Optimisation of nutrient budget in agriculture

D1.5 Algorithms quantifying impacts of measures via field based indicators from satellite derived indices

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	https://www.nutribudget.eu/
Deliverable Information	
Title	Algorithms quantifying impacts of measures via field based indicators from satellite derived indices
WP number and title	WP1 – Design Opportunity Map for Effective Measures
Lead Beneficiary	UGent
Authors	Gerard Ros (WU), Wim de Vries (WU), Hongzhen Luo (UGent)
Reviewers	Salim Belyazid (SU), Ruben Vingerhoets (UGent), Marcos Lana (SLU)
Description	Algorithms quantifying impacts of measures via field based indicators are modelled, and the code is shared via GitHub and made available via an API for further use.
Type	OTHER
Dissemination Level	PU
Status	Final version
Submission due date	31st August 2024
History of Changes	
Version 0.1	Draft created by WU and UGent (26.07.2024)
Version 0.2	Internal review by UGent and SLU (09.08.2024)
Version 0.3	Revised version by WU and UGent (21.08.2024)
Version 1.0	Submitted version (04.09.2024)

Disclaimer: *The wording "from satellite derived indices" in the title of D1.5 "Algorithms quantifying impacts of measures via field based indicators from satellite derived indices" does not fully cover the data sources that are used in this deliverable. The focus of D1.5 is on the application of the models on EU scale based on existing databases, which are partially satellite-derived. Meaning, data used in D1.5 is not based only on the satellite derived indices.*

Preface

Deliverable (D) 1.5 *“Algorithms quantifying impacts of measures via field based indicators from satellite derived indices”* is part of outcomes from Task 1.3 in work package (WP) 1 of NutriBudget project, funded by Horizon Europe programme (project number 101060455). The NutriBudget project aims to develop the prototype of a first-of-its-kind integrated nutrient management platform, called “NutriPlatform”, in various regions across Europe. The NutriPlatform will operate as a decision-support tool for farmers, advisors and regional authorities. Before the end of the project, the “NutriPlatform” (as a stand-alone or integrated in the existing European Commission promoted Farm Sustainability Tool (FAST) for nutrient management) will be tested and used by at least 40.000 farmers across Europe.

The WP1 *“Design Opportunity Map for Effective Measures”* aims to develop a Mitigation Measures Catalogue (MMC) by identifying relevant agronomic mitigation measures across the European Union (EU) that can contribute to agricultural sustainability across different agricultural systems (conventional, organic and agro-ecological), regions and countries. The objective of Task 1.3 is to derive predictive models or decision trees to predict the response of Key Performance Indicators (KPIs, selected from WP3) given the site properties of the farm, region or country thereby assessing the applicability as well efficiency of measures to alter the KPIs.

This deliverable aims to present the results of Task 1.3, building on the established protocol in D1.4 Algorithms quantifying impacts of measures via field based indicators from satellite derived indices initial version aims to implement the meta-analytical regression models developed in D1.3 *“Quantified measure-impact relationship of selected measures”* (under review). Specific agronomic and environmental indicators were selected in WP2/WP3 for the quantification of measure-impact relationship of selected mitigation measures regarding improved crop yield, soil health (e.g. soil organic carbon (SOC) content / sequestration), soil water retention, air quality (e.g. ammonia emissions) and water quality (e.g. nutrient surplus and nutrient use efficiency). Here we show how agricultural measures affect the crop yield (and hence the nutrient uptake and all associated nutrient surpluses), the nutrient use efficiency (being the counterpart of the nitrogen surplus), soil pH and soil organic carbon content.

Executive summary

Intensification in agriculture, driven by increased machinery and fertiliser use, has substantially boosted food production in Europe. However, the elevated application of nitrogen (N) and phosphorus (P) fertilisers has resulted in severe environmental consequences, impacting biodiversity, climate, water, air quality, and human health. For instance, excessive N leads to increased ammonia and nitrous oxide emissions, contributing to climate change and air pollution, while nutrient runoff or leaching to waterbodies pose risks to water quality, particularly affecting vulnerable populations. Moreover, decline in biodiversity and soil organic carbon further compound food security and environmental challenges. In responding to these issues, the Horizon Europe NutriBudget project aims to develop and implement integrated nutrient management platform, called NutriPlatform, as a decision support tool to intensify agriculture sustainably, ensuring optimal yields without compromising the environment or public health. Efforts have been made in WP1 to provide an overview of relevant agronomic mitigation measures contributing to agricultural sustainability and impact-specific information (i.e. environmental performance related use efficiency, nutrient losses), which resulted in an user-friendly catalogue consisting of 22 pre-identified mitigation measures (aiming to be more than 50 by end of the project).

Based on the inventory of existing agronomic mitigation measures in Task 1.1, and the meta-regression models build to estimate their impact on selected Key Performance Indicators in Task 1.2, Task 1.3 aims to apply these meta-regression models on an European scale while accounting for the spatial variability in soil properties, climatic conditions and management measures already applied. By applying these spatial explicit meta-regression models, one can identify the most effective measures to increase the agronomic and environmental performance of farming systems across Europe. Where the meta-regression models have been introduced in Deliverable (D) 1.3, and the methodology to apply these meta-regression models have been explained in D1.4, here in D1.5 we show for all European agricultural land whether the objectives for crop yield, nutrient surpluses (here illustrated for nitrogen only), and soil health (i.e. soil pH and soil organic carbon) can be met via the adoption of agricultural measures.

