



Optimisation of nutrient budget in agriculture



D2.5 Desired carbon and nutrient state of European agricultural systems



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Executive Summary

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 farmers and advisors (NutriFarm), and insights in regional nutrient (N, P, K, S, Mg, Ca, Cd, Zn) and carbon (C) budgets to serve regional, national and European stakeholders (MITERRA-Europe). NutriBudget will contribute to systemically optimizing nutrient flows and budgets across different agricultural production systems and regions in the EU to reduce nutrient losses to the environment and related impacts.

To assess the actual farm performance in view of agronomic and environmental targets, an integrative key performance indicator (KPI) framework has been designed in NutriBudget to monitor the transition from the current to the desired status to have optimised farming systems. In Deliverable 3.2 the thresholds for the critical or target values for carbon, nitrogen, phosphorus, potassium, calcium, magnesium, sulphur, copper, zinc and cadmium surpluses (inputs minus crop uptake) in view of agronomic and environmental targets for soil health, crop production, water quality, biodiversity and climate have been derived. The objective of this report is to provide the desired state for carbon and nutrient budgets for European agricultural soils that comply with the targets for water quality, air quality, climate, biodiversity and agricultural. The desired and current state of the carbon and nutrient budgets are calculated by the MITERRA-Europe model for the EU Member States at NUTS2 level.

The desired state for carbon and nutrient budgets is defined as target surplus for agronomic crop production and the critical surpluses for the environmental objectives: water quality, air quality climate and biodiversity. The methodology builds on the first draft NutriKPIs and their thresholds that were described in NutriBudget Deliverable 3.2. A target surplus is calculated as the sum of a target soil accumulation, bringing soils up to a desired carbon or nutrient soil content in a given time period, and the losses (emissions or leaching) from soil at the desired soil content. A critical surplus is calculated as the critical loss of carbon or nutrients to air and/or water. Those critical losses are only relevant for N, P and metals for which criteria exist with respect to air emissions (NH_3) and dissolved concentrations (NO_3 , P and metals). The critical input is calculated as the target (or current) uptake and the critical surplus (loss). The calculation rules have been implemented in the MITERRA-Europe model for the EU wide assessment. MITERRA-Europe is a deterministic model to simulate integrated flows and emissions of nutrient elements at various geographical scales.

The approach as used in this report is based on many assumptions and also the required input data has its uncertainties. The results should therefore be treated with care and be considered as first indications. During the remainder of the NutriBudget project, an update of these results might be required, building on more empirical data and further verification of the results in the NutriBudget case study countries.

Still the report provides valuable first insights with for some of the nutrients clear trade-offs between target surpluses for agronomic production and critical surpluses for environmental objectives, which are often much lower. This requires optimisation among different objectives and nutrients. This will be further elaborated in D2.6 when also the impact of measures from the NutriBudget roadmaps will be quantified.

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List of Abbreviations

C	Carbon
Ca	Calcium
Cd	Cadmium
CEC	Cation Exchange Capacity
CH ₄	Methane
CO ₂	Carbon dioxide
Cu	Copper
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
Mg	Magnesium
N	Nitrogen
N ₂ O	Nitrous oxide
NH ₃	Ammonia
NO _x	Nitrogen oxide
P	Phosphorus
S	Sulphur
SOC	Soil Organic Carbon
Zn	Zink

1. Introduction

1.1 Background

The NutriBudget project strongly focuses on using carbon and nutrient surpluses as effect indicators for which specific thresholds can be defined in view of the multidimensional agronomic and environmental targets. For this report we focus on soil nutrient balances in agriculture, which are equivalent to inputs of nutrients minus outputs of nutrients contained in plant products. A surplus means that inputs exceed outputs in the balance, thereby causing an accumulation of nutrients into soil, which might lead to losses into water as well as into air in the case of nitrogen.

As explored and reviewed by Ros et al. (2022), carbon and nutrient balances are of direct relevance to policies relating to agriculture and the environment including climate change, air quality, water quality, and biodiversity. These balances have been used in market initiatives and policy instruments as indicators of the pressure put by farming on the environment and how that pressure changes over time. They also allow direct feedback on crop and soil management, giving great opportunities to guide farming systems in their roadmap to more sustainable carbon and nutrient use in agriculture.

The NutriBudget project has set objectives for which carbon and nutrient balances should be optimised, which comprise water quality (mainly nitrogen and phosphorus), air quality (mainly carbon and nitrogen), biodiversity (mainly ammonia), climate (mainly carbon) and soil quality (mainly carbon, cations and anions), and optimal crop production. A desired nutrient and soil organic carbon state refers to potential target values for soil quality indicators (linked to crop production) and critical values for air and water quality indicators (linked to environmental protection).

1.2 Objective

The objective of this report is to provide the desired state for carbon and nutrient budgets for European agricultural soils that comply with the targets for water quality, air quality, climate, biodiversity and agricultural. The desired and current state of the carbon and nutrient budgets is calculated by the MITERRA-Europe model for the EU Member States at NUTS2 level. This work builds on de Vries et al. (2021) who quantified spatially explicit boundaries for agricultural nitrogen inputs in the European Union to meet air and water quality targets. Here we extent the analysis to carbon and other nutrients.

1.3 Outline of the report

In Chapter 2 the overall approach is described followed by a detailed description of the calculation rules that are used to quantify the target and or critical surplus for carbon, nitrogen, phosphorus, sulphur, base cations (Ca, Mg and K) and metals (Cu, Zn and Cd). In Chapter 3 the results of the carbon and nutrient surpluses of the desired state and current state are presented as maps and figures. The results and the limitations of the approach are discussed in Chapter 4 and some preliminary conclusions are provided in Chapter 5.

2. Overall approach for calculation of the desired state

2.1 The principle of calculating a target or critical surplus

In this study, the surplus of nutrients is defined as the difference between the total nutrient inputs by fertilizer, manure, other organic sources and deposition (and fixation in case of N) and nutrient removal by crop harvest. In the case of carbon, there is no uptake of C by crops from soil. The surplus is then defined as the input of carbon minus the CO₂-C emission due to decomposition of residue and manure input during the year of application.

The fate of the surplus is soil accumulation, and soil losses to air (carbon and nitrogen) and to water (all nutrients). In principle, there are also carbon losses to water, but those losses are neglected compared to air emissions. A target surplus aims to bring (mostly increase) carbon or nutrient contents in soil to a desired value in view of soil health and crop production, while a critical surplus aims to reduce carbon or nutrient losses from soil below a critical value.

A target surplus is calculated as the sum of a target soil accumulation, bringing soils up to a desired carbon or nutrient soil content in a given time period, and the losses (emissions or leaching) from soil at the desired soil content. When the soil has reached the desired carbon or nutrient soil content (an equilibrium after a defined time period), the target surplus only includes the losses (emissions or leaching) from soil at the desired soil content, which may differ from the current losses. The target surpluses before and after equilibrium after equilibrium are both calculated. If a target soil content does not exist (in case of sulphur), the target surplus is set at the current surplus. A target input is set equal at a target uptake and a target surplus.

A critical surplus is calculated as the critical loss of carbon or nutrients to air and/or water. Those critical losses are only relevant for N, P and metals for which criteria exist with respect to air emissions (NH₃) and dissolved concentrations (NO₃, P and metals). The critical input is calculated as the target (or current) uptake and the critical surplus (loss). Unlike target surpluses and inputs, we neglect soil accumulation or release, in line with the calculation of critical loads. The reason for this assumption is that after a delay time, during which soils reach equilibrium, the calculated critical surplus leads to dissolved element concentrations that are just at the critical level.

2.2 Use of a one-layer approach in calculating a target or critical surplus

The calculation of either the target or critical surplus for carbon and nutrients (N, P, S, the base cations, Ca, Mg and K and the metals Cu and Zn) and the pollutant Cd, is in all cases based on a one-layer approach. For N, a one-layer approach is logic, as it links to the emission of NH₃ to air or the losses of N to either ground water or surface water from the complete soils profile and making a distinction in two layers is highly artificial. We only need to check that a forward two-layer calculation with a crucial N surplus does indeed lead to critical N losses. For phosphorus (P), base cations (pH), sulphur and metals we should use a one-layer approach since target values in view of crop growth (P, pH, base cations) or critical values in view of crop quality (Cd) or soil biodiversity (Cu, Zn, Cd) are linked to the conditions in the topsoil (0-30cm). To make the calculations consistent with N, we also use the topsoil here and thus assess a critical leaching and runoff related to this layer.

Note that for P the target surplus is set equal to the critical P surplus. More specifically, the critical P surplus is equal to the target P surplus plus a critical P leaching which is very low and comparable to the neglected P deposition (Both in nearly all situations below 1 kg P ha-

1yr-1). Finally note that the target nutrient input is the P uptake at equilibrium and an extra amount in the period for build-up which depends on the target period used. Note that we also calculate critical or target inputs as this is more practical.

3. Carbon

For carbon, we must distinguish between soil organic carbon (SOC), being relevant to store in view of soil health, and losses of carbon as carbon dioxide (CO₂) and methane (CH₄), being greenhouse gases of which the emissions should be minimized. The latter criterion cannot really be translated into a carbon surplus (input) as explained below.

The target C surplus refers to the input of carbon minus the CO₂-C emission due to decomposition of residue and manure input during the year of application. This implies that the current C surplus should be calculated in a similar way, where RothCN should be able to distinguish CO₂-C emission from added material and from soil.

RothCN calculates the total CO₂-C emission from added material and from SOC content changes of four soil compartments (DPM, RPM, DMA and RMA), including the added input material, i.e., DPM & RPM for crop residues, and DMA & RMA for manure, according to:

$$C_{loss,comp} = \Delta SOC_{comp} \times f_{CO_2} \quad (3.1)$$

where ΔSOC_{comp} is the change of the C content of the compartment (DPM, RPM, DMA and RMA), f_{CO_2} is the fraction of CO₂ emission which was assumed same for all compartments.

The CO₂-C emission from added material ($C_{loss,mat,comp}$) is derived by a scaling procedure, comparing the C amount of added material to each compartment with the initial C amount in the compartment, according to:

$$C_{loss,mat,comp} = C_{loss,comp} \times \frac{C_{mat}}{C_{0,comp} + C_{mat}} \quad (3.2)$$

where $C_{0,comp}$ is the initial C amount in the compartment, and C_{mat} is the C amount of input material assigned to the compartment.

The actual C loss from the mineral soil only was then calculated based on the total C loss minus the sum of actual C loss from the input materials:

$$C_{loss,act} = C_{loss,total} - \sum C_{loss,mat,comp} \quad (3.3)$$

3.1 Target surplus for soil health and crop production

The target carbon surplus for soil health and crop production, being equal to the target carbon input as carbon uptake comes from air, aiming to bring soils up to a desired soil C content is assessed as:

$$C_{sp_target} = C_{loss,target} + \max(0, C_{target} - C_{act}) \times D \times \rho \times 0.01/T \quad (3.4)$$

where C_{act} refers to the actual soil organic carbon content (in mg kg⁻¹), C_{target} refers to the target value for SOC in view of soil health and crop production (mg kg⁻¹) in soil, $C_{loss,target}$ is the C loss to air by decomposition of SOC only at the target soil SOC content, D refers to the depth of the top soil (m), ρ refers to the bulk density of the soil (kg m⁻³), and 0.01 is a unit correction from mg m⁻² to kg ha⁻¹, and T refers to the time period (in years) to reach the desired target. For now, the target value for SOC below which a potentially serious decline in soil quality will occur is set at 2% (equal to 20 g kg⁻¹) based on Loveland & Web (2003) and Oldfield et al. (2019).

Assuming that there is a linear relationship in RothC between SOC and CO₂ loss by SOC decomposition, the target C loss is estimated based on the actual C loss and the ratio of target and actual soil organic carbon content, according to:

$$C_{loss,target} = C_{loss,act} \times C_{target}/C_{act} \quad (3.5)$$

where C_{act} is the actual C loss from the mineral soil only. In soils having an actual SOC content higher than the target value for soil health and crop production, there is no requirement to increase the carbon content in the soil. In that case, the desired C surplus equals to the C loss at the target SOC value, implying that the soil C content will slowly reduce to the target soil C content.

Figure 3.1 shows the current C inputs and the gap between current and target C input (current – target) for EU countries. A negative gap means that the current C input level is below the target value, whereas a positive gap indicates that the current input is above the target. There is a general trend of increasing C input from Southern to North-western Europe, with the Mediterranean regions having the lowest C input, and Ireland and the Benelux region having some of the highest C input, which is mostly related to high productive grasslands. The desired C input shows the amount of annual input required to reach or maintain no less than 2% SOC within a 30-year timeframe (2020-2050). In countries where the current SOC is already higher than 2%, the current input level is kept. To reach the 2% target, the Mediterranean and Eastern European countries must increase their annual C inputs significantly to increase C sequestration (Figure 3.2).

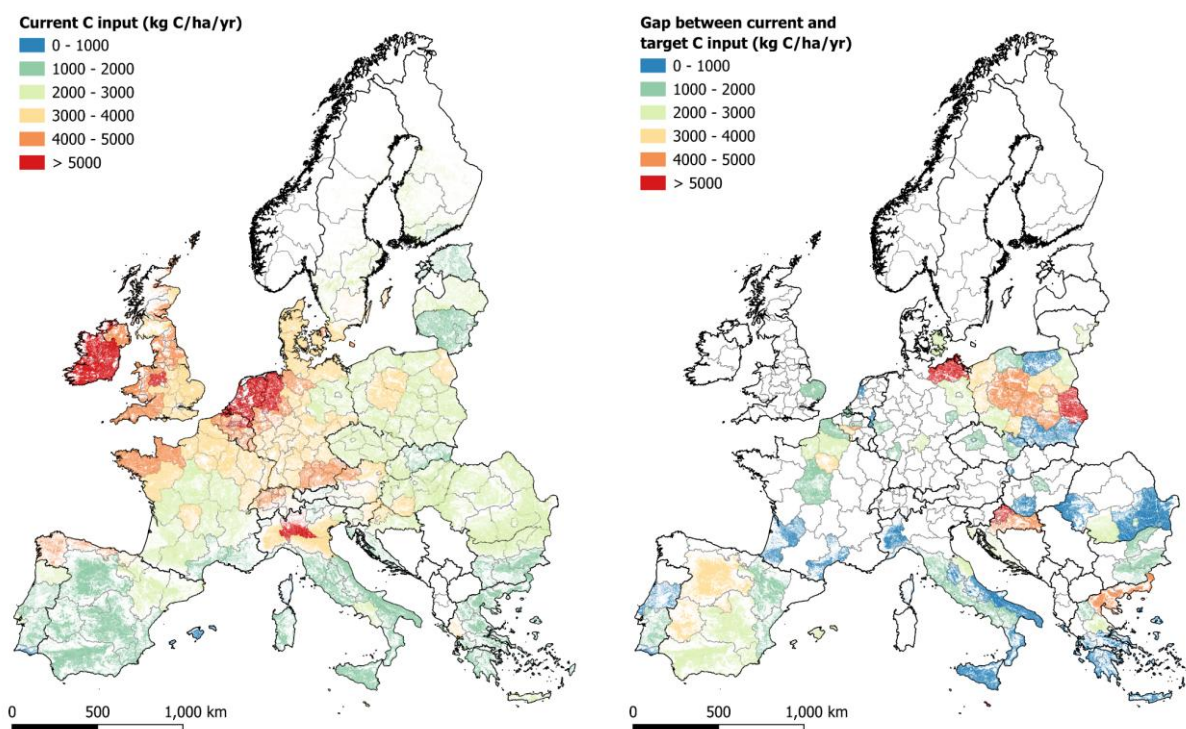


Figure 3.1. Current carbon inputs (left), and the gap between target and current carbon inputs (right, showing only regions where current input is below target) in view of soil health and crop production for agricultural soils at NUTS2 level.

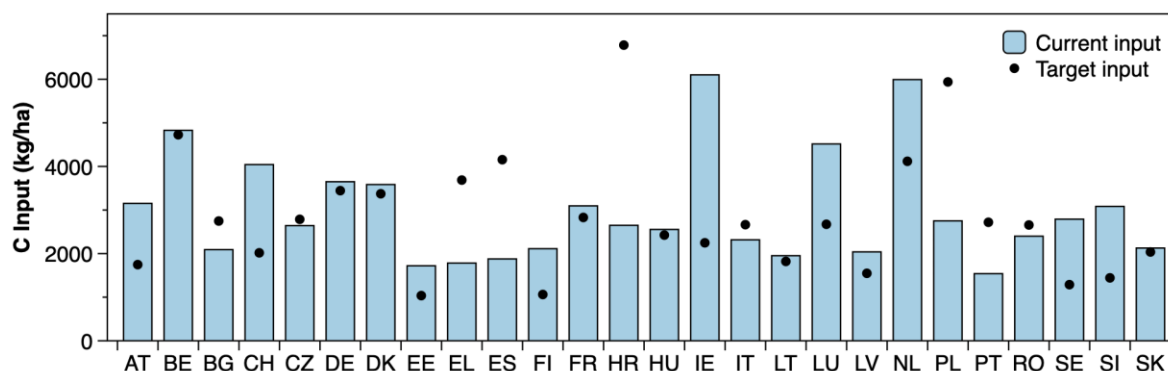


Figure 3.2. Current and target carbon input in view of soil health and crop production per country.

3.2 Critical carbon inputs for climate change mitigation

The target for greenhouse gas emissions in Europe is to be carbon neutral in 2050, implying that the sum of CH₄ (and N₂O) and CO₂ emissions, combined in terms of CO₂ equivalents should be zero. Even though there is an overall ambition for net zero CO₂ equivalent emissions in view of climate change, this will likely not be the ambition for agriculture since it would imply that all net CH₄ and N₂O emissions have to be compensated by soil carbon sequestration, which is impossible. It would imply a target annual C surplus (annual C input to the soil minus the CO₂-C emission due to decomposition of residue and manure input during the year of application) that is equal to:

$$C_{sp_target} = CH4_{loss} \times GWP_{CH4} + N2O_{loss} \times GWP_{N2O} + CO2_{loss} \quad (3.6)$$

where GWP_{CH4} and GWP_{N2O} are the global warming potentials of CH₄ and N₂O in CO₂ equivalents (27 and 273 according to IPCC AR6); $CH4_{loss}$, $N2O_{loss}$ and $CO2_{loss}$ are the emissions under either the current situation or after implementing a mitigation measures with CO₂ emission being limited to decomposition of soil organic carbon. This approach implies a continually moving target due to changes in N₂O and CH₄ emissions and soil CO₂ emissions in response to a mitigation measures. Even though the target C surplus, based on an ambition of net zero CO₂ equivalent emissions in agriculture, will not be reached for livestock systems, the indicator will still be used to evaluate the impacts of measures (where a decline towards zero is a positive impact).

