA Interim Report. IIASA, Laxenburg, Austria: IR-05-055.

Yu, L., Zanchi, G., Akselsson, C., Wallander, H., Belyazid, S., 2018. Modelling the forest phosphorus nutrition in a southwestern Swedish forest site. Ecological modelling 369: 88-100.

Zanchi, G., Lucander, K., Kronnäs, V., Lampa, M.E., Akselsson, C., 2021. Modelling the effects of forest management intensification on base cation concentrations in soil water and on tree growth in spruce forests in Sweden. European Journal of Forest Research 140: 1417 – 1429. DOI: 10.1007/s10342-021-01408-6.

Zanchi, G., Yu, L., Akselsson, C., Bishop, K., Köhler, S., Olofsson, J., Belyazid, S., 2021. Simulation of water and chemical transport of chloride from the forest ecosystem to the stream. Environmental Modelling & Software, 138, 1364-8152. https://doi.org/10.1016/j.envsoft.2021.104984.

Optimisation of nutrient budget in agriculture

Project Coordinators:

Prof. Erik Meers, Erik.Meers@UGent.be
Dr. Ivona Sigurnjak, Ivona.Sigurnjak@UGent.be
Ghent University, Sint Pietersnieuwstraat 25, Ghent 9000, Belgium.

The Consortium:

Funded by the European Union