The content of D1.5 is divided in four Chapters. **Chapter 1** provides a general introduction to the nutrient challenge in agricultural across Europe, highlighting the importance of developing and implementing effective mitigation measures to improve nutrient use efficiency and nutrient budgets within various agricultural systems, regions and countries. **Chapter 2** describes the methodology to apply developed meta-analytical regression models on European scale and to identify appropriate measures, including an overview of existing databases (partly satellite derived) to tailor the calculated impacts on field, farm and regional scale. **Chapter 3** shows the impact of various agricultural crop, soil, fertiliser and water management practices on crop yield, nutrient surpluses (for nitrogen), soil organic carbon and soil pH. Lastly **Chapter 4** describes and summarizes results of the model quantification and recommendations for future implementation.

The study concluded that adopting a combination of soil, crop, and fertiliser management practices significantly enhances crop yield, NUE, SOC and soil pH. For crop yield, combining all three management measures showed an average yield increase of 33%, with 52% of EU agricultural areas reaching the targeted yield. Crop and fertiliser practices were also recognized as effective measures to increase the NUE, thus improving 78% of agricultural land towards nitrogen surpluses below critical levels. Soil management practices like reduced tillage positively influenced SOC. It was estimated that with optimized practices, 90% of soils can achieve the target SOC level. While most measures negatively impacted soil pH, liming emerged as an effective strategy for maintaining soil acidity within optimal ranges, given that currently 96% of soils are already above the critical pH level of 5.5. The findings offer actionable insights and effective strategies for improving agricultural sustainability across the EU, which can be utilized as reference for the further quantification in WP2 by process-driven models.

Table of Contents

List of Figures

List of Abbreviations

CF	Combined fertilisation
D	Deliverable
DoA	Description of the Action
EE	Enhanced Efficiency fertiliser
EU	European Union
FaST	Farm Sustainability Tool
GHG	GreenHouse Gasses
KPI	Key Performance Indicators
MD	Mean difference
MMC	Mitigation Measures Catalogue
N	Nitrogen
NCU	Nitrogen Calculation Unit
NUE	Nitrogen use efficiency
NUTS	Nomenclature of Territorial Units for Statistics
OF	Organic fertilisation
P	Phosphorus
RFR	Right Fertiliser Rate
RFT	Right Fertiliser timing
SD	Standard deviation
SMD	Standard mean difference
SOC	Soil Organic Carbon
SPAM	Spatial Production Allocation Model
WP	Work package

1. Introduction

Agricultural management practices play a pivotal role in shaping the sustainability of agriculture with respect to crop production, soil quality, and environmental health. Numerous practices have been demonstrated to positively impact crop yield and soil fertility while mitigating nutrient losses and enhancing carbon sequestration. However, these practices also exhibit negative consequences, including decreased nutrient use efficiencies and increased emissions of greenhouse gases. The escalating nutrient losses to air and water pose significant challenges, leading to issues such as air pollution, water pollution, eutrophication, biodiversity loss, and soil degradation. Mitigating the adverse effects of nutrient pollution hinges on the judicious use of agricultural practices, necessitating a focus on impacts and improvements in nutrient use efficiencies, particularly nitrogen (N) and phosphorus (P).

Agronomic measures optimising the carbon and nutrient budgets in agriculture result in improved nutrient use efficiency of applied fertilisers, enhance crop yield and soil health together with minimised nutrient losses to air and water. The number of studies examining impacts of agronomic measures are rapidly increasing, confirming their key role in improving sustainability, including studies examining the impact of crop diversification and cover crops, reduced tillage, and precision fertilisation practices (Bolinder et al., 2020; Eagle et al., 2017a; Haddaway & Rytwinski, 2018). Because agricultural management practices are part of sustainable intensification, it is key that we understand their effects on crop production, soil nutrient status and environmental quality. The existing body of research has a notable limitation—it tends to be confined to individual crops, agricultural practices and using single indicators. When only single measures and impacts are considered, this can lead to suboptimal outcomes due to adverse impacts on other indicators (pollution swapping), while also the potential benefits on other indicators are not accounted. The consequence of this system approach is a gap in our comprehension of the intricate dance of potential trade-offs and co-benefits that might unfold across a tapestry of indicators. Moreover, the impacts of practices are highly contingent on site-specific properties (Abdalla et al., 2016; Qin et al., 2015), emphasizing the need for a more nuanced and tailored approach to agricultural optimization. These site properties, ranging from crop type and soil characteristics to climatic conditions such as precipitation and temperature, serve as dynamic factors affecting the outcomes of agricultural interventions.

Zooming into the specifics of the NutriBudget project, WP1 aims to develop a mitigation measures catalogue (MMC) by identifying relevant agronomic measures across the EU (Task 1.1) and quantifying the measure-impact relationships through meta-regression models (Task 1.2). A range of approaches has been used to assess the applicability and impact of measures including experimental evidence from individual research (Rozemeijer et al., 2010), and data-driven statistical (Young et al., 2021a, 2021b; Djodjic et al., 2002) and process-based models (de Vries et al., 2023). Among these approaches, meta-analytical models have advantages for spatial explicit modelling since these models can potentially assess the averaged impacts of agronomic measures on crop yield, soil organic matter levels, nutrient surpluses and nutrient losses while accounting for site properties controlling these impacts (Haddaway et al., 2017; Meurer et al., 2018). The meta-regression models developed in Task 1.2 (methodology described in *D1.2 Quantified measure-impact relationship of selected measures initial version* and results in *D1.3 Quantified measure-impact relationship of selected measures final version (under review)* calculated the tailor-made response of key performance indicators (KPIs, as identified in *D1.1 Mitigation Measures Catalogue - first draft version* and *D3.1 Overview of existing indicators used in national and European policies*) to the applied measures at the influence of certain site properties, thereby providing a comprehensive understanding of the impacts of agricultural management practices on crop yield and nutrient use efficiency, soil health and water quality. Beyond the meta-analytical quantification based on literature data, research efforts are needed to assess the applicability and effectiveness of management practices as well as their interactions in different agricultural systems, landscapes, and climatic conditions. And this is exactly the Task 1.3 being described as "*This task will design (and apply) meta-models to extrapolate the findings of T1.2 (meta-regression models linking* *impacts to indicators) and site property data to all other agricultural fields across Europe, and integrates this outputs in decision support algorithms assessing both the applicability and efficiency of measures depending on agro-ecological site specific factors (where efficiency is defined in relation to multiple objectives of sustainable agriculture)"* . Therefore, the main objective in Task 1.3 is to develop spatial explicit maps guiding the selection of appropriate measures to improve the performance of farming systems on these KPIs. The value of this quantification extends far beyond the project's boundaries; it stands as a critical informational repository for policymakers, researchers, and stakeholders navigating the realms of nutrient management and environmental sustainability within the agricultural sector.