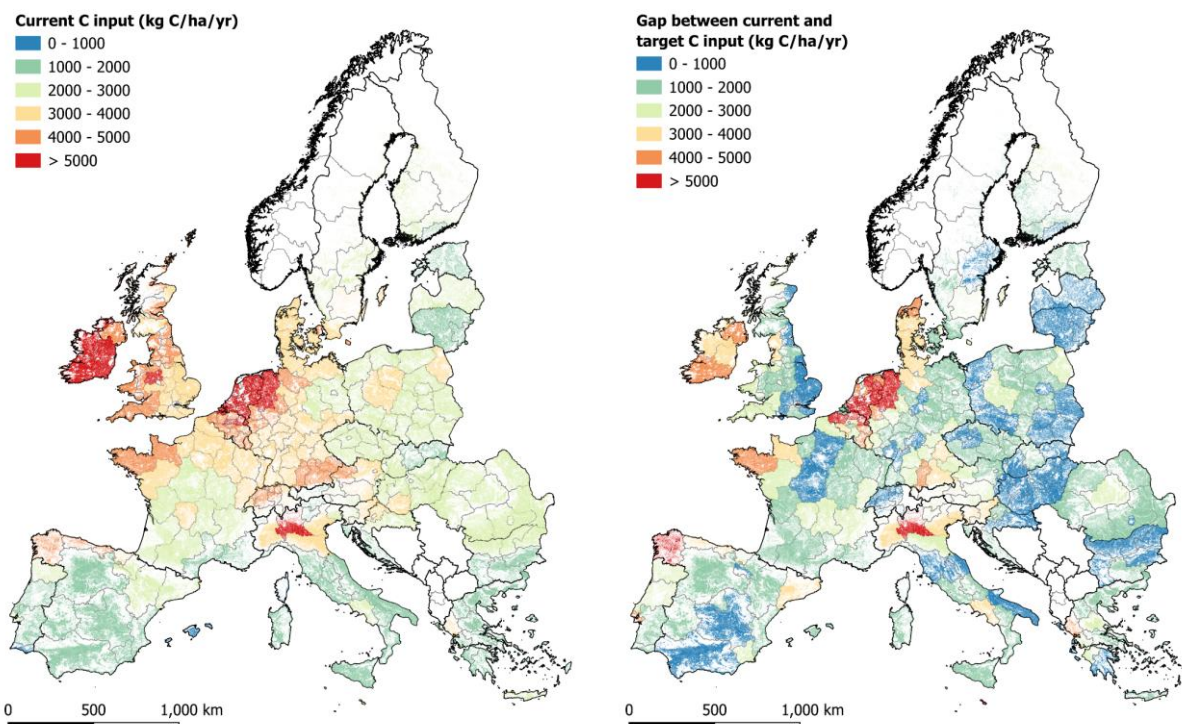


Figure 3.3. Current carbon inputs (left), and the gap between target and current carbon inputs (right, showing only regions where current input is below target) in view of climate change mitigation for agricultural soils at NUTS2 level.

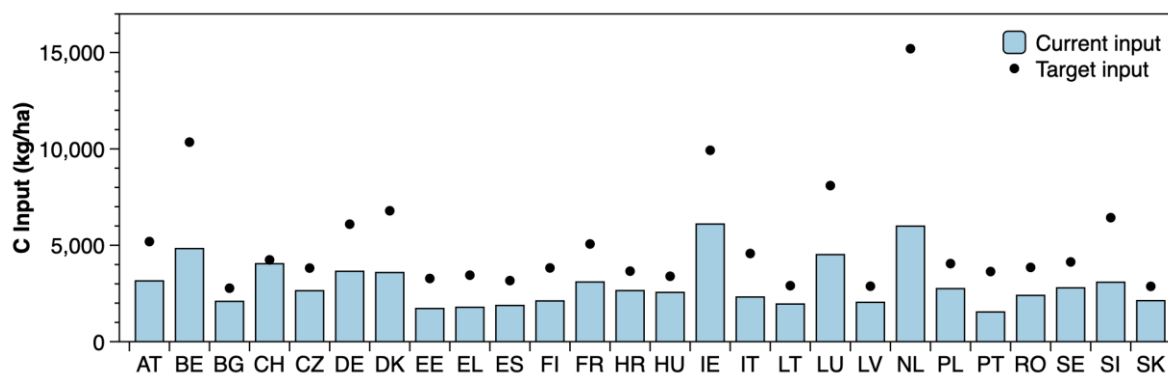


Figure 3.4. Current and target carbon input in view of greenhouse gas emissions per country.

4. Nitrogen

4.1 Target surplus and input for soil health and crop production

The target surplus for soil health and crop production is here defined as the desired N input to ensure a N supplying capacity of soils (N mineralization) of 70 kg N ha⁻¹ yr⁻¹ for cropland (including perennials) and 100 kg N ha⁻¹ yr⁻¹ for grassland (Ros et al, 2022). The current N mineralization is calculated as the sum of the mineralized N from the soil, and the amount of N that is mineralized from the supplied organic N products, simulated by the RothCN model. Following this reasoning, the target organic N input, which ensures a target N mineralization, is estimated as:

$$N_{in_org_target} = N_{in_org_current} \times \frac{N_{ss,target}}{N_{ss,act}} \quad (4.1)$$

where $N_{ss,target}$ refers to the desired N supply for agricultural soils (i.e., 70 kg N ha⁻¹ yr⁻¹ for cropland and 100 kg N ha⁻¹ yr⁻¹ for grassland), $N_{ss,act}$ refers to the actual N supply (being estimated as function of soil organic carbon, C-to-N ratio and the temperature). Note that the total N input via manure is not allowed to exceed the 170 kg N ha⁻¹ given the European Nitrate Directive. The target input is the sum of the N surplus and the N uptake at the target N surplus.

The target organic N input is estimated to ensure 70 (for arable and perennial crops) or 100 (for grassland) kg/ha N supply from mineralization. In countries like Belgium, the Netherlands, and Ireland, where current organic N supply is high, input must be reduced to meet the target. Whereas in Spain, as well as central and eastern European region, there is room to increase organic N input.

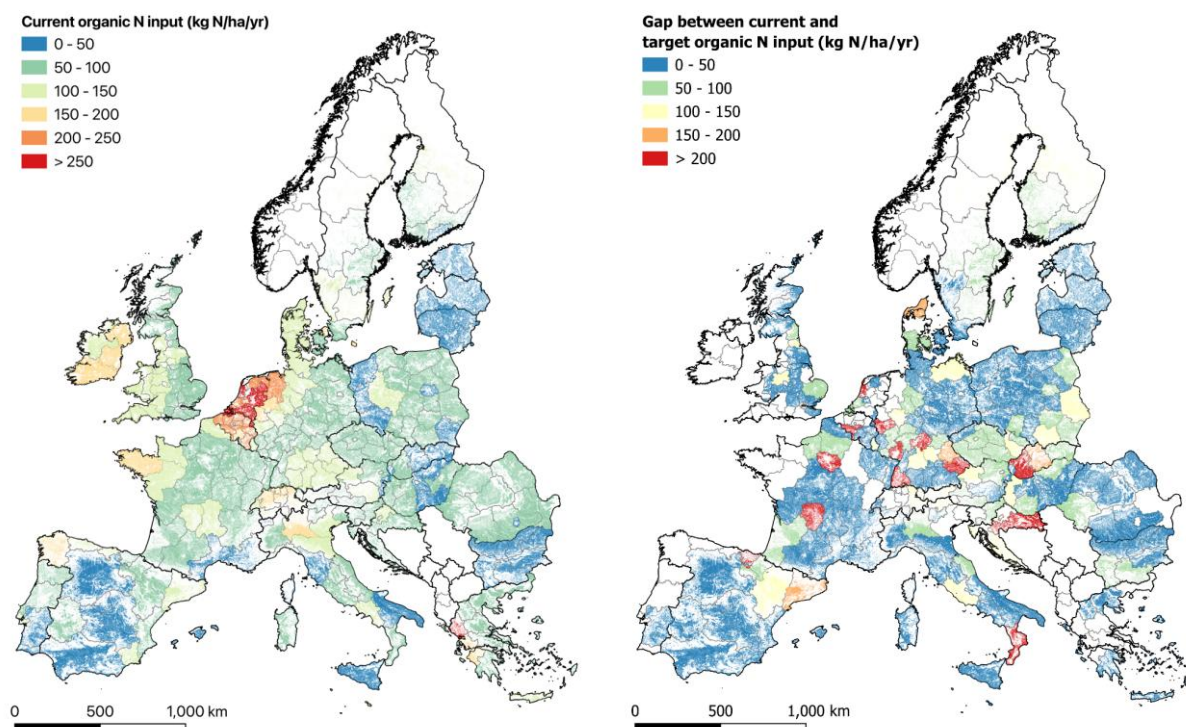


Figure 4.1. Current organic N input (left), and the gap between target and current organic N input (right, showing only regions where current input is below target) for soil health and crop production at NUTS2 level.

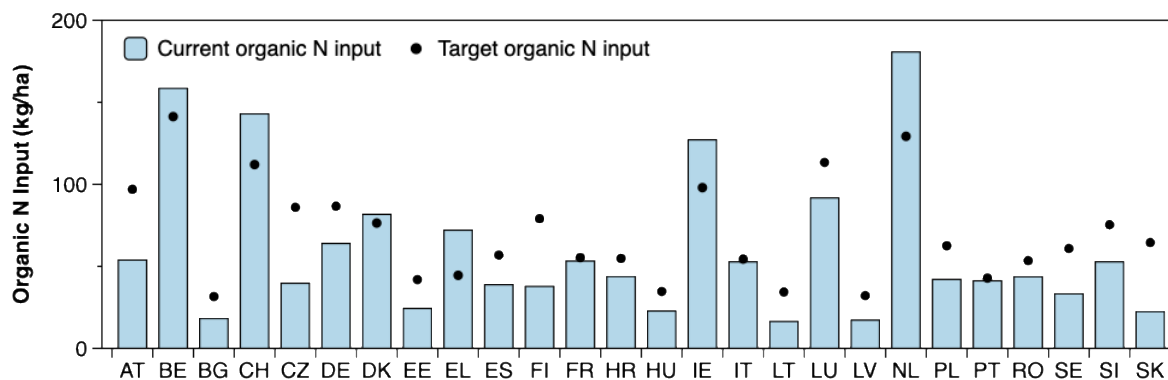


Figure 4.2. Current and target organic N input for soil health and crop production per country.

4.2 Critical surpluses and input for groundwater and surface water quality

Figure 4.3 illustrates the linkage between N surplus and N losses to air (NH_3 emissions and denitrification losses of N_2 , N_2O and NO_x) and N losses to water due to N leaching and N runoff. These relationships are used to underpin the critical values for the various N losses.

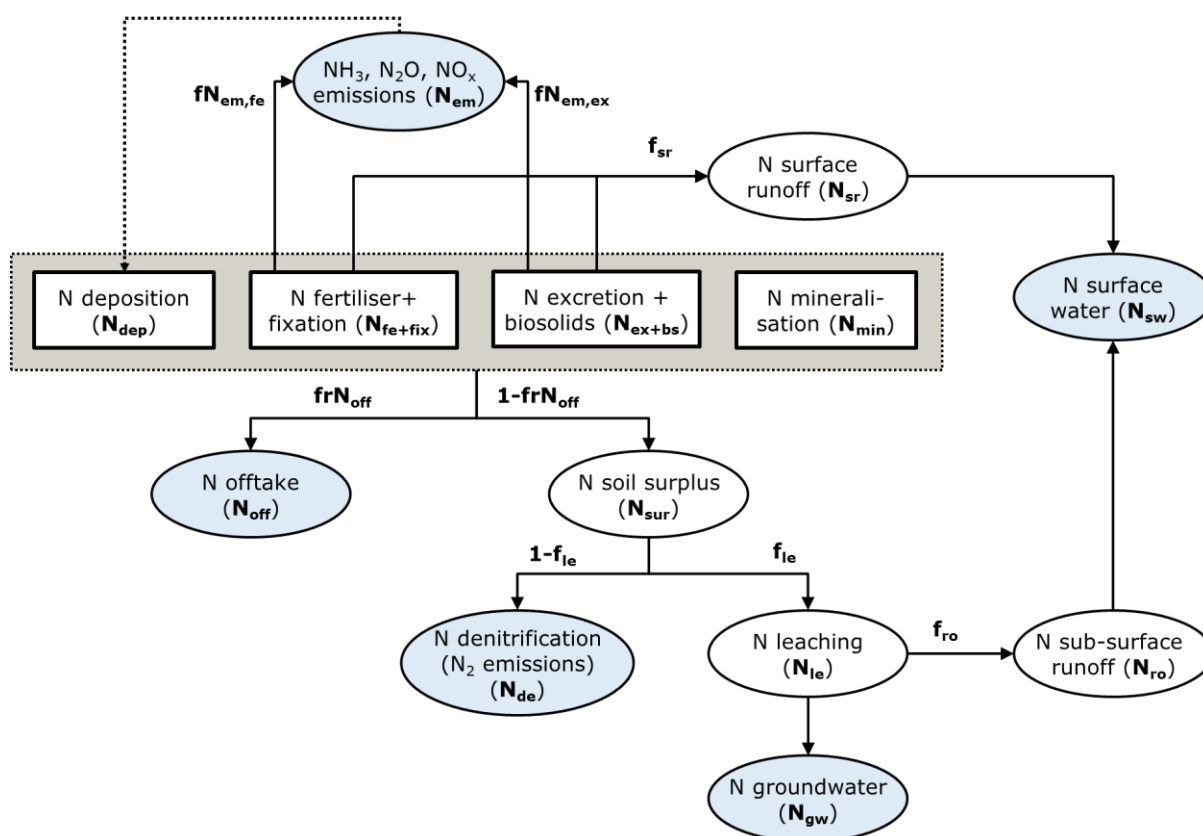


Figure 4.3. Linkage between N soil surplus, N losses to air by NH_3 emissions and denitrification (losses of N_2 , N_2O and NO_x) and N losses to water due to N leaching and N runoff at steady state (Source: De Vries et al., 2022a). Note that N losses by emission and runoff from biological N fixation are excluded.

The critical N surplus is constrained by thresholds for NH_3 -N emissions, N concentrations in and related runoff to surface water and for critical concentrations in and related NO_3 -N leaching to groundwater (blue boxes). Nitrogen inputs also cause N_2O emissions, but since

there are no clear limits for N₂O emissions, apart from a required reduction target, this aspect is not included in the derivation of critical thresholds for the N surplus as Key Performance Indicator. Another argument for not including N₂O emissions is the fact that emissions due to agricultural N inputs cause an enhanced CO₂ sequestration in response to elevated NH₃ deposition, largely compensating for the global warming potential caused by N₂O emissions (De Vries et al., 2017). Note that the surplus is defined here as N input minus N uptake minus N surface runoff (NH₃, N₂O and NO_x) emission (see Fig. 4.3).

4.2.1 Critical surplus in view of groundwater quality

The critical surplus for protecting groundwater quality is defined as the N surplus that should not be exceeded to avoid a groundwater nitrate concentration above 50 mg NO₃ L⁻¹. In MITERRA-Europe, the calculation critical N surplus focuses on the topsoil where most uptake occurs (for many crops near 100%). The critical N leaching flux to groundwater (N_{lea_crit} in kg N ha⁻¹ yr⁻¹) is thus derived as:

$$N_{lea_crit} = [NO_3]_{gw_crit} \times Q_{eff1} \times cF_{NO_3} \quad (4.2)$$

where $[NO_3]_{gw_crit}$ is the critical nitrate concentration in leaching flux towards groundwater (set to 50 mg NO₃ L⁻¹), Q_{eff1} is the water flux leaching towards groundwater from layer 1 (m³ ha⁻¹ yr⁻¹), and cF_{NO_3} is the conversion factor from (mg NO₃ L⁻¹) (m³ ha⁻¹) to kg N ha⁻¹, i.e. (14/62)/1000. The critical N surplus is the sum of N leaching from the soil and N denitrification (gas emissions) in the soil, being a fraction of the N surplus (see Figure 3.1). The critical N surplus is thus calculated from the critical N leaching flux (N_{lea_crit} in kg N ha⁻¹ yr⁻¹) according to (see Figure 3.1):

$$N_{sp_crit} = \frac{N_{lea_crit}}{f_{lea} \times (1 - f_{ro})} \quad (4.3)$$

where f_{lea} is the leaching fraction, and f_{ro} is the fraction of subsurface runoff (interflow).

4.2.2 Critical surplus for surface water quality

The critical surplus for protecting surface water quality is here defined as the N surplus that should not be exceeded to avoid nitrogen concentrations in surface water exceeding 2.5 mg N L⁻¹. Nitrogen inputs contribute to runoff through two pathways:

- (i) surface runoff (or direct runoff), being a fraction of N inputs, and
- (ii) sub-surface runoff, being a fraction of N leaching below the root zone.

Critical loss for surface water quality

The critical N runoff flux is the sum of surface and sub-surface runoff and is derived by multiplying the critical N concentration for surface waters $[N]_{sw(crit)}$ (2.5 mg N L⁻¹) with the total water runoff volume, distributed over surface runoff (Q_{sr}), sub-surface runoff in the topsoil (Q_{int1}) and a unit correction factor:

$$N_{crit_runoff} = [N]_{ag,crit} * (Q_{sr} + Q_{int1})/1000 \quad (4.4)$$

$[N]_{ag(crit)}$ is the critical N concentration in runoff from agriculture to surface water, which depends on the critical N concentration in surface water, $[N]_{sw(crit)}$, which is affected by dilution of N from non-agricultural sources, according to (De Vries et al., 2021; 2022a):

$$[N]_{ag(crit)} = \frac{[N]_{sw(crit)} - (1 - f_{ag}) \times [N]_{nag}}{f_{ag}} \quad (4.5)$$

where $[N]_{nag}$ is the N concentration in water coming from non-agricultural land, f_{ag} is the fraction agricultural land in a region, Q_{sr} is the water flux via surface runoff ($m^3 ha^{-1} yr^{-1}$) and 1000 is a conversion factor from $g N ha^{-1}$ to $kg N ha^{-1}$.

Thresholds for N concentrations in runoff water are higher in areas with a fraction agricultural land below 1 and an N concentration in water coming from non-agricultural land, $[N]_{nag}$ below the critical N concentration in surface water, $[N]_{sw(crit)}$, (see Eq. 4.5). For now, we use a value $[N]_{nag}$ of $0.5 mg N l^{-1}$ based on De Vries et al (2021).

An even higher value for $N]_{ag(crit)}$ could be acceptable due to denitrification or N retention in surface water. Likewise, however, a stricter limit value for runoff water could be used because of the mixing of runoff water with point loads of N into surface water. To avoid complex interactions between agricultural and non-agricultural point N sources to surface water, we assumed that inputs of non-agricultural point N sources to surface water are comparable to the N removal by denitrification or retention in surface water.

Critical surplus in view of surface water quality

Calculation of the critical N surplus related to a critical N runoff follows from the flows given in Figure 3.1. The total critical runoff is the sum of critical surface runoff and subsurface runoff:

$$N_{ro_crit} = N_{sro_crit} + N_{ssro_crit} \quad (4.6)$$

where critical surface runoff N_{sro_crit} is calculated based on the critical N input multiplying with surface runoff fraction:

$$N_{sro_crit} = N_{in,crit} * f_{r_{sro}} \quad (4.7)$$

where $N_{in(crit)}$ refers to the sum of the inputs by excreted manure and biosolids and N fertilizer (see Figure 1 and the footnote that we do not include surface runoff due to biological N fixation).

Critical subsurface runoff N_{ssro_crit} is calculated based on:

$$N_{ssro_crit} = f_{r_{le}} * f_{r_{ssro}} * N_{sp,crit} \quad (4.8)$$

where $N_{sp,crit}$ is the critical N surplus, which is calculated as (see Fig. 4-1):

$$N_{sp,crit} = (1 - f_{r_{Nem}} - f_{r_{sro}}) * N_{in,crit} - N_{upt(crit)} \quad (4.9)$$

Combining Eq. 4.6 to 4.9, the critical N input, $N_{in,crit}$, can be derived as:

$$N_{in,crit} = \frac{N_{ro_crit} + N_{upt(crit)} * f_{r_{le}} * f_{r_{ssro}}}{f_{r_{sro}} + f_{r_{le}} * f_{r_{ssro}} * (1 - f_{r_{Nem}} - f_{r_{sro}})} \quad (4.10)$$

The critical N surplus, $N_{sp,crit}$ is then calculated from Eq. 4.9. In our calculations $N_{upt(crit)}$ has been set at the current N uptake.

The Benelux region with intensive livestock production showed the highest N surplus, followed by Switzerland, Greece, and northern part of Italy. The critical N surpluses were determined separately in view of groundwater and surface water quality. In most cases, critical N surplus

to meet the groundwater quality standard was much higher than that for surface water quality, therefore surface water quality was the main factor determining the overall critical N surplus.

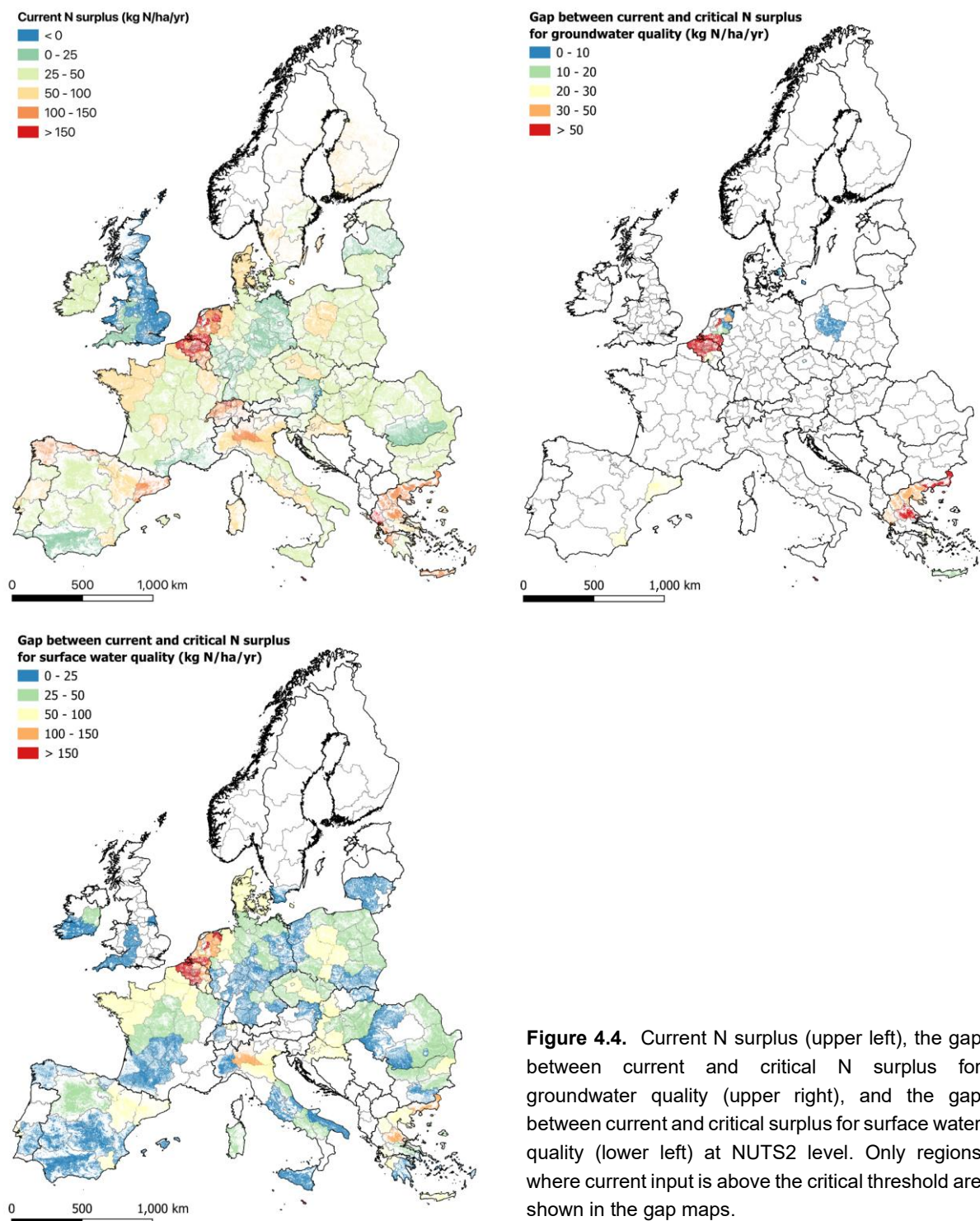


Figure 4.4. Current N surplus (upper left), the gap between current and critical N surplus for groundwater quality (upper right), and the gap between current and critical surplus for surface water quality (lower left) at NUTS2 level. Only regions where current input is above the critical threshold are shown in the gap maps.

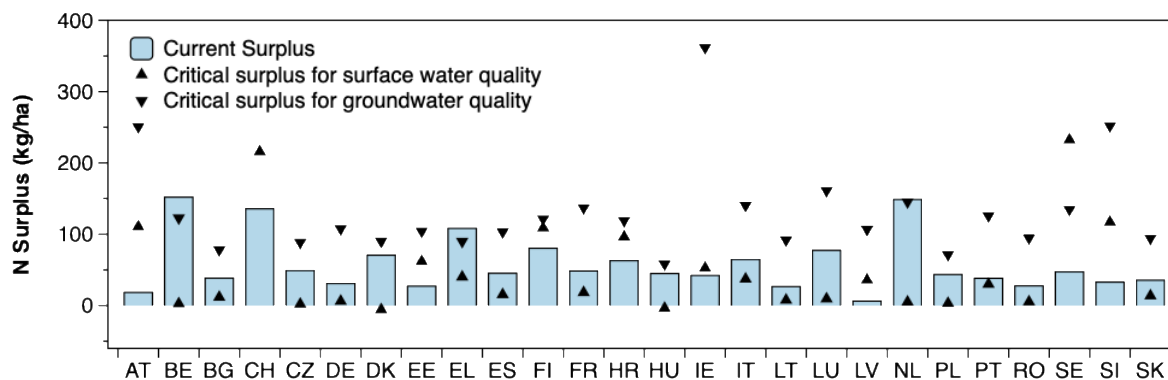


Figure 4.5. Current and critical surpluses (kg N/ha/yr) for ground- and surface water quality per country.

4.3 Critical inputs for ammonia emissions and nature quality

The critical surplus for ammonia emissions and nature quality is here defined as the N surplus that should not be exceeded to avoid nitrogen depositions exceeding the critical N load on ecosystems in nature areas (in the same region where the farms and fields are located).

Critical NH_3 emissions and associated critical N inputs and N surpluses is derived from critical levels of N deposition. NH_3 emissions from agriculture to air are diluted by emissions from non-agricultural land in the area. Therefore, we accounted for differences in the fraction of agricultural land when assessing critical NH_3 emissions for a given spatial geometry. Critical levels of NH_3 emission from agricultural land is calculated as:

$$\text{NH}_3_{em_crit} = \text{Ndep}_{tot_crit} * \frac{f_{\text{NH}_3}}{f_{ED} * f_{ag}} \quad (4.11)$$

Where Ndep_{tot_crit} is the critical N deposition on non-agricultural terrestrial ecosystems, calculated as the area-weighted average critical N load for those ecosystems in nature areas ($\text{kg N ha}^{-1} \text{ yr}^{-1}$), f_{ag} is the fraction agricultural land, f_{NH_3} is the fraction NH_3 in the total ($\text{NO}_x + \text{NH}_3$) deposition and f_{ED} is the ratio of deposited versus emitted ammonia. The calculated NH_3 emissions are based on the assumptions that within the spatial geometry evaluated

- (i) the average N deposition rate on agricultural land equals the average N deposition rate on non-agricultural land (both in kg N ha^{-1}),
- (ii) the amount of NH_3 that is emitted (coming from agriculture) is deposited in the same region, but then on all (agricultural land and non-agricultural) land (both in kg N),
- (iii) the current shares of NH_3 and NO_x in total N deposition stay constant (and thus NO_x emissions/deposition increase or decrease in the same proportion as NH_3 emissions/deposition). The derivation of Eq. 4.11, based on these assumptions is given in de Vries et al. (2022a). This derivation is however updated by including the ratio of deposited versus emitted ammonia, since the assumption that NH_3 emissions and NH_3 deposition are equal in a region (even a country) is not correct. We assume that all NH_3 originates from agricultural sources.

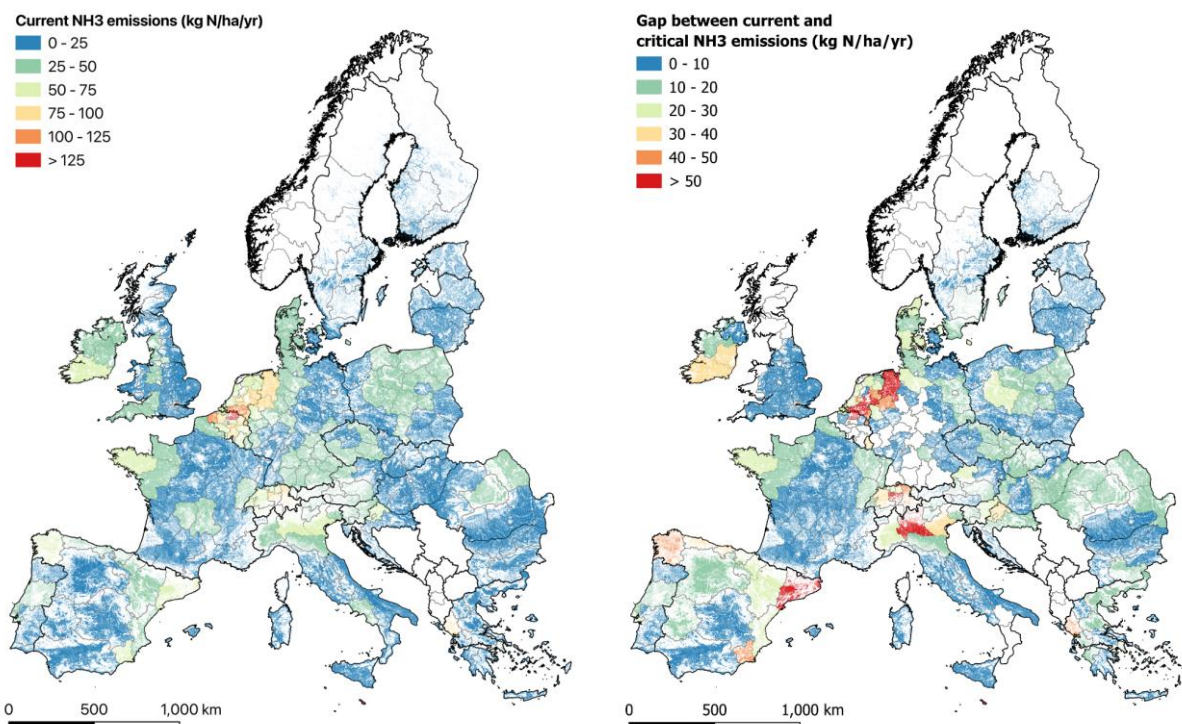


Figure 4.6. Current NH₃ emissions (left), and the gap between current and critical NH₃ emissions (right, showing only regions where current input is above the critical threshold) for nature quality at NUTS2 level.

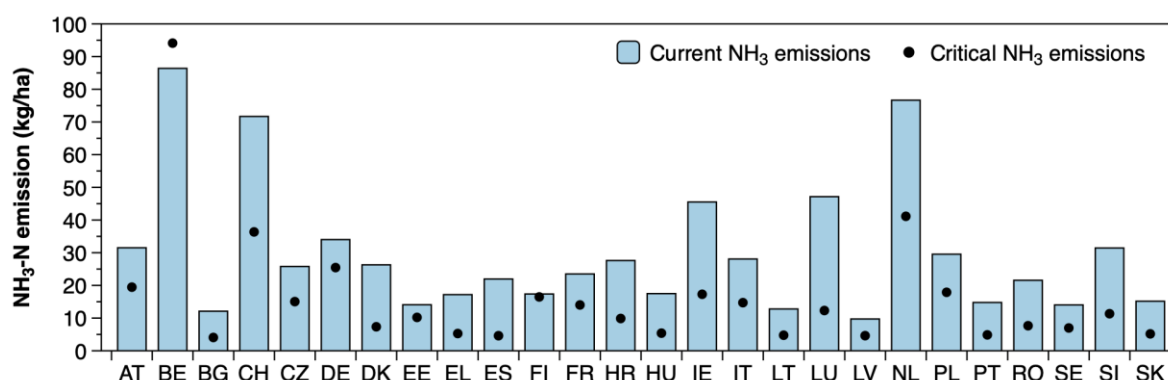


Figure 4.7. Current and critical NH₃ emissions (kg N/ha/yr) for nature quality per country.

Critical NH₃ emissions determine critical N inputs from fertilizer (including fixation) and from excretion (including biosolids), and (constant) emission fractions, whereas NH₃ emissions are calculated as a fraction of these inputs according to:

$$NH3_{em,crit} = (N_{fe_fix_crit} \times f_{NH3_{em,fe}} + N_{ex_bs_crit} \times f_{NH3_{em,ex}}) / Area \quad (4.12)$$

where $N_{fe_fix_crit}$ is the total N inputs from fertilizers and fixation and $N_{ex_bs_crit}$ is from excretion and biosolids (kg), $f_{NH3_{em}}$ is the fraction of NH₃ emission from inputs, estimated by the total NH₃ emission divided by the corresponding amount of input, Area is the area of the agricultural sector (ha).

For an arable farm with a condition that either fertilizer or biosolids are not applied, Eq. 4.12 only has one unknown, the critical fertilizer or manure input is then calculated by the critical NH_3 emission divided by the average emission fraction of either fertilizer or biosolids. If both fertilizer and manure are applied, Eq. 4.12 has two unknowns, i.e. $N_{fe_fix_crit}$ and $N_{ex_bs_crit}$. By assuming constant relative contributions to total NH_3 emissions from N fertilizer and N fixation (N_{fe_fix}) and N excretion by animals and N biosolids (N_{ex_bs}), we can express $N_{fe_fix_crit}$ as a function of $N_{ex_bs_crit}$:

$$N_{fe_fix_crit} = \frac{fN_{fe}}{1-fN_{fe}} \times N_{ex_bs_crit} \quad (4.13)$$

The fraction of N inputs from fertilizer and fixation in total critical N inputs (fN_{fe}) is calculated by dividing actual N inputs from fertilizer and fixation by actual N inputs from fertilizer, fixation, manure and biosolids for each crop combination:

$$fN_{fe} = \frac{N_{fe}+N_{fix}}{N_{fe}+N_{fix}+N_{am}+N_{bs}} \quad (4.14)$$

Replacing $N_{fe_fix_crit}$ in Eq. 4.13 with the right-hand side of Eq. 4.14 and solving the equation for $N_{ex_bs_crit}$, critical N inputs from excretion in view of critical NH_3 emission are derived as (De Vries et al., 2022):

$$N_{ex_bs_crit_NH3} = \frac{NH3em_{crit}}{fNH3_{em,ex} + fNH3_{em,fe} \times \frac{fN_{fe}}{1-fN_{fe}}} \quad (4.15)$$

where $N_{ex_bs_crit_NH3}$ is the critical N inputs from excretion and biosolids in view of a critical ammonia emission rate ($\text{kg N ha}^{-1} \text{ yr}^{-1}$).

The related critical N input from fertilizer and fixation is calculated with equation 4.13. Equation 4.14 and 4.15 implies that the critical nitrogen input to the soil via fertiliser ($N_{fe_fix_crit_NH3}$) and excretion ($N_{ex_bs_crit_NH3}$) in view of critical NH_3 emissions depends on (i) the NH_3 emission fraction for fertiliser applied to land ($fNH3_{em,fe}$), (ii) the NH_3 emission fraction for excretion ($fNH3_{em,ex}$) and the share of N fertilizer + fixation in total critical inputs (fN_{fe}).