Note that this deliverable (i.e. D1.5), related to Task 1.3, follows upon the earlier report *(D1.4 Algorithms quantifying impacts of measures via field based indicators from satellite derived indices_initial version)* that focuses on the methodological approach to apply meta-regression models using open (satellite) derived data sources to estimate the impact of measures on KPIs for sustainable agriculture. While the meta-regression models have been introduced in *D1.3 (under review)*, and the methodology to apply these meta-regression models have been explained in D1.4, here in D1.5 we show for all European agricultural land whether the objectives for crop yield, nutrient surpluses (here illustrated for nitrogen only), and soil health (i.e. soil pH and soil organic carbon) can be met via the adoption of agricultural measures. These variables are highly sensitive to site-specific conditions such as soil type, climate, and topography, which can vary greatly across different regions in Europe. The inclusion of spatial parameters like longitude, latitude, and climate conditions (e.g., temperature and precipitation) allows for a more accurate quantification of these impacts at the landscape scale, enhancing the precision and relevance of the models. In contrast, animal feeding and manure processing measures quantified in *D1.3 (under review)* are typically conducted in indoor environments, where external site properties are not directly influential. As a result, publications on these topics often lack detailed data on spatial and climatic conditions, making it challenging to incorporate these variables into spatial quantification models. Consequently, the focus of D1.5 was on quantifying the impact of crop-related measures on the response KPIs influenced by the availability and relevance of site properties, while acknowledging the negligible influence of spatial data for the impact of the animal feeding and manure management measures, given the controlled indoor environment of these measures.

2. Methodology

2.1 Optimising management measures across farming systems

To assess the actual farm performance in view of agronomic and environmental targets, an integrative KPI framework has been designed in WP3 to monitor the transition from the current to the desired status to have optimised farming systems in equilibrium with maximum agricultural performance and minimal environmental pressure. As such, this framework will guide the actual decision support as well the identification of appropriate roadmaps to reach the desired status for soil surpluses of carbon and nutrients in view of targets for soil quality, water quality, climate, biodiversity and crop production. The KPIs selected include site specific thresholds for carbon and nutrient budgets in view of agronomic and environmental targets (for full details, see *D3.1 Overview of existing indicators used in national and European policies*). Since farmers can adjust their management to improve their agronomic and environmental impact, Task 1.3 aims to deliver site specific decision support for the best measures to be applied in order to reach the desired targets.

To guide the appropriate selection of effective measures in view of the agronomic and environmental targets (quantified in KPIs), five steps need to be taken (see Figure 1).

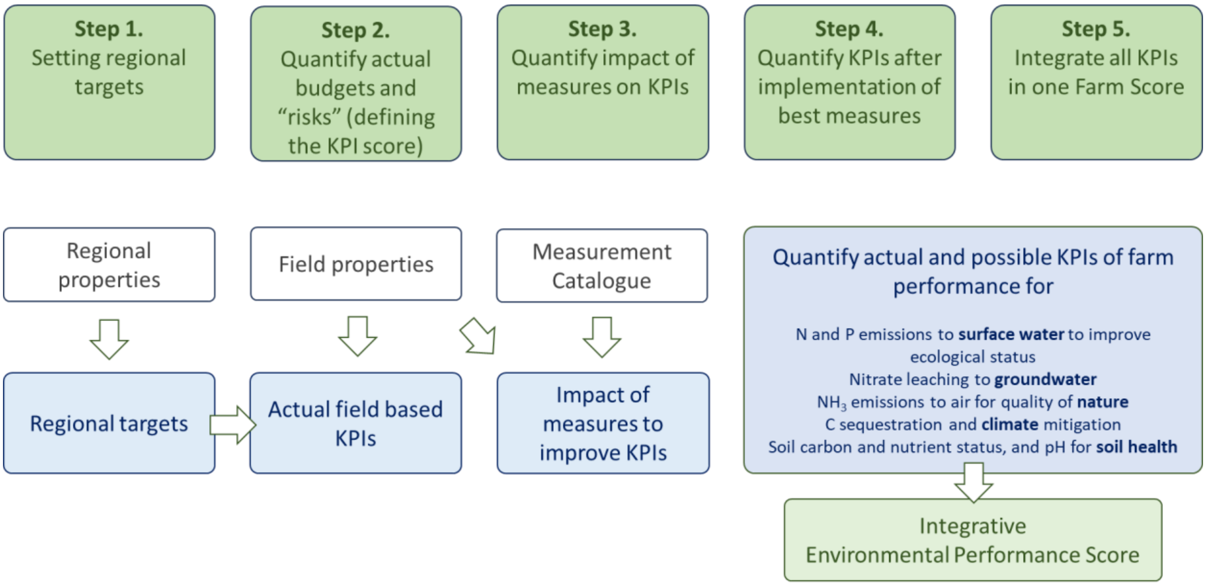

Figure 1. *Model framework to assess the environmental impact of farming systems and to select the most appropriate measures to maximize the sustainability of farming in view of targets for surface water quality, groundwater nitrate concentration, ammonia emission for the biodiversity in nature areas, carbon sequestration for climate mitigation, and soil nutrient status and pH for improvement of soil health.*