Note that the value for the NH_3 emission fraction for excretion ($fNH3_{em,ex}$) in farms with livestock is a weighted average value of emission fractions from housing systems, grazing animals and applied manure. This value can be calculated as the total NH_3 emission from housing systems, grazing animals and applied manure divided by N_{ex_bs} :

$$fNH3_{em,ex} = (NH_{3,em,housing} + NH_{3,em,grazing} + NH_{3,em,bs})/N_{ex_bs} \quad (4.16)$$

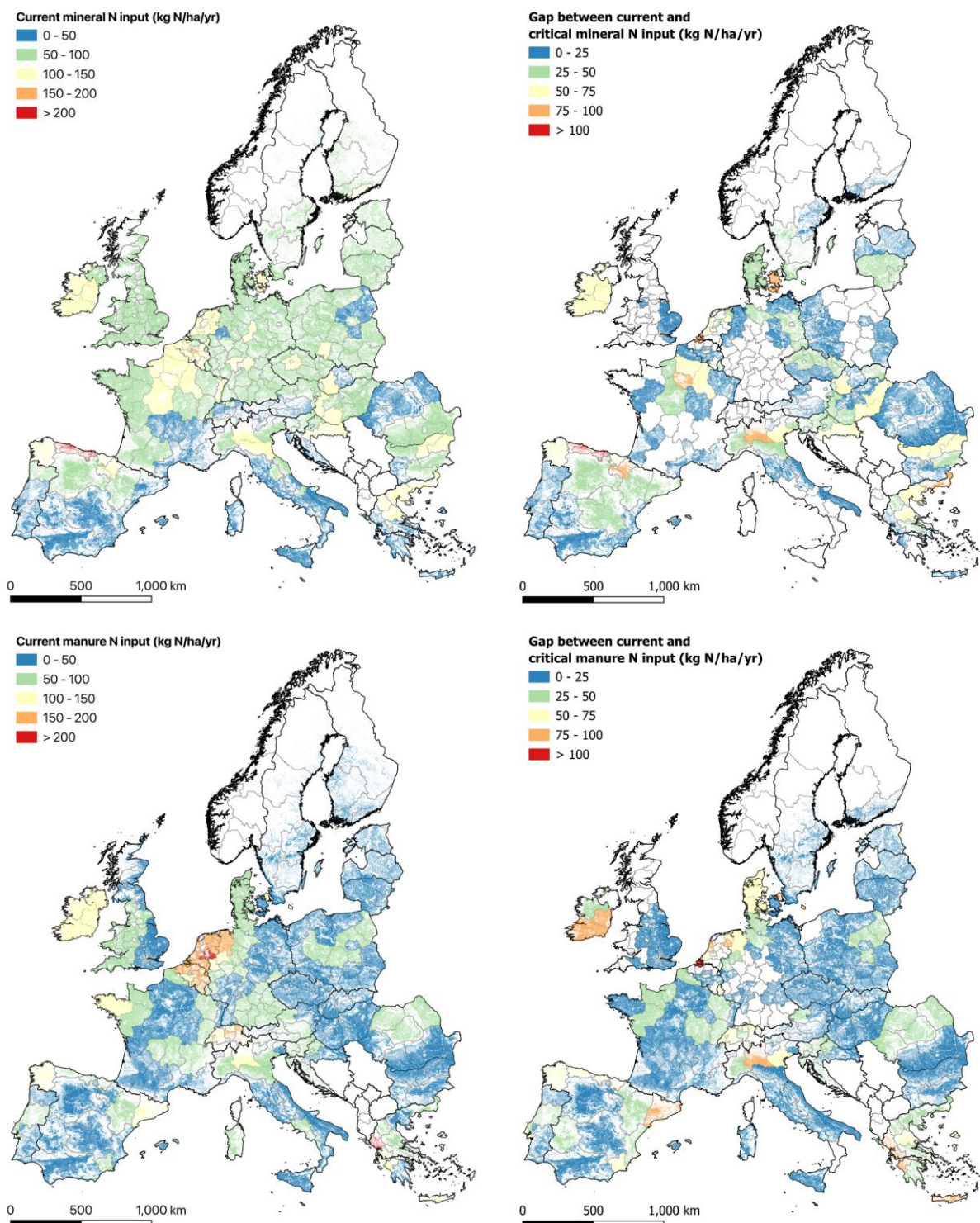


Figure 4.8. Current mineral (upper-left) and manure N input (lower-left), and the gap between current and critical mineral (upper-right) and manure (lower-right) input for NH_3 emissions and nature quality at NUTS2 level. Only regions where current input is above the critical threshold are shown in the gap maps.

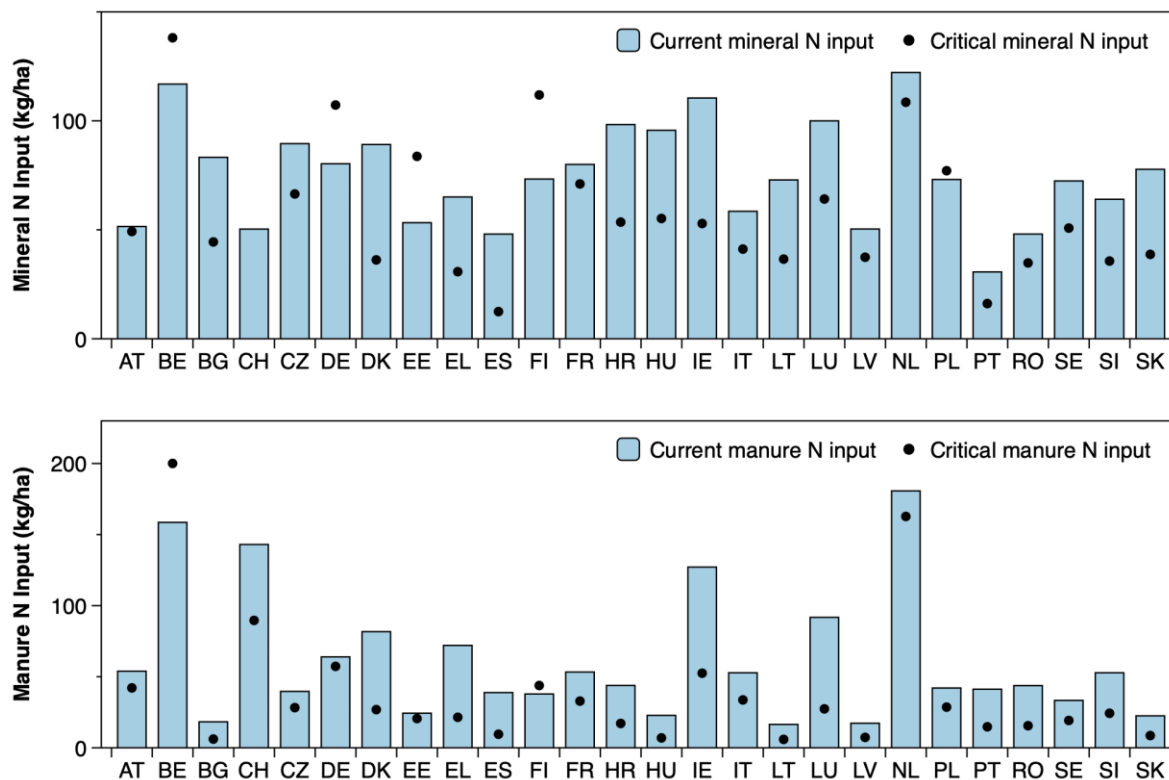


Figure 4.9. Current and critical mineral (upper) and manure N input (lower) in kg N/ha/yr for NH₃ emissions and nature quality per country.

5. Phosphorus

Unlike N, there are P containing minerals in (agricultural) soils and P can dissolve, precipitate and be adsorbed or desorbed, especially on aluminium and iron hydroxides. The P surplus is generally adsorbed to soil in a readily available (adsorbed) P pool. A small part is retained in a poorly available stable inorganic P pool. Furthermore, organic P added by crop residues and manure increases P in soil organic matter (an organic P pool), which is the substrate for P mineralization. Plants take up P from the soil solution but the concentration in solution is buffered by the pool of adsorbed soil P, which is thus termed readily available or plant-available P. A small part of the dissolved P is also leached from the soil. Since P is adsorbed in soil and P concentrations in soil solution are governed by soil P contents, changes in soil P contents drive changes in P leaching and runoff to water. P losses to surface water thus react with a large delay time to changes in P input, and P behaviour should be modelled by a dynamic approach.

5.1 Target surplus and input for soil fertility and crop production

The target P surplus and target P input aims to: (i) build up soil P up to a desired P soil content where P is not deficient and not limiting crop growth in view of crop production, or (ii) mine soil P to the desired P soil content if P is not deficient to avoid unnecessary high P inputs, making use of the soil legacy P pool. Both aspects can be put into one equation for either surplus or input, according to:

$$P_{sp_target} = P_{loss,target} + [\rho \cdot D \cdot (P_{ox_target} - P_{ox_current}) \cdot P_{total}/P_{ox} \cdot 0.01]/T \quad (5.1)$$

$$P_{in_target} = \max(0, P_{upt_target} + P_{sp_target}) \quad (5.2)$$

where P_{sp_target} is the target P surplus in kg P ha⁻¹ yr⁻¹, P_{in_target} is the required P input in kg P ha⁻¹ yr⁻¹, P_{upt_target} is the P uptake at the target soil P content, $P_{loss,target}$ is the P loss (total of P leaching and subsurface runoff out of the topsoil) at the target soil P content, P_{total} is the total content of P in the soil solid phase (mg kg⁻¹), ρ is the bulk density of the soil (kg m⁻³), D the thickness of the soil layer (m), and P_{ox} the oxalate P (plant available content of P) in the soil solid phase (mg kg⁻¹) for the current situation ($P_{ox_current}$) as well the desired situation (P_{ox_target}), T is the defined target time in which the soil P level should come to acceptable status and 0.01 is used to convert mg P m⁻² to kg P ha⁻¹.

The target P_{ox} content, P_{ox_target} is the plant available-P level above which crop yields hardly respond to an increase in soil plant available P. The target P_{ox} content may vary per crop type but for now it is set at a P saturation index ($P_{ox}/(Al_{ox} + Fe_{ox})$) of 0.15 based on Gu et al. (2024) implying that $P_{ox_target} = 0.15 \times (Al_{ox} + Fe_{ox})$. The relationship between P_{ox} and P_{tot} is based on data given in Gu et al. (2024), distinguishing between non-calcareous soils (185 data points) and calcareous soils (233 data points), is given below:

For non-calcareous soils:

$$\text{Oxalate P (mg/kg)} = 0.53 \times \text{total P (mg/kg)} - 4.6 \times \text{Clay (\%)} - 6.7 \times \text{pH} \quad (5.3)$$

For calcareous soils:

$$\text{Oxalate P (mg/kg)} = 0.11 \times \text{total P (mg/kg)} + 8.6 \times \text{SOM (g/kg)} \quad (5.4)$$

Note further that this approach assumes that part of the added P transforms to stable P forms (given the ratio P_{total}/P_{ox}) by diffusion-precipitation, making the P unavailable for uptake.

However, the ratio P_{total}/P_{ox} most likely decreases when adding P, as added P is more available for uptake than soil-available P. For a fast calculation, the integral average P_{total}/P_{ox} ratio going from the current to the critical P status should be used.

Since an increased P content may affect water quality (see below), it is important that P is not only enhanced when P_{ox_target} is higher than $P_{ox_current}$, but it should also be reduced when the reverse is true. Equation (5.1) is relevant for both crop production, which holds when $P_{ox_target} > P_{ox_current}$ and for water quality protection, which holds when $P_{ox_target} < P_{ox_current}$. The required mining in the latter case is possible by crop P removal unless the required negative surpluses is so large that it would require a negative P input (the required net release of P from soil is higher than the crop P uptake). In this situation the target P input is set at 0 (see Eq. 5.2).

For now, the target P uptake is set at the current P uptake, thus neglecting the effect of changes in soil P status on crop yield, since yield is affected by many other factors as well. For now, we can also assume that P losses by the sum of leaching and subsurface runoff fluxes at the target soil P content are in the same order of magnitude as P deposition. The target soil P surplus and P inputs in view of P fertilizer and P manure inputs can thus be calculated by using Eq. 5.1 and 5.2, while neglecting $P_{loss,target}$. At steady state (after the period T), the target P surplus should thus equal 0, while the target P input should equal the target P uptake (equilibrium fertilization).

Current P surpluses were highest in regions with high livestock densities (Netherlands, Belgium, Ireland, Brittany), but also some regions in Southern Europe. Target P surpluses for crop production were higher compared to current surpluses for regions with sandy soils (e.g. Northern Germany and Poland), which are low in carbon and have low pH. Critical surpluses for water quality were lower than current levels in most regions across Europe, with values less than 5 kg P/ha and in many regions close to 0, suggesting P fertilisation should be significantly reduced to meet the requirement for water quality.

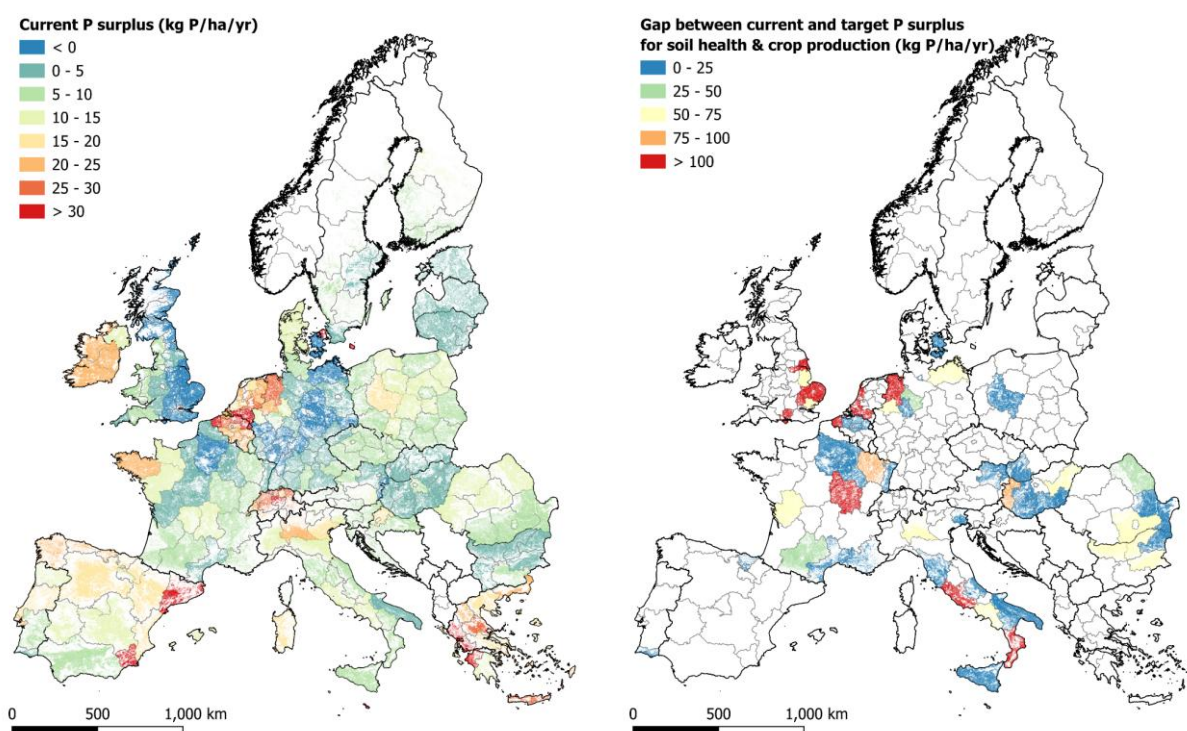


Figure 5.1. Current P surplus (left) and the gap between target and current P surplus (right, showing only regions where current input is below target) for soil health and crop production at NUTS2 level.

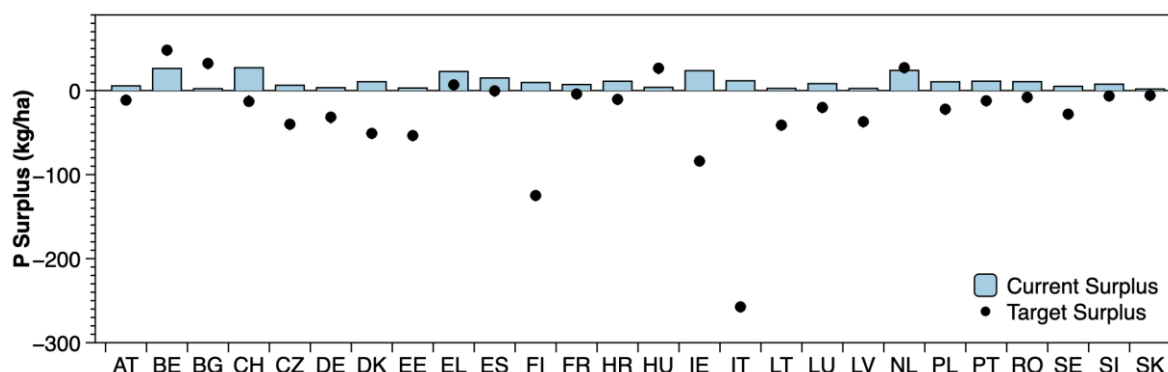


Figure 5.2. Current P surplus and target P surplus (in kg P/ha/yr) for soil health and crop production per country.

5.2 Critical surplus and input for water quality

Since an increased P content may affect water quality, it is important that P is not only enhanced in view of crop production when P_{ox_target} is higher than $P_{ox_current}$, but it should also be reduced when the critical level for water quality protection is below the current level ($P_{ox_critical} < P_{ox_current}$). Comparable to the target P surplus, the critical P surplus (and related critical P input) that aims to avoid soil P contents causing P losses to surface water that lead to P concentrations exceeding a critical P concentration, is calculated as:

$$P_{sp_critical} = P_{loss_critical} + [\rho \cdot D \cdot (P_{ox_critical} - P_{ox_current}) \cdot P_{total}/P_{ox} \cdot 0.01]/T) \quad (5.5)$$

$$P_{in_critical} = \max(0, P_{upt_critical} + P_{sp_critical}) \quad (5.6)$$

The critical oxalate P content in view of water quality protection is derived as:

$$P_{ox_critical} = PSD_{critical} \cdot (Al_{ox} + Fe_{ox}) \cdot 2 \quad (5.7)$$

in which critical PSD threshold, corresponding to an environmentally critical ortho-P concentration in soil solution (as surrogate for surface water) was estimated as (based on Schoumans & Groenendijk, 2000):

$$PSD_{critical} = \frac{100 \cdot \alpha_{max} \cdot K_L \cdot P_{ss_crit}}{(\beta_{max} + \alpha_{max} \cdot K_L \cdot P_{ss_crit})} \quad (5.8)$$

where P_{ss_crit} is the critical P concentration in soil solution (mol m^{-3}), set at the critical concentration in surface water (0.15 mg L^{-1}), K_L is the Langmuir affinity constant ($\text{m}^3 \text{ mol}^{-1}$), α_{max} is the factor relating PSC to the contents of Fe_{ox} and Al_{ox} (0.5) and β_{max} to the scaling factor to calculated the adsorption maximum of P binding sites located at the surface of Fe_{ox} and Al_{ox} (0.167).

If the critical P content was higher than the target P content, we put the critical P content equal to the target P content (If $P_{ox_critical} > P_{ox_target}$ then $P_{ox_critical} = P_{ox_target}$) implying that Eqs (5.5) and 4.6 are then equal to Eqs (5.1) and (5.2) and the critical P surplus equals the target P surplus. This was done to avoid building up of the soil P content to a level above what is needed for crop P uptake. Up to the target level, however, we accepted building up of P since it is needed for crop production while it does not exceed limits in view of water quality. Inversely,

we aimed for mining up to a target level, even if it is not needed for water quality (since the critical P content exceeds the target P content) since the legacy P pool can be used to avoid a waste of applied P. If the critical P content, however, was lower than the target P content, we only accepted building up of soil P up to that content if the current P content is below that critical P content while we required mining if the current P content is above the critical P content. Building up in the first case was accepted to avoid unnecessary losses in crop production while mining in the second case was required to avoid water quality problems.

We checked if the P loss that occurs at the target soil P content $P_{loss,target}$ (see Eq. 5.1) stays below a critical P loss ($P_{loss,target} < P_{loss,critical}$) where the critical P loss is calculated as (De Vries et al., 2022b):

$$P_{loss,critical} = (Q_{int1} + Q_{eff1}) \times P_{ss_crit} / 1000 \quad (5.9)$$

where $Q_{int1} + Q_{eff1}$ is the total water flux via sub-surface runoff from the topsoil (Q_{int1}) and leaching from the topsoil (Q_{eff1}) to groundwater ($m^3 \text{ ha}^{-1} \text{ yr}^{-1}$), P_{ss_crit} is the critical P concentration in surface water (set at 0.15 mg L^{-1}) and 1000 is a conversion factor from $g \text{ P ha}^{-1}$ to $kg \text{ P ha}^{-1}$.

The total P loss to surface water includes in principle dissolved P in surface and subsurface runoff and particulate P due to (surface) erosion. In MITERRA-Europe, however, we neglected P losses in surface runoff and also the loss of particulate P by erosion from the surface of the topsoil. The erosion flux was neglected since it is assumed to be equal to the renewal of P from the subsoil into a fixed soil layer of 30 cm, since the soil is generally ploughed up to 30 cm. From an environmental point of view, however, erosion is an important input to the water system, but this input can be limited by erosion control and does not necessarily require a reduction in the P content of eroded material. Therefore, we decided to compare the loss at the target soil P content $P_{loss,target}$, including runoff of dissolved P only, while neglecting P loss by erosion.

The results for the calculated gap between the current and critical P surplus for water quality is shown in Figure 5.3 and at country level in Figure 5.4. The map shows a patchy pattern, which is the result of the interaction between soil properties that determine P_{ox} , leaching and runoff and the livestock density (which mainly determines the current P surplus). These results still require a further more detailed analysis.

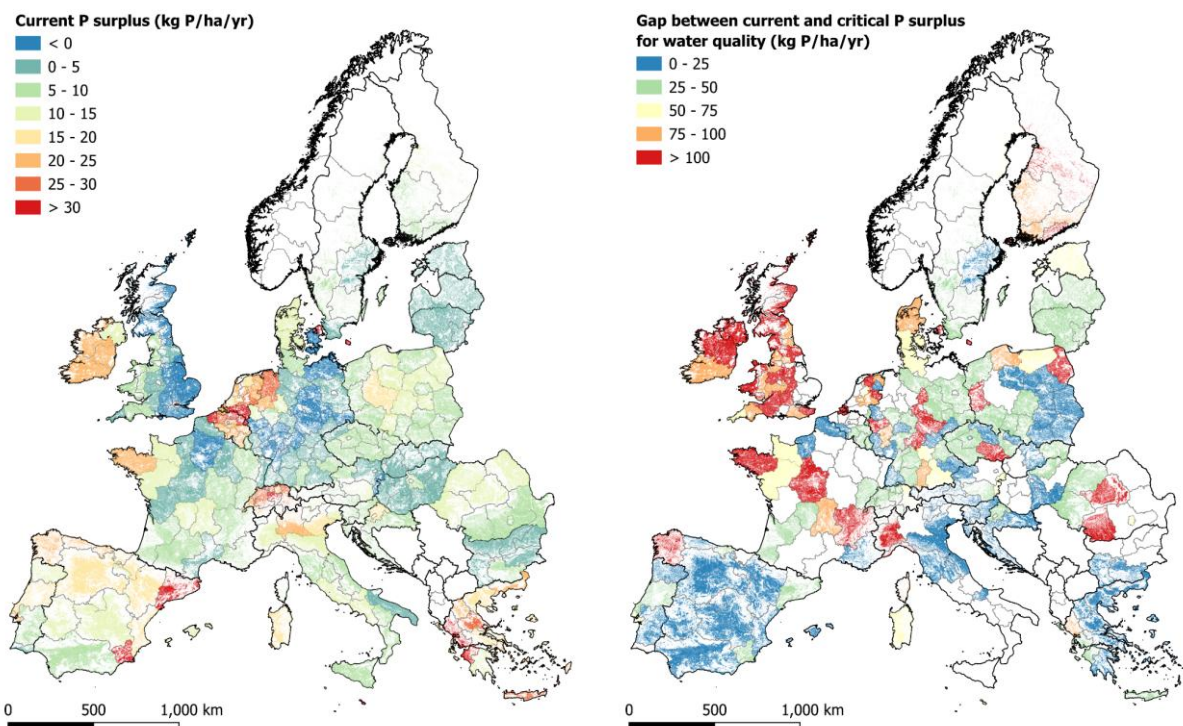


Figure 5.3. Current P surplus (left) and the gap between current and critical P surplus (right, showing only regions where current input is above the critical threshold) for water quality at NUTS2 level.

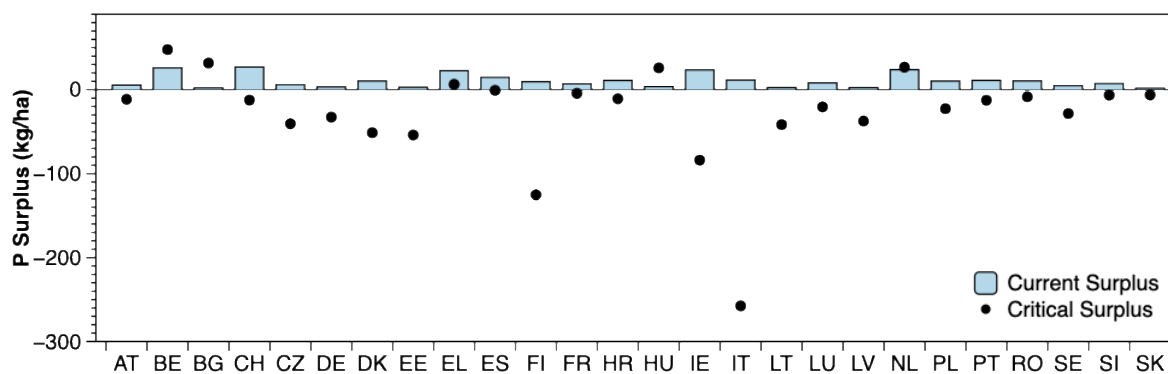


Figure 5.4. Current P surplus and critical P surplus (in kg P/ha/yr) for water quality per country.

6. Sulphur

6.1 Target surplus for soil health and crop production

Sulphur bioavailability in grasslands and croplands is calculated from carbon decomposition and the C-to-S ratios. Currently there are no guidelines regarding optimum S levels in soil or the capacity of soils to supply them. Best agronomic practices for S would imply that crop S removal is replaced by fertilizers while also accounting for the unavoidable S leaching and runoff losses. In that case the desired target surplus and target input for S in view of crop production and soil health is defined as.

$$S_{sp_target} = S_{loss} = 0.001 \cdot [S_{ss_top} \cdot (Q_{int1} + Q_{eff1})] \quad (6.1)$$

$$S_{in,target} = S_{upt} + S_{loss} \quad (6.2)$$

where S_{sp_target} refers to the target S surplus in view of soil health and crop production (kg S ha^{-1}), the factor 0.001 is the conversion from g ha^{-1} to kg ha^{-1} , S_{ss_top} is the SO_4 concentration in soil solution of topsoil (mg L^{-1}), Q_{int1} refers to the subsurface runoff out of the topsoil ($\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$), Q_{eff1} refers to the leaching out of the topsoil ($\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$). As with the soil solid phase, there are no guidelines regarding optimum S levels in soil solution, and the target S loss can thus be set at the current S loss.

Current S surpluses are negative in France, Germany, and the Baltic region, suggesting insufficient S input and that the soil is being mined for S. To maintain soil health and crop production, a target S surplus of at least 0-2.5 kg/ha is desired, and moderate S fertilisation may be advised for these regions.

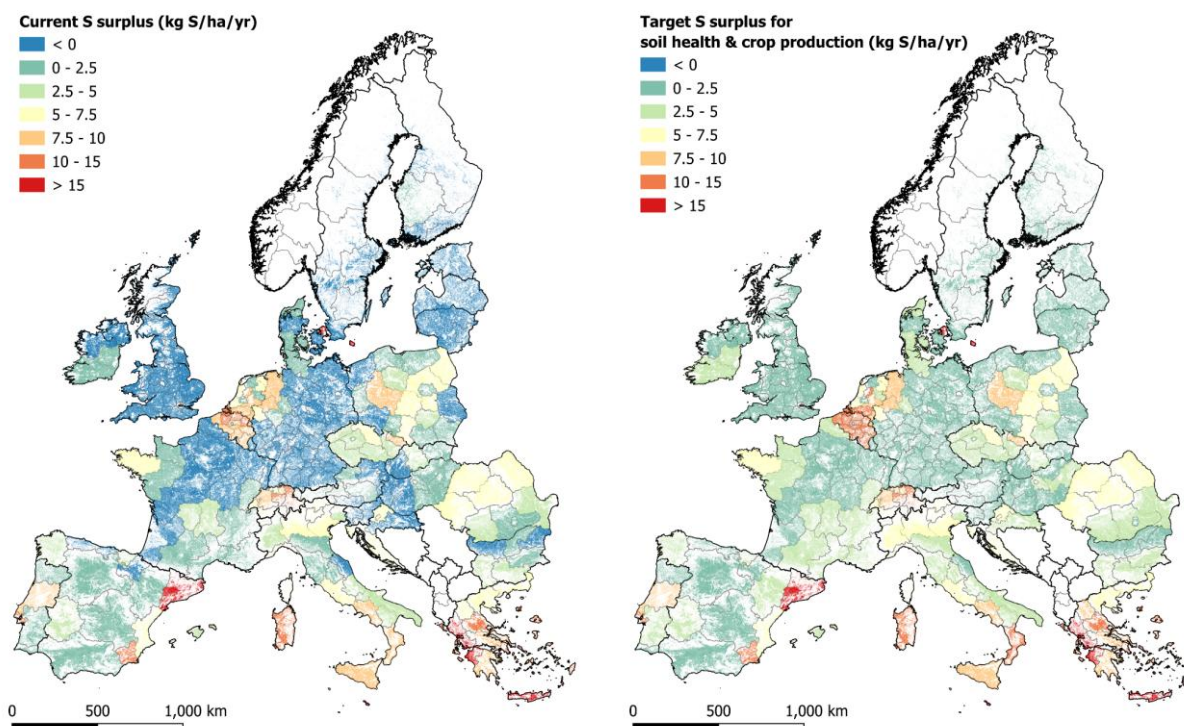


Figure 6.1. Current S surplus (left) and target S surplus (right) for soil health and crop production at NUTS2 level.

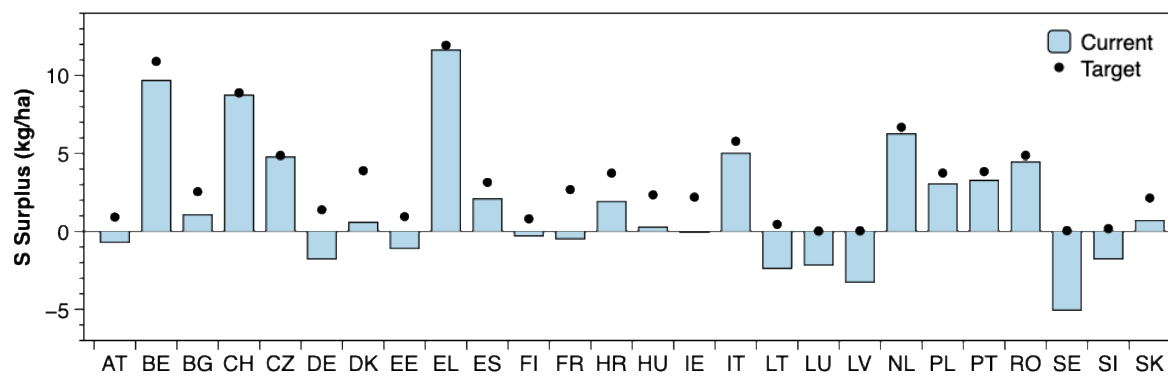


Figure 6.2. Current S surplus and target S surplus (in kg S/ha/yr) for soil health and crop production per country.

6.2 Critical surpluses for water quality

Given the fact that leaching of S does not lead to environmental problems, there is no need for critical values for S surplus in view of surface water and groundwater.

7. Base cations (Ca, Mg and K)

7.1 Target surpluses for soil health and crop production

To maintain the capacity of soils to buffer acidity and to supply sufficient cations for crop production, the target values for the soil surplus of Ca, Mg and K is derived from a given target pH, and the associated base saturation. We use an empirical relationship between pH and base saturation (BS) derived from various field experiments being applicable in the pH range between 4 and 6.5, being in line with previous studies.

$$BS_{target} = \min(100, (pH_{target} - 4)/0.025) \quad (7.1)$$

Where BS_{target} is the target base saturation (%) related to a target (desired) pH value required for crop production, and pH_{target} refers to the target pH in soil solution, being set at 5.5 for most agricultural crops.

The target BC surplus, and target BC input for soil health and crop production, aiming to bring soils up to a target base saturation, based on a related target soil pH which is not limiting crop growth, are calculated as:

$$BC_{sp_target} = BC_{loss,target} + \max(0, BS_{target} - BS_{act}) / (CEC \cdot \rho \cdot D \cdot 10) / T \quad (7.2)$$

$$BC_{in_target} = BC_{upt_target} + BC_{sp_target} \quad (7.3)$$

where BC_{sp_target} is the target BC surplus in $\text{mol ha}^{-1} \text{yr}^{-1}$, BC_{in_target} is the required BC input in $\text{mol ha}^{-1} \text{yr}^{-1}$, BC_{upt_target} is the BC uptake at the target soil base saturation, $BC_{loss,target}$ is the BC loss (total of BC leaching and subsurface runoff out of the topsoil) at the target soil pH (base saturation), CEC is cation exchange capacity (mmol kg^{-1}), ρ is bulk density of the soil (kg m^{-3}) and D is soil thickness (m), T refers to the time period (in years) to reach the desired target and 10 is the conversion factor from $\text{mmol m}^{-2} \text{yr}^{-1}$ to $\text{mol ha}^{-1} \text{yr}^{-1}$. When the actual value is above the target value, we limit to 0 (we do not include a target decline in BS).

The target BC loss is calculated on the basis of the charge balance principle, where the sum of major cations (the base cation) is equal to the sum of major anions, being NO_3 , SO_4 , Cl and HCO_3 according to:

$$BC_{loss,target} = \text{SO}_4_{loss,current} + \text{NO}_3_{loss,crit} + \text{Cl}_{loss,current} + \text{HCO}_3_{loss,target} \quad (7.4)$$

In Eq 7.4, NO_3 is the minimum of the current NO_3 leaching and the critical NO_3 leaching in view of ground water quality. SO_4 and Cl are calculated on the basis of their current loss, as there are neither target nor critical levels, and HCO_3 is calculated using a target soil pH level. Note that their losses should be converted from kg ha^{-1} to mol ha^{-1} if necessary.

Unlike P, there are no critical limits for BC losses, and there is thus no need to reduce the base saturation when it is above the target value. Then the calculation on target soil accumulation can be skipped and the same holds at steady state (after the period T) when the base saturation was initially below a target value. For these situations, the target BC surplus and BC input are calculated as

$$BC_{sp_target} = BC_{loss,target} \quad (7.5)$$

$$BC_{in_target} = BC_{upt_target} + BC_{loss,target} \quad (7.6)$$

Considering the limited impact of changes in base saturation on BC loss, the value of $BC_{loss,target}$ can be set at the current BC loss and the same holds for $BC_{upt,target}$ which can be set at the current BC uptake.

The fraction of Ca, Mg, K in the release from or accumulation of base cations on the adsorption complex is set equal to the fraction of these elements (Ca/BC, Mg/BC, and K/BC) on the adsorption complex. The target value for the surplus of the base cations is thus proportioned over Ca, Mg, and K with the initial respective fractions on the adsorption complex being derived from data and assumed to stay equal over time. When the cation occupation of the CEC is unknown, then the cation fractions are set at 0.7 for Ca, 0.2 for Mg, and 0.1 for K. This leads to the following critical surpluses for Ca, Mg and K:

$$Ca_{sp,target} = BC_{sp,target} * Ca_{cec} \quad (7.7)$$

$$Mg_{sp,target} = BC_{sp,target} * Mg_{cec} \quad (7.8)$$

$$K_{sp,target} = BC_{sp,target} * K_{cec} \quad (7.9)$$

where Ca_{cec} , Mg_{cec} and K_{cec} represent the occupation of the CEC (being a fraction, -) for Ca, Mg and K, respectively.

In calcareous soils, base saturation is set equal to 100% and the change in base saturation is assumed to be negligible since the acid production rate is fully counteracted by the dissolution of $CaCO_3$. In these soils the desired surplus is set equal to zero.

For Calcium the current surplus is in most regions between 0 to 100 kg/ha, while in Ireland and Germany more lime is being used, which results in higher surpluses (Figure 7.1). According to the calculations, the Ca surpluses and thus the Ca inputs should increase in several countries, especially in the Mediterranean area (Italy, Croatia, Greece). However, as Ca content in these soils are often high, soil mining would in general not be a problem and the target surplus might be too high. The high target Ca surplus for Switzerland (Figure 7.2) should be considered carefully, this might be due to conflicting data, as Switzerland was not in the LUCAS soil data and additional data has been collected.