These five steps include:

- **set regional targets (step 1)** for the carbon and nutrient budgets in view of targets for effect indicators, such as soil health, including soil carbon and phosphorus status and associated crop yields, air quality, such as ammonia emissions for quality of nature, and water quality, including nitrate leaching (in view of and groundwater quality), and nutrient runoff to surface water (in view of aquatic ecological biodiversity). Here we focus on the contribution of agriculture to these targets knowing that in reality also other sectors contribute to the emissions of nutrients to the environment.
- **quantify the actual carbon and nutrient budgets as compared to targets (step 2)** expressed as distance to target, defined as Key Performance Indicators (KPIs) for agronomic or environmental

effects for all soil types, land uses and farming systems across Europe thereby defining the actual risks (i.e. losses or decline in soil nutrient status). Critical targets have been derived in *D3.2_Report with selected critical KPI with their thresholds*.

- **quantify the potential impact of measures (step 3)** to minimize undesired carbon and nutrient losses or accumulation in soil given their applicability and effectiveness, thereby taken into account the site conditions controlling these risks.
- **quantify the actual and possible KPIs (step 4)** for all fields and farms after **identification of appropriate measures that need to be taken** to reach the desired status for those KPIs (in view of the contribution that agriculture actually can take).
- aggregate the actual performance over the various KPIs into one **integrative score** reflecting the overall farm and field performance in view of the desired targets (step 5).

The results in the current deliverable focus on the measurement impact on a series of selected KPIs for which the meta-regression models have been developed (see D1.2 and D1.3). For each of the KPIs we show the current situation and the desired target while accounting for the spatial variation in soil types, climate and land use (step 1), thereby quantifying the desired distance to targets (step 2), after which we assess the impact of agronomic measures on these KPIs (step 3).

2.2 Upscaling of meta-regression models

Our analysis applies four meta-regression models quantifying the impact of agronomic measures on crop yield, soil pH, SOC, and nitrogen use efficiency (NUE) to showcase how farmers can optimise their crop, soil, fertiliser and water management to reach the desired agronomic and environmental targets.

The evaluation focuses on a series of agronomic practices, including (a) crop management measures such as diversification (by addition of a cover crop, legume crop, extra crop species or green manure into rotation) and crop residue incorporation, (b) soil tillage practices, and (c) multiple fertilisation strategies. These fertilisation strategies include the following measures: (i) combined fertilisation (CF) where organic and inorganic fertilisers are applied in various combinations to supply sufficient nutrients for crop growth as well to improve soil health by organic matter inputs, (ii) organic fertilisation (OF) where (part of the) inorganic fertilisers are completely replaced by organic ones, (iv) the use of enhanced efficiency fertilisers (EE) including controlled release fertilisers and the use of inhibitors to avoid nitrogen losses during the growing season, (v) right fertiliser rate (RFR) where the nutrient dose is adjusted to crop nutrient uptake and unavoidable losses, (vi) right fertiliser timing (RFT) where the nutrient dose is split over multiple gifts to avoid or minimize the occurrence of losses, and (vii) the right fertiliser placement where the default broadcasted application technique is replaced by other techniques such as banding, injecting or incorporation. Impacts of these measures are assessed for indicators of crop productivity, soil quality and environmental losses.

The performances of these measures are evaluated based on minimization of the distance between the current and desired situation, given target values for crop yield and SOC as well as critical limits for N surplus. This distinction between target and limit values is made in order to distinguish between targets that need to be maximized (e.g., crop yield, pH, SOC and NUE) and limits that need to be minimized (e.g., N surplus). Target crop yields were defined as 80% of the water-limited yield potential, or the exploitable yield that can be achieved when crops are grown under optimal nutrient supply and protection against pests, based on cost-effectiveness. National estimates were downscaled to reflect subnational variation from the Global Yield Gap Atlas (Van Ittersum et al., 2013). Targets for SOC were based on the analysis performed by Körschens et al. (1998). Using long-term experiments that began in 1902, they proposed critical limits for SOC for optimum crop production in relation to clay content, ranging from 0.5% SOC at 4% clay to 1.75% SOC at 38% clay. With this approach we recognize the fact that one common or uniform threshold for SOC that limits crop production does not seem appropriate (See D3.2). Critical limits for N surpluses were calculated by multiplying the precipitation surplus with a critical nitrate concentration, divided by the leaching and runoff fractions of the surplus leaching from the root zone. The leaching fraction is calculated as a function of land use, soil type, precipitation surplus and SOC content (de Vries et al., 2020).

Since the impacts strongly depend on the actual management practices being applied, one can derive spatial explicit maps of current practices, following the procedures outlined by Lessmann et al. (2021). This includes spatially explicit data from the Koeppen Geiger classification map (Peel et al., 2007), the spatial production allocation model (SPAM) for land use (Wood-Sichra et al., 2005) or remote sensing derived cropping maps (Ghassemi et al., 2022), maps on N fertiliser application rates (from WP2 or Lu & Tian, 2017), N manure production (excluding transport) and application rates on cropland and grassland (from WP2 or from Xu et al., 2019; Zhang et al., 2017), the global tillage system dataset (Porwollik et al., 2019) and FAO and Eurostat databases on cropping systems, crop residue retention, and crop residue burning (FAO, 2024; Eurostat, 2015; 2020). Combing these maps allows the identification of potential areas for application of agronomic measures related to fertilisation (such as EE, CF, OF, fertiliser placement, fertiliser rate, fertiliser timing, and biochar application), crop management such as residue retention, cover cropping, and crop rotation, as well as soil management including zero and reduced tillage. Spatial explicit information (total numbers at national level) on mineral fertiliser and manure application was taken from INTEGRATOR database for 40.000 Nitrogen Calculation Units (NCUs), which are NUTS3[1] subdivisions of 1x1 km^2 representing unique combinations of soil type, administrative region, slope class and altitude class (De Vries et al., 2011b). INTEGRATOR is a predecessor of the MITERRA-EUROPE model being developed in the NutriBudget project WP2 and used for calculating N balances, N emissions to the atmosphere, and N losses to groundwater and surface water using empirical linear relationships between various N fluxes

Information on tillage and cropping practices were taken from Eurostat farm structure survey databases on management and practices (Eurostat, 2016), where total hectares of arable land area on which each management measure is applied is provided at the level of NUTS2 statistical units (Eurostat, 2020). These are downscaled to NCU level following probability rules following agronomic guidelines. Similarly, current tillage and cropping practices are downscaled from Eurostat to NCU level.

2.3 Data and code availability

All data, algorithms and code to develop and apply the meta-regression models are available as open-source R code on GitHub. These can be downloaded here.

---

[1] To reference countries' regions for statistical purposes, the EU has developed a classification known as NUTS (Nomenclature of territorial units for statistics). NUTS divides each EU country into 3 levels: NUTS 1: major socio-economic regions; NUTS 2: basic regions (for regional policies); NUTS 3: small regions (for specific diagnoses)

3. Results and discussions

3.1. Targets for crop yield, soil pH, SOC and nitrogen surplus

The current situation for the KPIs crop yield, soil pH, SOC and nitrogen surplus are illustrated in Figure 2. Across the EU, current cereal crop yields ranged from 0.8 to 10.7 tons ha^{-1}, maize from 1.5 to 14.4 tons ha^{-1} and root crop from 12.5 to 133 tons ha^{-1} under different soil and climate types (with data derived from the INTEGRATOR database from 2011, illustrated for these three major crops whereas the maps include 20 crops in total). Target yields ranged from 0.8 to 13.8 tons ha^{-1} for cereal, 4.1 to 14.4 tons ha^{-1} for maize, and 15.4 to 133 tons ha^{-1} for root crop, with variation by climate but not soil type. The current value of SOC ranged across all soil types from 0.5% to near 30% for peat soils whereas the target SOC ranges for mineral soils from 1% to 1.5%. The current N surpluses ranged from 0 to 336 kg ha^{-1} while critical N surpluses ranged from 1 to 661 kg ha^{-1}. Due to the fact that N surpluses varied with crop type, estimated impacts of measures on crop yield and N surplus are represented at the NCU level as an area-weighted mean based on the total area per crop. Regarding the soil pH, the pH$_{water}$ varied from 4.9 to 8.3, with more calcareous soils occurring in the Southern part of Europe and the more acidic ones (though still above pH$_{water}$ values of 5, partly due to the presence of forests) occurring the Scandinavian countries as well the eastern part of Europe.