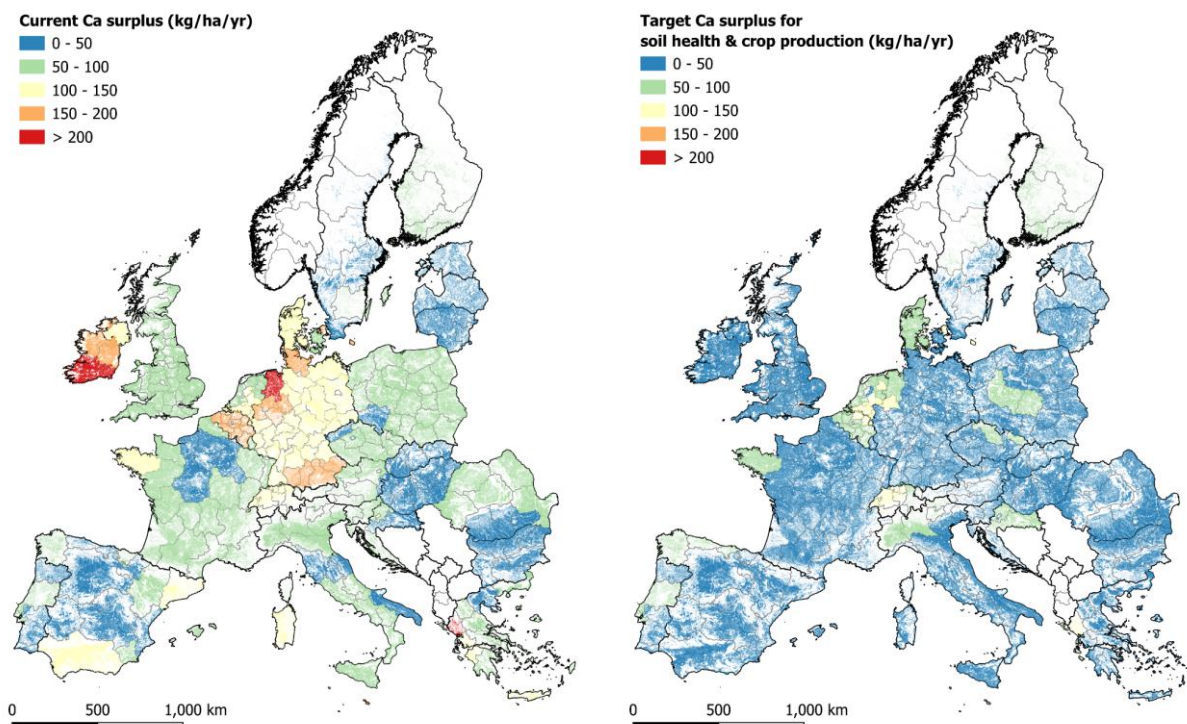


Figure 7.1. Current Ca surplus (left) and target Ca surplus (right) for soil health and crop production at NUTS2 level.

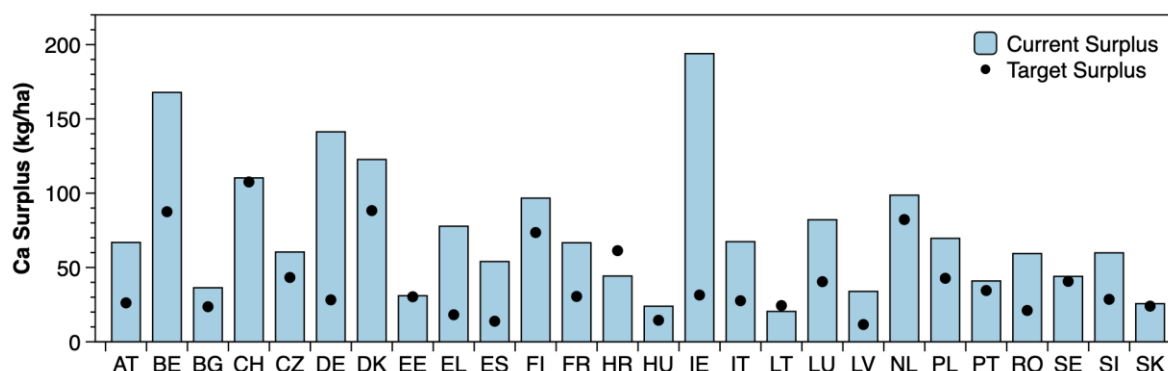


Figure 7.2. Current Ca surplus and target Ca surplus (in kg Ca/ha/yr) for soil health and crop production per country.

For Magnesium the surpluses are in general lower compared to Ca, but the regional patterns are more or less similar (Figure 7.3). Only for Mg the current surplus is negative in Germany, while Ca had a high surplus, probably because of mainly Ca based liming in Germany. The target surpluses are mostly higher for Mediterranean countries (Figure 7.4).

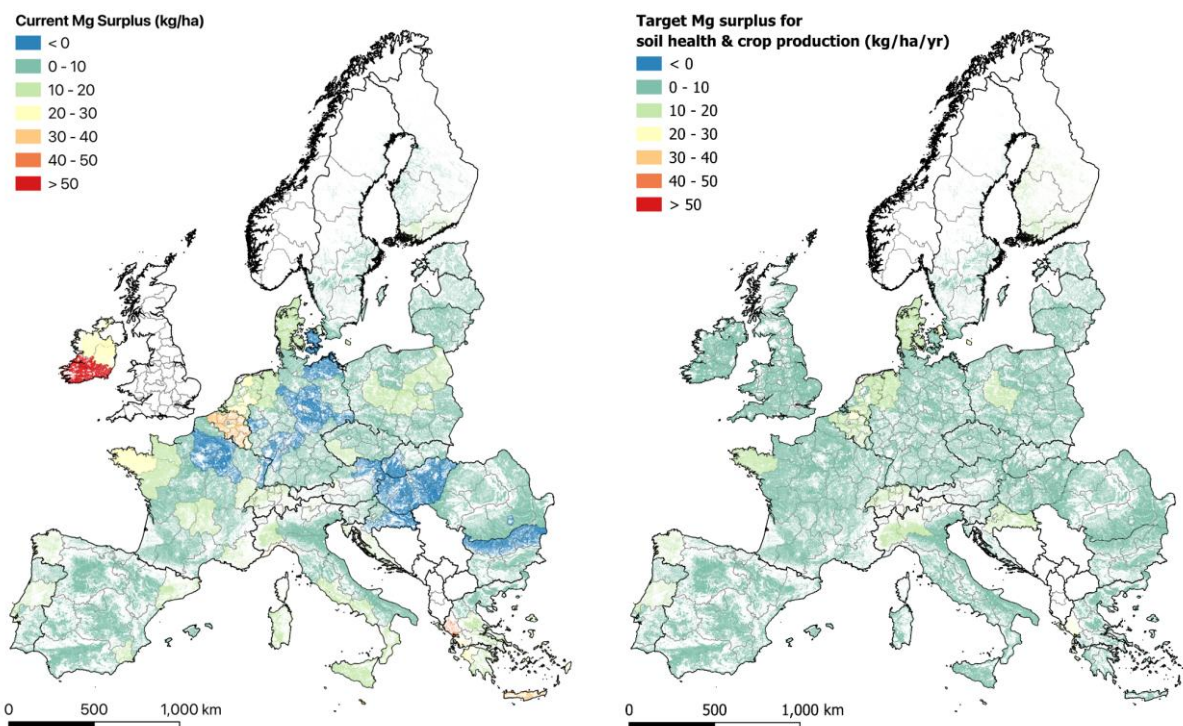


Figure 7.3. Current Mg surplus (left) and target Mg surplus (right) for soil health and crop production at NUTS2 level.

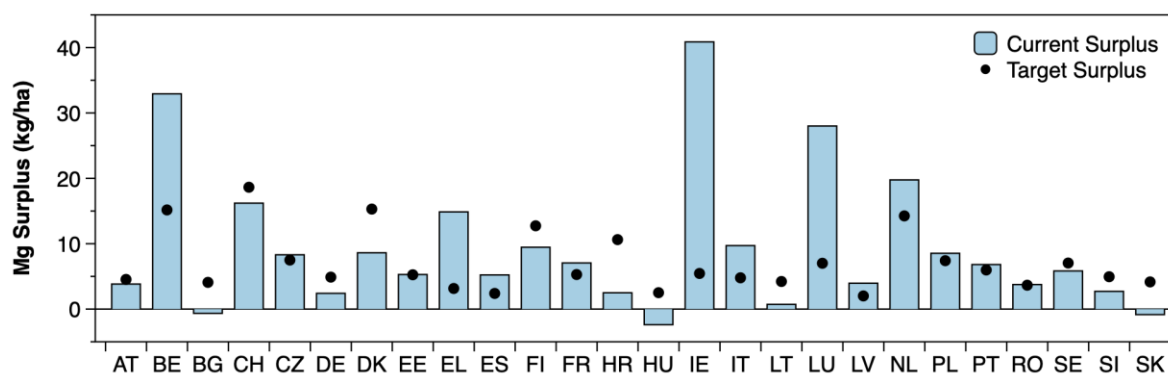


Figure 7.4. Current Mg surplus and target Mg surplus (in kg Mg/ha/yr) for soil health and crop production per country.

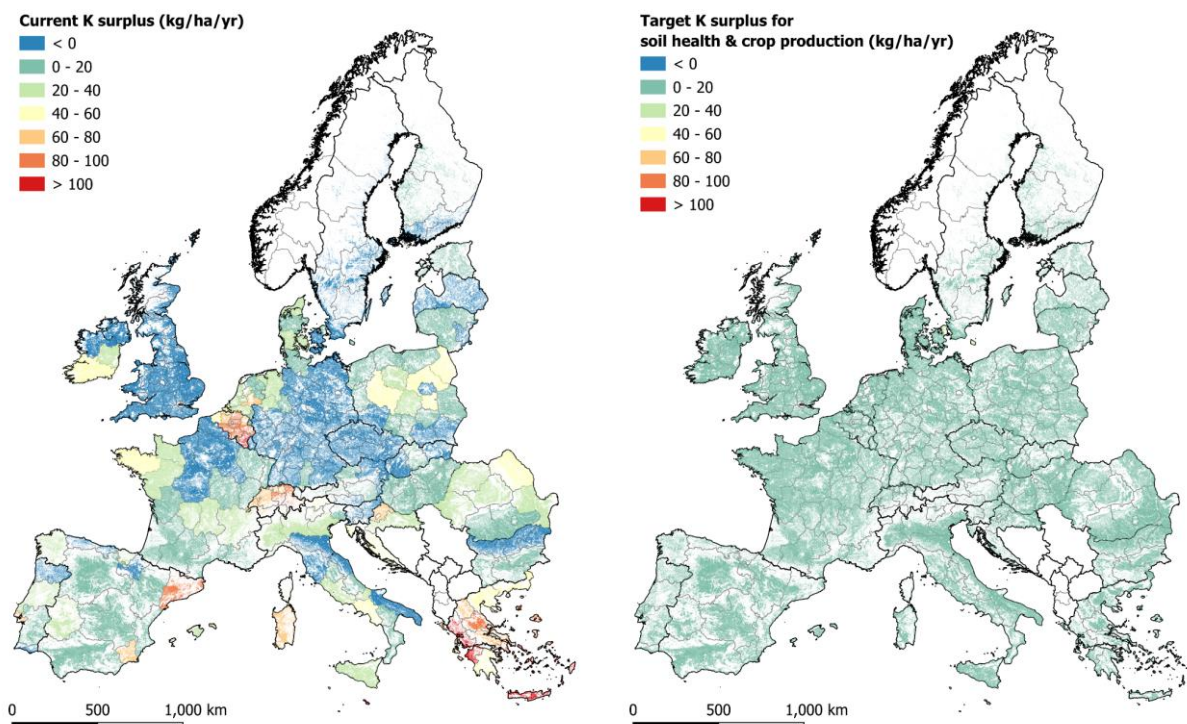


Figure 7.5. Current K surplus (left) and target K surplus (right) for soil health and crop production at NUTS2 level.

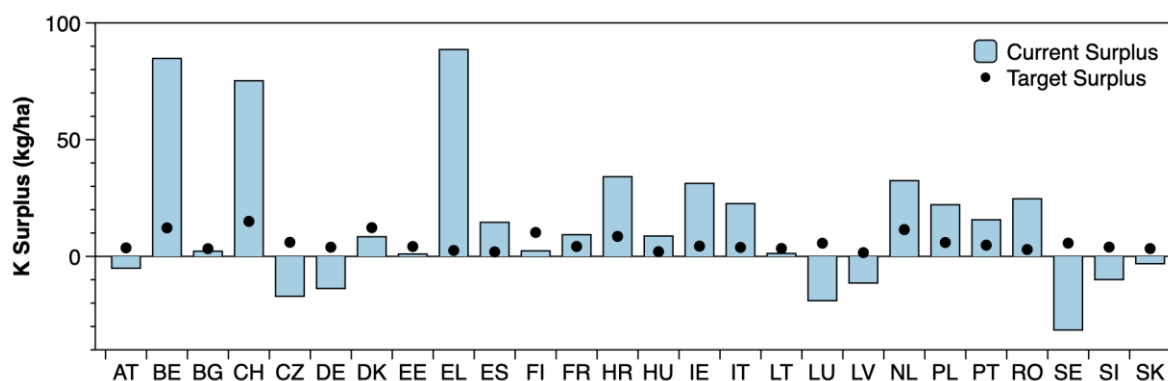


Figure 7.6. Current K surplus and target K surplus (in kg K/ha/yr) for soil health and crop production per country.

7.2 Critical surpluses for water quality

Given the fact that the loss of Ca, Mg or K to ground or surface water is not leading to adverse environmental impacts (see above), there is no need to derive critical surpluses in view of water quality.

8. Metals (Cu, Zn and Cd)

The MITERRA-Europe model focuses on three metals: copper (Cu), zinc (Zn) and cadmium (Cd). A key aspect related to the risk of Cd, Cu and Zn present in soil (or water) can pose is the fact that their impact is largely related to their actual availability for crop uptake or leaching rather than the total concentration (in soil or water). Here we define availability as the degree to which these metals can be taken up by crops, soil organisms or leached to the ground- and surface water. For most metals the availability strongly depends on a combination of type of input and soil properties like pH and the amount (and quality) of organic matter and clay. This implies that the critical surplus for metals will vary depending on soil texture and soil acidity.

8.1 Target soil Cu and Zn surpluses for soil health and crop production

The target metal surplus in view of soil fertility (Cu and Zn, being minor nutrients) is estimated as:

$$X_{sp_target} = X_{loss,target} + \max(0, X_{target} - X_{act}) \cdot D \cdot \rho \times 0.01/T \quad (8.1)$$

where X_{act} refers to the actual metal content in the soil (in mg kg^{-1} , with X being either Zn or Cu), X_{target} refers to the target metal content in the soil (mg kg^{-1}) in soil, $X_{loss,target}$ is the loss of Cu or Zn by leaching and subsurface runoff out of the topsoil at the target soil Cu or Zn content, D refers to the depth of the top soil (m), ρ refers to the bulk density of the soil (kg m^{-3}), and 0.01 is a unit correction from mg kg^{-1} to kg ha^{-1} , and T refers to the time period (in years) to reach the desired target. When the actual value is above the target value, we limit to 0 (no target decline in BS). A target metal content value can be set at 1-2 mg /kg and at 2-5 mg /kg for Zn, based on a Mehlich extraction (Siatwiinda et al. 2024). The related target content can be derived by using a ratio of total Cu/Mehlich Cu of 8 (6-10) and a ratio total Zn/Mehlich Zn of 20 (10-30) (Behera et al., 2011).

The loss of Cu or Zn by leaching and subsurface runoff out of the topsoil at the target soil Cu or Zn content is calculated as

$$X_{loss,target} = (Q_{eff1} + Q_{int1}) \cdot X_{ss,target} \cdot M_X/1000 \quad (8.2)$$

where $X_{ss,target}$ is the target Cu or Zn concentration in soil solution (mmol L^{-1}) which is derived from the target soil reactive Cu or Zn content according to:

$$X_{ss,target} = \left(\frac{X_{soil,re,target}}{K_F \times M_X \times 1000} \right)^{1/n} \quad (8.3)$$

where K_F is a Freundlich coefficient ($\text{mol.l}^{-1n}.\text{kg}^{-1}$), ($M_X \times 1000$) is to convert soil reactive Cu or Zn content from mg kg^{-1} to mol kg^{-1} with M_X being the molar mass of Cu (63 g mol^{-1}) or Zn (65 g mol^{-1}). To derive a value of $X_{ss,target}$ in mg L^{-1} the concentration in mmol L^{-1} has to be multiplied by M_X . The value of K_F is also calculated as a function of the content of organic matter (in %), clay (in %) and pH-H₂O (unitless) according to:

$$\log K_F = b_0 + b_1 \cdot \log (\text{SOM}) + b_2 \cdot \log (\text{clay}) + b_3 \cdot \text{pH-H}_2\text{O} \quad (8.4)$$

where $b_0 \dots b_3$ the model coefficients, SOM is soil organic matter content (%), clay is clay (< 2 μm or lutum) content (%) and pH-H₂O is the pH determined in water (or soil solution). Values for the coefficients used are given in Table 8.1 (see also De Vries et al., 2008b).

Table 8.1. Values for the coefficients b_0 - b_3 and n in the relationships relating dissolved total concentrations and reactive soil concentrations of Cu, Zn and Cd (see Eq 8.3 and 8.4). Note that Cd has been added in view of calculation of the critical dissolved Cd concentration based on critical reactive metal concentration in view of soil biodiversity impacts (see section 7.2 below).

Metal	b_0	b_1	b_2	b_3	n	R^2	se- y_{est}
Cu	-3.55	0.48	0.18	0.16	0.47	0.62	0.35
Zn	-4.51	0.39	0.35	0.45	0.74	0.82	0.40
Cd	-4.85	0.58	0.28	0.27	0.54	0.79	0.33

The reactive target metal concentrations in Eq. (8.3) is derived from total critical metal concentrations (Cu, Zn or Cd,) by accounting for the variation in organic matter and clay content, according to Römken et al. (2004):

$$\log X_{soil, re, target} = c_0 + c_1 \cdot \log (\text{SOM}) + c_2 \cdot \log (\text{clay}) + c_3 \cdot \log X_{soil, tot, target} \quad (8.5)$$

where both $X_{soil, re}$ and $X_{soil, tot}$, being the reactive and total metal (Cu, Zn or Cd) concentrations in soil, are given in $\text{mg} \cdot \text{kg}^{-1}$ Values for the coefficients used are given in Table 8.2 (see also De Vries et al., 2008b).