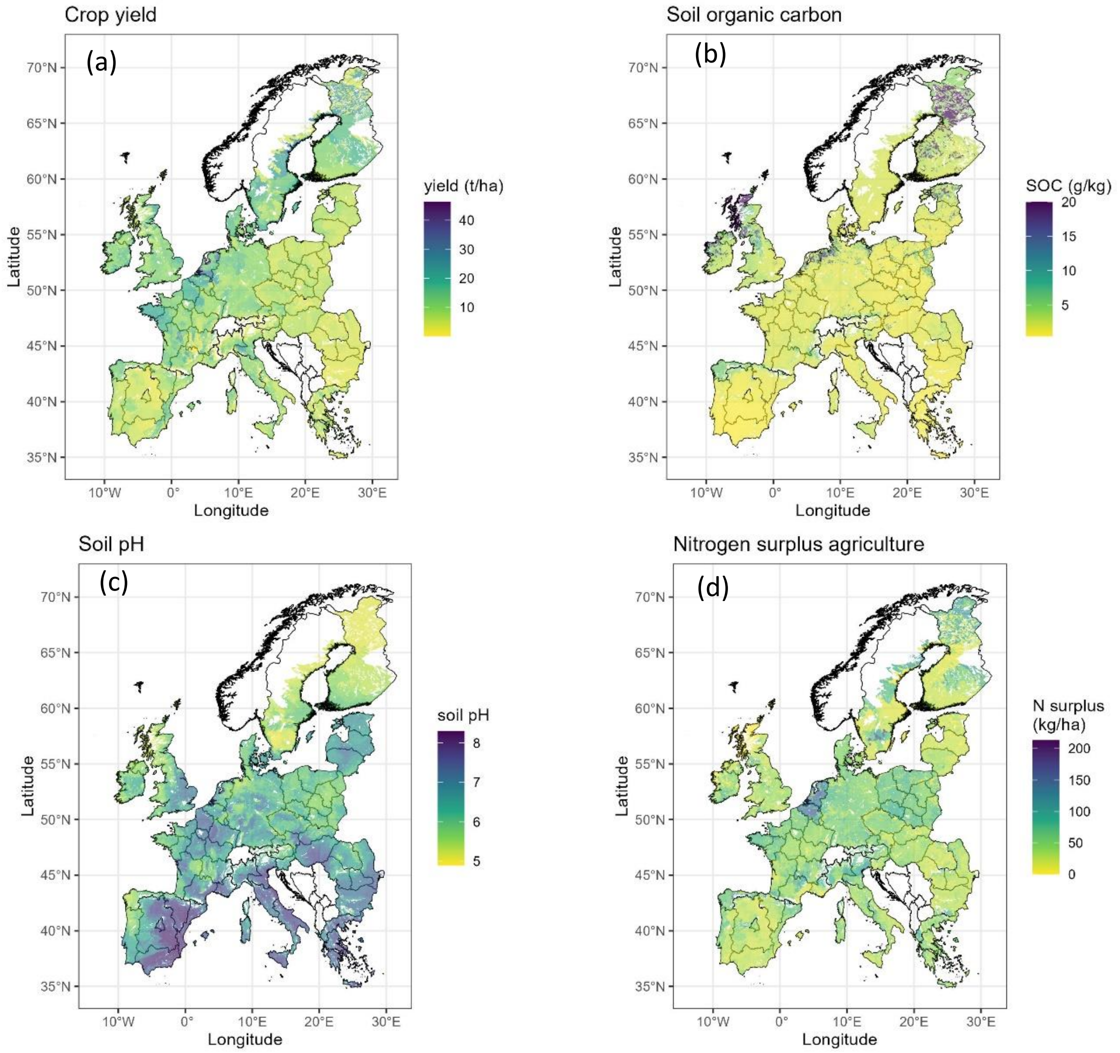

Figure 2. *Spatial variation in the current status of (a) crop yield (ton ha^{-1}), (b) soil organic carbon (g kg^{-1}), (c) soil pH and the (d) nitrogen surplus (kg N ha^{-1}) across Europe.*

The distance to target for the four KPIs is illustrated in Figure 3. Current crop yields were higher in North-western Europe, particularly the Benelux region and western France, as well as parts of Scandinavia, Italy, and the UK (Figure 2). Target yield followed a similar pattern, although targets throughout Eastern and Southern Europe were particularly higher than current yields. The ratio of reference to target yield shows that in North-western Europe, targets are closer to being met (10-20% under targets), while Eastern and Southern Europe in particular have larger gaps, ranging from 30% to 80% below targets (Figure 3). On average, current yield was above target in 13% of NCUs in Europe. Spatial patterns for SOC and distance to desired SOC show a similar patterns across Europe with low SOC values found in Southern and Eastern Europe (Figure 3). The gap to desired levels was on average higher in dry, warmer Mediterranean regions whereas Northern areas of colder, wetter climates were far above desired target levels. Overall, well above half of SOC targets (~65%) are met. There was considerable need to decrease current N surplus across Europe, since only 45% of critical N surpluses were within limits for water quality (Figure 3). Critical limits for N surplus were exceeded in many parts of Europe with main challenges occurring in areas with high livestock numbers per squared kilometre such as Northern/Central regions of France, Benelux, Germany, Poland, and Northern Italy. Compared to the situation for soil pH the majority of the croplands and grasslands had a soil $\mathrm{pH}_{\mathrm{water}}$ value above 5.5 (85%) due to presence of carbonates in the top soil or due to the frequent addition of lime or animal manure being rich in cations, thereby compensating the natural acidification occurring in croplands.

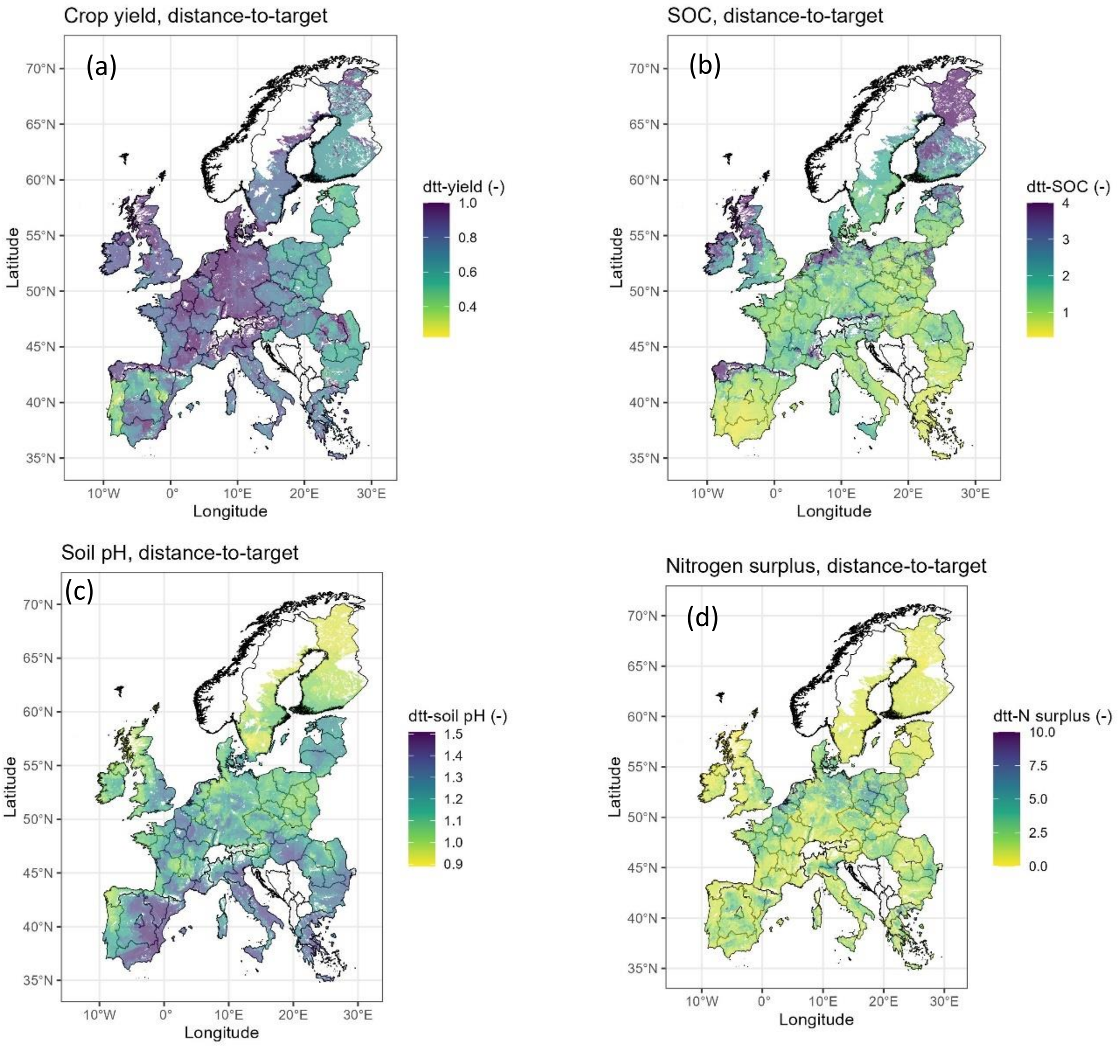

Figure 3. *Spatial variation in the distance to target (dtt-) for (a) crop yield, (b) soil organic carbon, (c) soil pH and the (d) nitrogen surplus across Europe.*

Variation in critical NH_3 emissions in view of biodiversity impacts (being more related to inputs than to nitrogen budgets) are mainly driven by variation in critical loads (i.e., ecosystems' sensitivity to N deposition), and to a smaller extent by variation in the share of agricultural area and the contribution of NOx to N deposition (Schulte-Uebbing et al., 2021). Critical NH_3 emissions are lowest in Spain, Italy, Romania, Bulgaria and Greece whereas the largest exceedances of critical N inputs occur in regions with high N manure inputs and/or low critical NH_3 emissions.

3.2. Impacts of measures on crop yield

The meta-regression model developed to assess the impact of measures on crop yield has been derived from 1227 observations retrieved from scientific publications. The management practices included can be categorised as targeting crop (crop rotation, cover crop, intercropping, and ley), soil (reduced tillage like ridge or strip, biochar application, residue retention, drilling and mulching), and fertilisation (organic fertilisation, drip fertilisation and N or P or K or Mg fertilisation) management.