Table 8.2. Values for the coefficients c_0 - c_3 in the relationships between reactive and total concentrations of Cu, Zn and Cd, according to Eq. 8.5 (after Römken et al., 2004, Table A1.1).

Metal	c_0	c_1	c_2	c_3	R^2	se- y_{est}
Cu	-0.331	0.023	-0.171	1.15	0.93	0.13
Zn	-0.703	0.183	-0.298	1.24	0.96	0.16
Cd	-0.089	0.022	-0.062	1.08	0.96	0.11

Note that the values for Cd are used when back transforming a critical crop content to a critical total soil content and then a critical reactive soil content and finally to a critical dissolved Cd concentration (see below).

8.2 Critical soil Cu, Zn and Cd surpluses for soil, water and crop quality

The critical metal surplus in view of soil quality (soil biodiversity), water quality and crop quality is estimated via:

$$X_{sp, crit} = X_{loss, crit} \quad (8.6)$$

$$X_{loss, crit} = (Q_{eff1} + Q_{int1}) \cdot X_{ss, crit} / 1000 \quad (8.7)$$

where $X_{loss, crit}$ is the critical total metal loss by leaching and subsurface runoff ($\text{g ha}^{-1} \text{yr}^{-1}$), $X_{ss, crit}$ represents the critical metal concentration (Cd, Zn, Cu) in soil solution ($\mu\text{g L}^{-1}$), and $Q_{eff1} + Q_{int1}$ is the total water flux via leaching and subsurface runoff out the topsoil ($\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$), 1000 is a unit correction from mg ha^{-1} to g ha^{-1} .

Note that the calculation of critical metal losses via leaching and subsurface runoff (Eq. 8.7) is applied after calculation of the critical dissolved concentration from a critical reactive soil metal content in view of soil biodiversity impacts or from a critical crop content in view of human or animal health impacts, which is then related to a critical total soil content and then a critical reactive soil content (see below). In case of water quality, the critical limit for the metal concentration in soil solution (X_{crit}) can be derived from the critical limit for groundwater and surface water, that equals $3 \mu\text{g Cd L}^{-1}$, $75 \mu\text{g Cu L}^{-1}$ and $800 \mu\text{g Zn L}^{-1}$.

8.2.1 Critical reactive soil metal contents in view of soil biodiversity impacts

As a threshold for ecotoxicological effects on soil biota, critical reactive metal concentrations as a function of soil organic matter (SOM) and pH were used, as derived by Loftis et al. (2004) and De Vries et al. (2007a). Their analysis resulted in the following critical limits for the reactive soil concentration of Cd, Cu and Zn:

$$Cd_{soil,re,crit_soilbiodiversity} = 10^6 \times M_{Cd} \times 10^{-0.43 \times pH_{ss} - 5.66} \quad (8.8)$$

$$Cu_{soil,re,crit_soilbiodiversity} = 10^6 \times M_{Cu} \times 10^{-1.21 \times pH_{ss} - 2.57} \quad (8.9)$$

$$Zn_{soil,re,crit_soilbiodiversity} = 10^6 \times M_{Zn} \times 10^{-0.34 \times pH_{ss} - 4.66} \quad (8.10)$$

where $Cd_{crit_soilbiodiversity}$, $Cu_{crit_soilbiodiversity}$ and $Zn_{crit_soilbiodiversity}$ are the reactive metal concentrations in soil solution (in $mg\ L^{-1}$), and M_{Cd} , M_{Zn} , M_{Cu} are the molar mass ($112.414\ g\ mol^{-1}$ for Cd, $65.35\ g\ mol^{-1}$ for Zn and $63.55\ g\ mol^{-1}$ for Cu), pH_{ss} represents the pH in soil solution. The multiplication with 10^6 is done to convert the mass unit from nanomolar (nM) to $mg\ L^{-1}$. Note that the critical Cd, Cu or Zn concentration in soil solution is calculated by using Eq. 8.3 and 8.4 with the input data in Table 8.1.

8.2.2 Critical soil Cu, Zn and Cd concentrations for crop quality

Since Cd is a pollutant, too high Cd concentrations in crops may cause an excess of food quality criteria. While copper and zinc are essential nutrients, excessive amounts in animal feed can also lead to toxicity, causing various animal health problems.

Zn and Cu uptake by crops is dependent on soil Cd, Zn and Cu concentration as well as soil properties, with soil-plant relationships for Cu being limited to feed crops (grass and maize only), according to:

$$\log X_{crop} = n \cdot \log X_{soil} + a_0 + a_1 \cdot pH_{KCl} + a_2 \cdot \log SOM + a_3 \cdot \log clay \quad (8.11)$$

where X stands for Cd, Zn or Cu, pH is determined in a KCl extraction, and the clay and soil organic matter (SOM) content are in units of percentage, *log* indicates logarithms base 10. The negative coefficients in these functions imply that an increase in pH, clay or organic matter content leads to a lower metal content in the soil. This result is in agreement with the impact of the aforementioned soil properties on the availability of metals in soil.

The critical Cd, Zn or Cu concentration in soil ($mg\ kg^{-1}$) can then be estimated as a function of the critical limit for the crop quality and the associated soil properties controlling the metal availability, according to:

$$X_{crit_soil_crop} = 10^{\frac{\log X_{crop_crit} - (a_0 + a_1 \cdot pH_{KCl} + a_2 \cdot \log SOM + a_3 \cdot \log clay)}{n}} \quad (8.12)$$

Values used for in the Cd, Cu and Zn are given in Tables 8.3, 8.4 and 8.5.

Table 8.3 Values for the coefficients $a_0 - a_3$ and n in the soil– plant relations for Cd according to Eq. (8.12) in grass, maize, potatoes wheat and sugar beet, based on De Vries et al. (2008a).

Crop	a_0	$a_1(\text{pH})$	$a_2(\text{SOM})$	$a_3(\text{clay})$	n	R^2	$\text{se-}y_{\text{est}}^{(1)}$
Grass	1.45	-0.38		-	1.22	0.63	0.23
Maize	0.90	-0.21		-0.32	1.08	0.62	0.26
Potatoes	0.97	-0.21	-0.41	-0.2	0.81	0.78	0.26
Wheat ¹	0.22	-0.12	-0.33	-0.04	0.62	0.64	0.20
Sugar beet	1.33	-0.22		-0.13	0.62	0.83	0.15

¹ The standard error of the y-estimate on a logarithmic basis

Table 8.4 Values for the coefficients $a_0 - a_3$ and n in the soil– plant relations for Zn according to Eq. (8.12) in grass, maize, potatoes wheat and sugar beet, based on De Vries et al. (2008b).

Crop	a_0	$a_1(\text{pH})$	$a_2(\text{SOM})$	$a_3(\text{clay})$	n	R^2	$\text{se-}y_{\text{est}}^{(1)}$
Grass	2.06	-0.09	1.09	-1.05	0.41	0.49	0.11
Maize	3.05	-0.31		-0.61	0.64	0.67	0.12

¹ The standard error of the y-estimate on a logarithmic basis

Table 8.5 Values for the coefficients $a_0 - a_3$ and n in the soil– plant relations for Cu according to Eq. (8.12) in grass and maize, based on De Vries et al. (2008b).

Crop	a_0	$a_1(\text{pH})$	$a_2(\text{SOM})$	$a_3(\text{clay})$	n	R^2	$\text{se-}y_{\text{est}}^{(1)}$
Grass	1.41	-0.18	0.65	0.0	0.83	0.37	0.08
Maize	0.0	+0.07	0.0	-0.11	0.20	0.40	0.09

¹ The standard error of the y-estimate on a logarithmic basis

Since the critical Cd, Zn or Cu surplus requires the critical Cd, Zn or Cu concentration in soil solution (see Eq. 7.2), the calculated critical soil content is then used to derive the critical reactive soil content based on Eq. 7.5 and then to derive the critical Cd, Zn or Cu concentration in soil solution based on Eq. 7.3 and 7.4. The critical Cd limit for the harvested crop content is expressed in the unit mg kg^{-1} has been at a food quality criterion value of 0.2. Note that the critical Cd content for grass should be determined for animal health in view of the Cd uptake via fresh feed intake by animals. This value is set at $1.1 \text{ mg Cd kg}^{-1}$ based on De Vries et al. (2007b).

The critical Zn limit for the harvested content of feed crops has been set at 100 mg kg^{-1} (EFSA, 2014). While zinc is an essential nutrient, excessive amounts can lead to toxicity, causing various health problems. For example, in pigs, high zinc levels in feed can result in reduced growth rate, diarrhea, and impaired immune function. Proposed total maximum contents in feed are 150 mg Zn/kg for piglets, sows, rabbits, salmonids, cats and dogs; 120 mg Zn/kg for turkeys and 100 mg Zn/kg for all other animal species (EFSA, 2014). We thus set the level at 100 mg/kg . In ration recommendations for dairy cows an optimum range of 25 to 50 mg kg^{-1} is usually recommended.

The critical limit for the harvested crop Cu content has been set at a value of 25 mg kg^{-1} (EFSA, 2016). Too much copper in animal feed can lead to copper poisoning and accumulation in animal products, ultimately harming livestock and potentially affecting public health (Ma et al., 2021). For grassland the critical Cu content depends also on animal category and the ratio

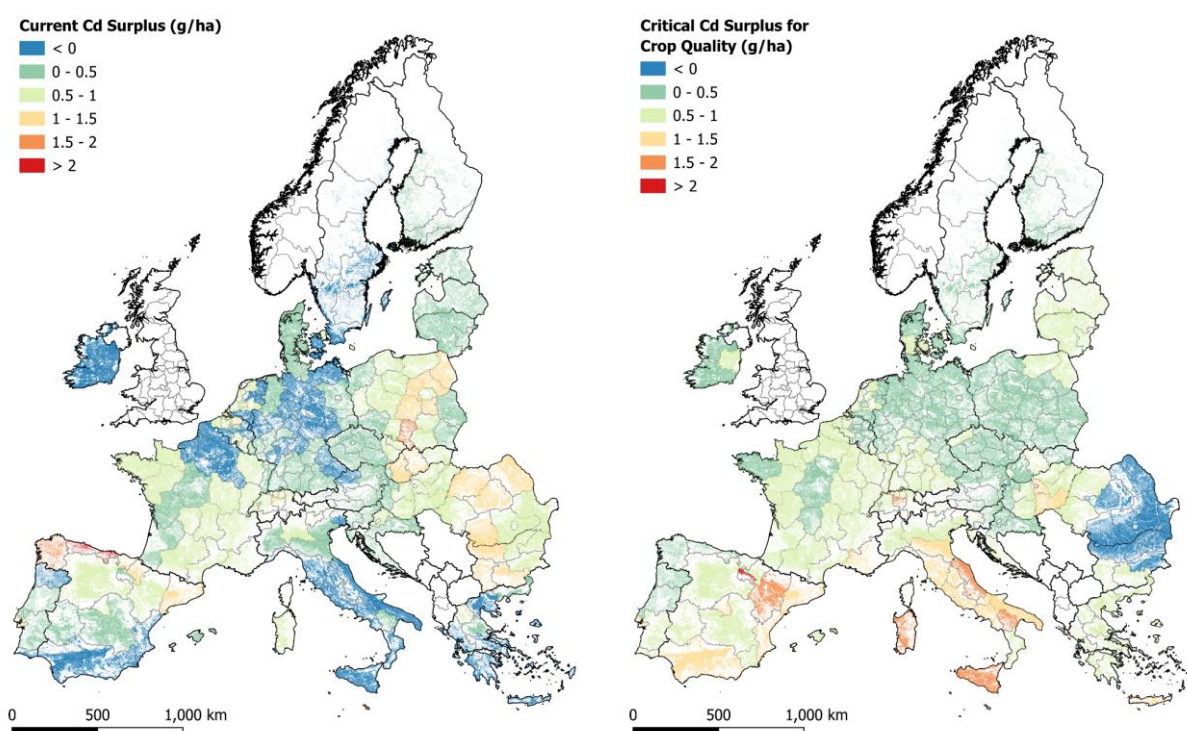
between copper with zinc and molybdenum. In the ration assessment the optimum range varies between 12 and 15 mg kg⁻¹ whereas the maximum may increase up to 40 mg kg⁻¹ for cows. Here we use a critical value of 25 mg/kg.

8.3 Results of current and desired state

Results for Cadmium are shown in Figure 8.1 and Figure 8.2 and for Zinc in Figure 8.3 and Figure 8.4. Cd surpluses are generally low, with some higher values in Eastern Europe. In most regions the critical Cd surplus for crop quality is higher than the current surplus, but in Romania and Bulgaria the current surplus exceeds the critical surplus. For soil biodiversity there should not be any Cd surplus, whereas for water quality the critical surplus is much higher and not a limiting factor.

For zinc the current surplus shows a patchy pattern, with highest surpluses mostly linked to regions with high livestock densities. In those regions the critical Zn surplus for crop quality is exceeded. Similar to Cd the critical Zn surplus for soil biodiversity is exceeded everywhere, while for water quality there is no problem.

For Cu results were not reliable yet, probably due to incorrect values for the parameterisation of Eq. 8.12 for Cu, and have therefore not been included in this report.



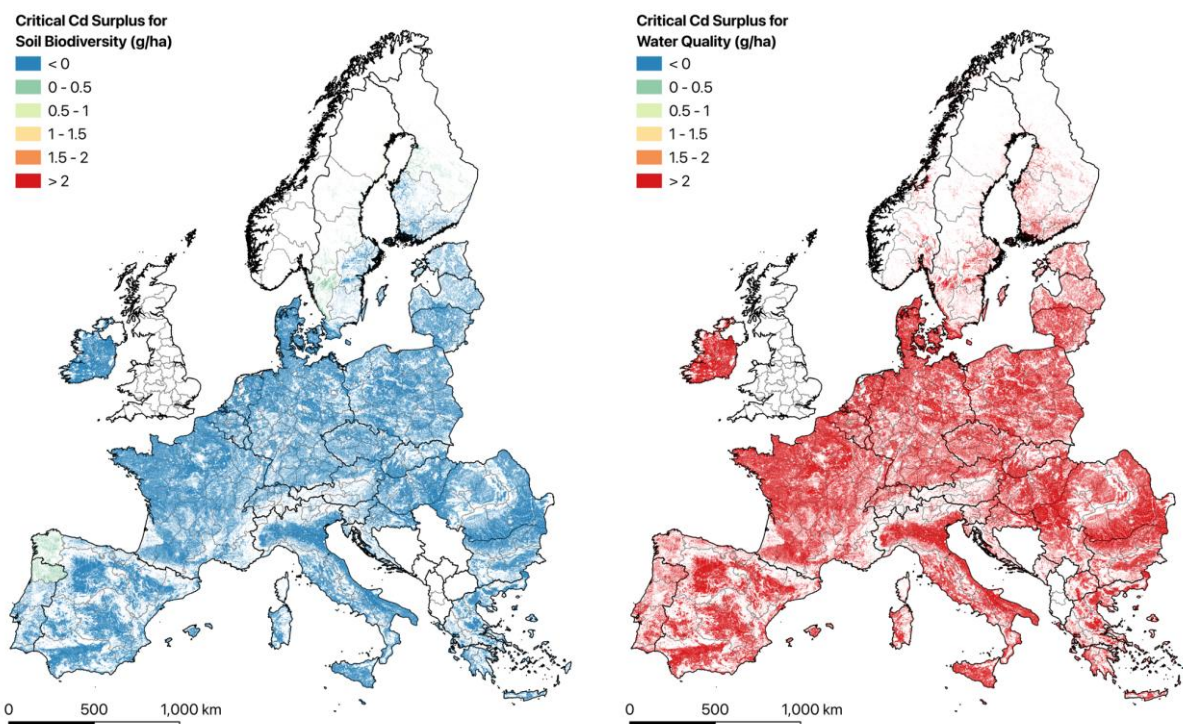


Figure 8.1. Current Cd surplus (upper left), critical surplus for crop quality (upper right), critical surplus for soil biodiversity (lower left), and critical surplus for water quality (lower right).

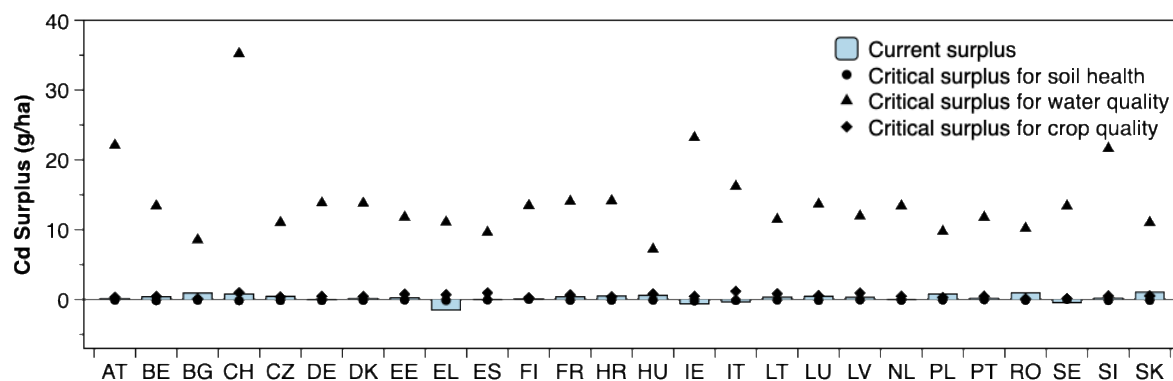


Figure 8.2. Current Cd surplus and critical Cd surplus for soil health, water quality, and crop quality per country.

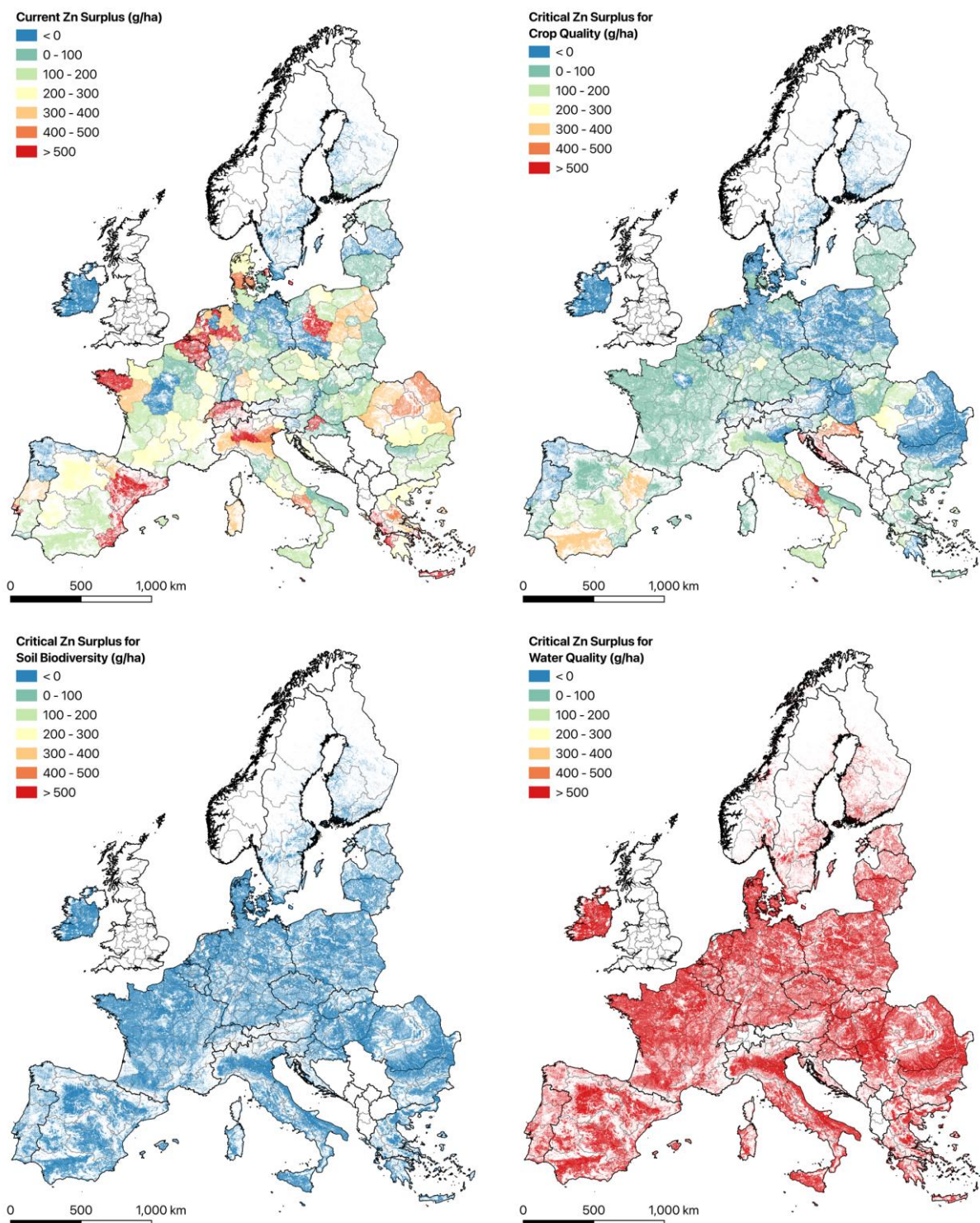


Figure 8.3. Current Zn surplus (upper left), critical surplus for crop quality (upper right), critical surplus for soil biodiversity (lower left), and critical surplus for water quality (lower right).

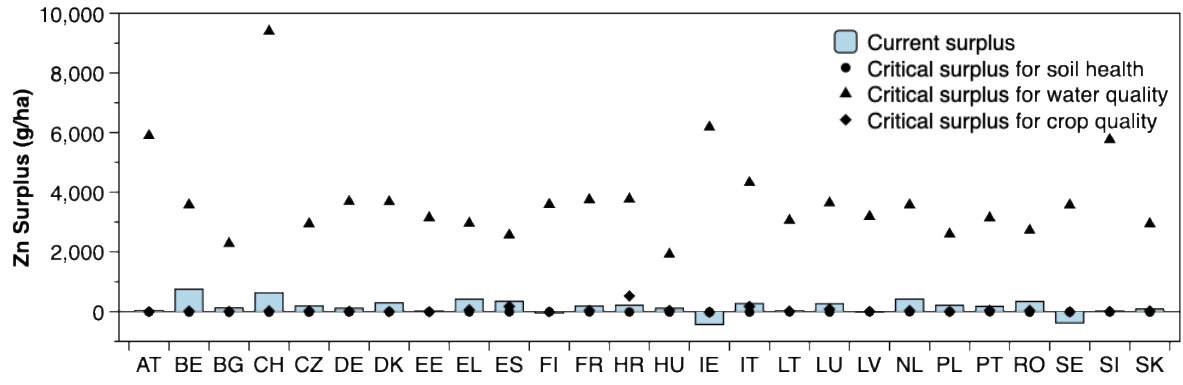


Figure 8.4. Current Zn surplus and critical Zn surplus for soil health, water quality, and crop quality per country.

9. Discussion and conclusion

This report presented the approach to estimate target and/or critical inputs and surpluses for C, N, P, S, base cations, and heavy metals. The approach was implemented in the MITERRA-Europe model, and outputs were presented at regional (NUTS2) and country levels for EU member states. Comparison of target and critical input/surpluses against current levels helped to identify the gap for key environmental objectives.

The approach as used in this report is based on many assumptions and also the required input data has its uncertainties. The results should therefore be treated with care and be considered as first indications. During the remainder of the NutriBudget project, an update of these results might be required, building on more empirical data and further verification of the results in the NutriBudget case study countries.

Still the report provides valuable first insights with for some of the nutrients clear trade-offs between target surpluses for agronomic production and critical surpluses for environmental objectives, which are often much lower.

For carbon the input in most countries is sufficient to maintain soil health and crop production, but in some others, mainly Mediterranean countries and countries and some Eastern European countries, higher carbon inputs are needed. However, from a climate change mitigation perspective higher carbon inputs are required in almost all countries, which are for some countries unrealistically high, which means that carbon sequestration will not be able to compensate GHG emissions from agriculture.

For nitrogen the results show diverse picture, in some countries higher organic N inputs are desired from an agronomic point of view, but other countries with high livestock densities should lower the organic N input. The current N surplus is mostly higher than the critical N input in view of either critical NH_3 emissions or critical N losses to surface water or ground water in countries with intensive agriculture and it is often even higher than the target N input to maintain soil health and crop production. Surface water quality is in most regions a much more stronger limiting factor than groundwater quality. Ammonia emissions, as indicator for nature quality, should also decrease in most countries, often reductions of more than 50% are required to reach the desired status.

For phosphorus, the current P surplus is higher than the target P surplus in regions where soils are exceeding an appropriate soil P status in view of crop production and this also holds for the critical P surplus. Unlike N, the correlation is less with the P input level since the soil P status mainly determines the fate of P.

In general, the surplus of base cations is sufficient in view of target levels to maintain soil health and crop production, except for magnesium. The sulphur (S) surplus is also not sufficient in parts of Europe, indicating the need for enhanced S fertilization, which reflect the lower S input by atmospheric deposition in response to various air quality control policies.

Finally, the current Cd and Zn surplus mostly exceed the critical Cd and Zn surplus in view of impacts on soil health (soil biodiversity) but not in view of water quality and crop quality

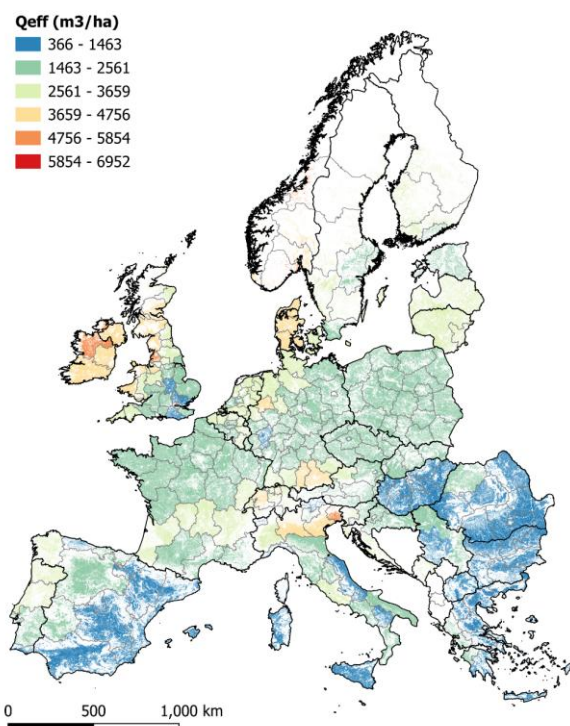
Apart from further verification of the results, future work will focus on optimisation among different objectives and nutrients. This will be further elaborated in D2.6 when also the impact of measures from the NutriBudget roadmaps will be quantified.

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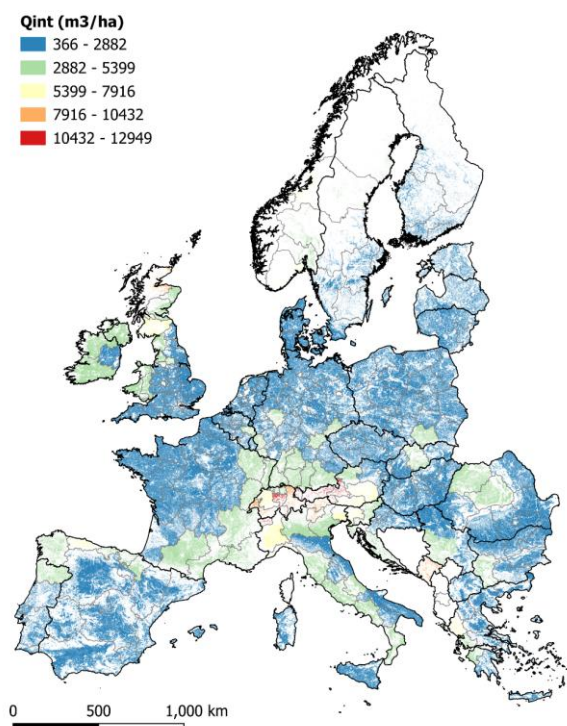
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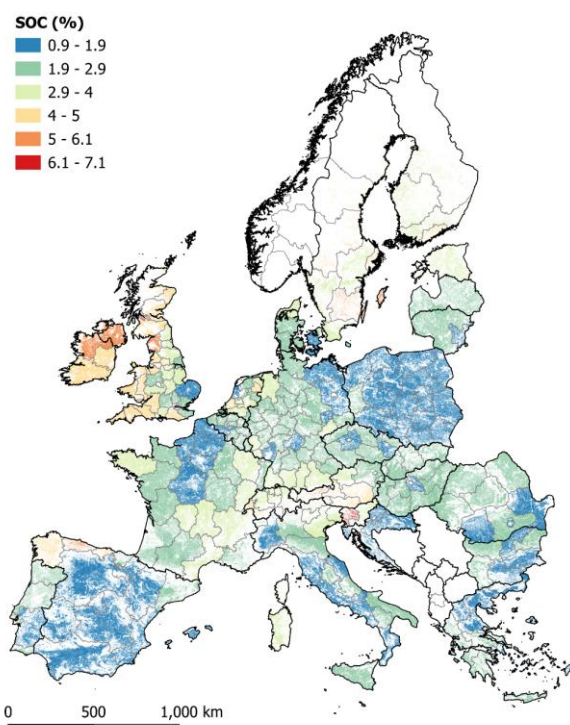
Annex A. Maps of soil related input parameters



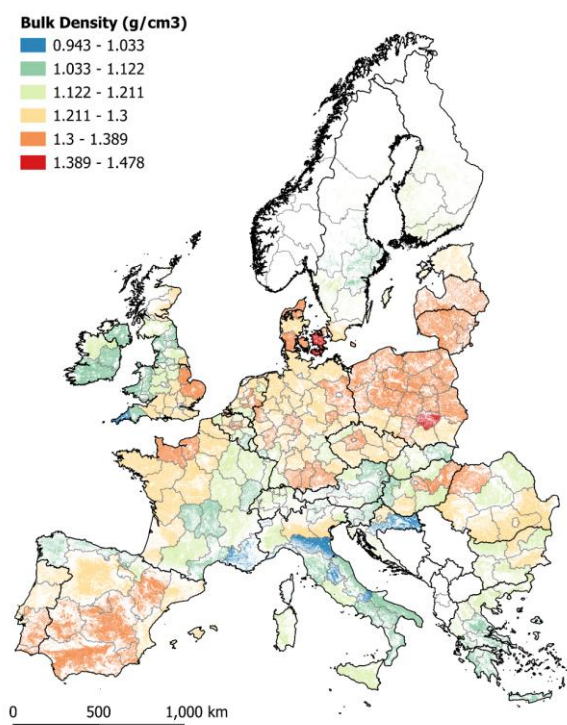
Annual leaching water flow (m³/ha)



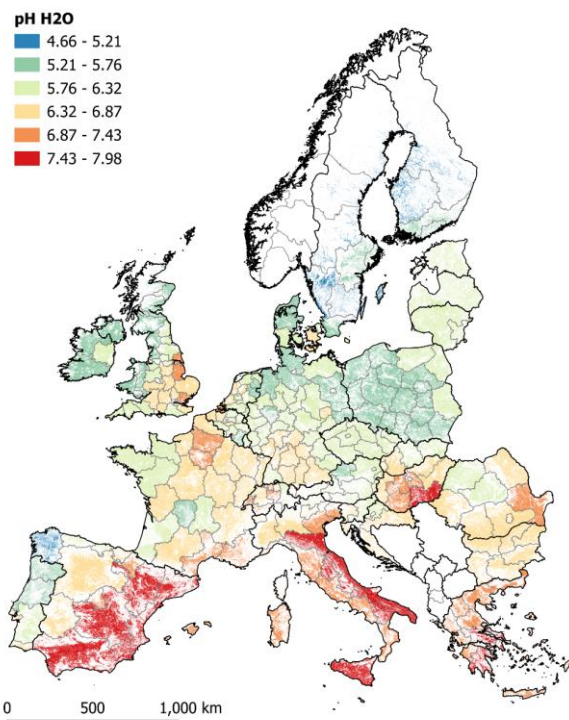
Annual subsurface runoff water flow (m³/ha)



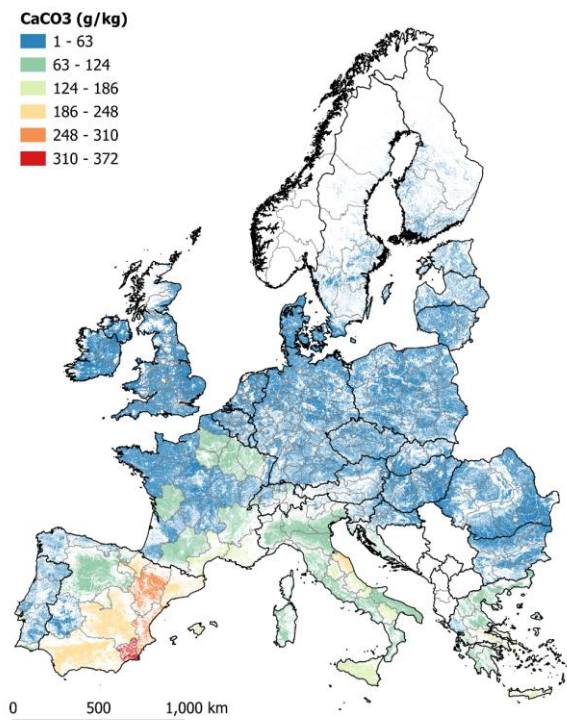
Soil organic carbon content (%)



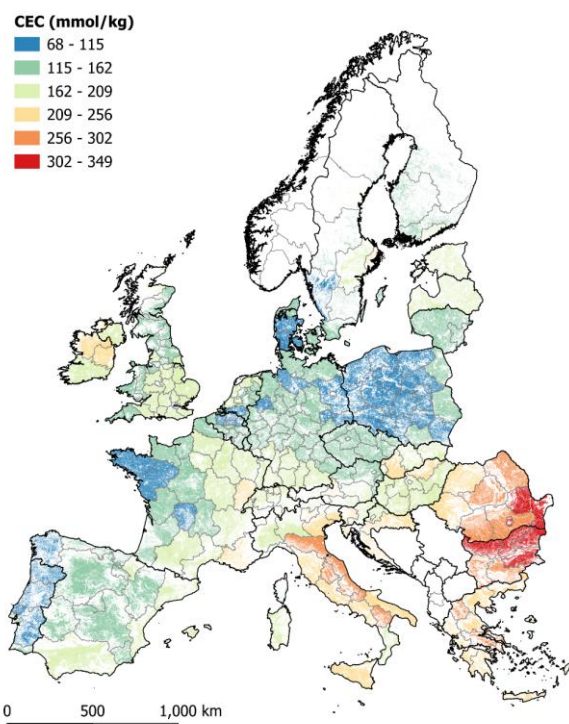
Soil bulk density (g/cm³)



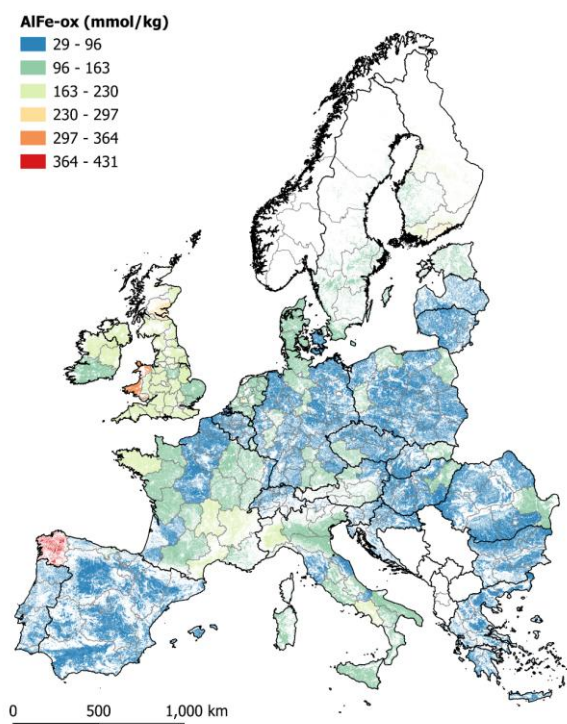
Soil pH measured in H₂O



Soil CaCO₃ content (g/kg)



Soil cation exchange capacity (mmol/kg)



Soil oxalate-extractable Al and Fe content (mmol/kg)



Optimisation of nutrient budget in agriculture

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