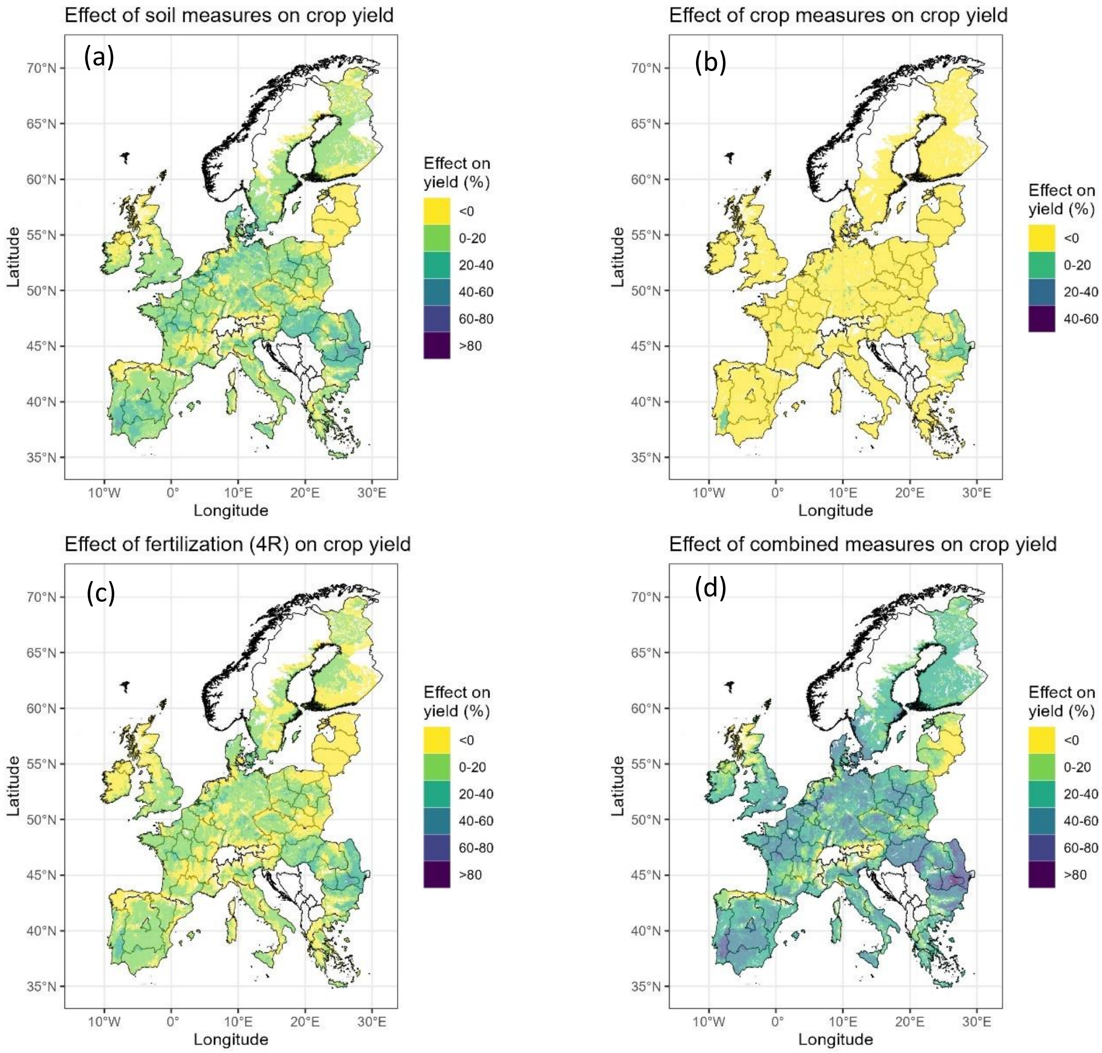

Figure 4. *Spatial variation in the impact of (a) soil, (b) crop, (c) fertiliser and (d) a combination of these practices on crop yield across Europe. The maps show the relative change in crop yield (in %).*

The impact of these categories on crop yields strongly varied. The biggest change in crop yields occur when all three measures are combined, thereby accounting for the applicability of these measures. When combining the measures the crop yields can decrease by 5% up to an increase of 62%. On average the impact is estimated at an increase of 33%. A negative impact was observed for crop measures where in all cases the current yield declined, with an average decline of 18% (not shown), probably explained by tendencies of some crop practices like cover crops taking up the residual nutrients from soil which might hinder arable crop yields, as observed for maize and soybean (Deines et al., 2023). More likely however is that practices as intercropping and more crop diversity will decline the total biomass production by the inclusion of crops that produce less dry matter in the yielded product (e.g. cereal production leads to lower yields than potatoes and sugar beets). The exact reason for the observed decline could not be retrieved from the underlying publications used for the meta-regression model, and requires further analysis. Optimising soil health via soil management increased crop yields on average with 7.5% whereas it varied between -24% up to 32% across Europe. Similar variation was found for fertiliser practices where their impact on crop yield varied from -28% up to 24%.

The current yield is on average lower than the target yield in most of the croplands in Europe: only in 7% of the NCUs the desired target yields are actually achieved. By adopting and implementing a combination of soil, crop and fertiliser practices, the crop yields substantially increased, resulting in 52% of the total area where the target yields are met (Figure 5). This is particularly true in Southern and Eastern part of Europe, suggesting that environmental constraints limit the achievement of target yields there or that more time is required than indirectly assumed from the field trials underlying the data-driven meta-regression model.

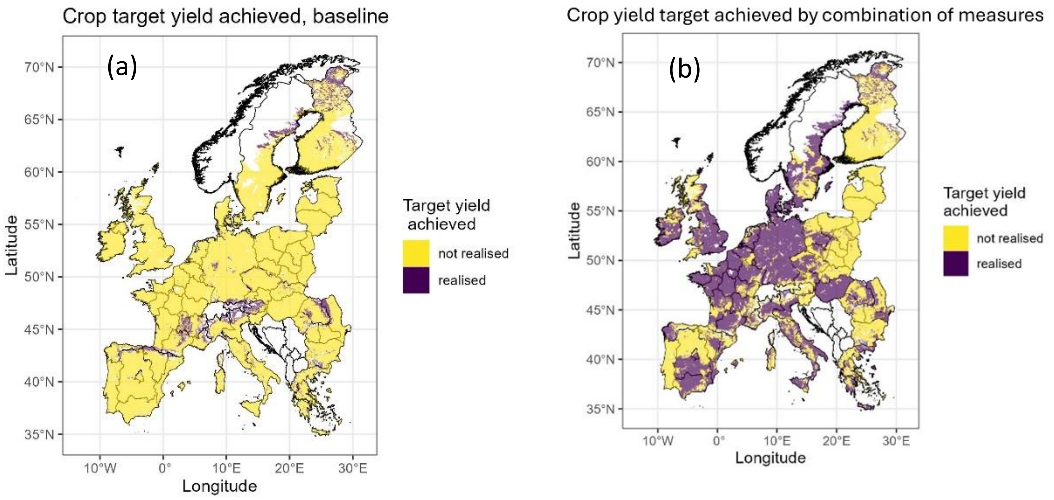

Figure 5. *Spatial variation in the performance of crops across Europe in view of their desired target yields (being realised or not) for the current situation (a) as well the situation after a combination of crop, soil, and fertiliser practices have been optimised (b).*

Note that the nutrient uptake is equally increasing with the management impact on crop yields when evaluating the potential of measures on regional and European scale. This implies that a positive change in crop yield will also benefits the environment, making it easier to reach the defined targets for carbon and nutrient surpluses (see D3.2). Given the fact that the fate of carbon and nutrients is well modelled by the MITERRA-Europe and NutriFarm model using process based algorithms, there is no need to develop meta-regression models for all the surpluses independently.

3.3. Impacts of measures on NUE

An increase in NUE is crucial to reconcile food production and environmental health. Recently, You et al. (2023) assessed the effects of nutrient, crop and soil management on NUE accounting for its dependency on site conditions, including mean annual temperature and precipitation, soil organic carbon, clay and pH, by meta-regression models using 2436 pairs of observations from 407 primary studies. Nutrient management increased NUE by 3.6-11%, crop management by 4.4–8%, while reduction in tillage had no significant impact. Site conditions strongly affected management induced changes in NUE, highlighting their relevance for site-specific practices. We used this meta-regression model to assess the impact of measures on high spatial resolution (1 x 1 km^2) across Europe.

Optimized agricultural management strategies increase NUE and covers a combination of nutrient, crop, and soil management practices. Nutrient management includes fertiliser strategies to increase NUE by synchronizing crop demand and nutrient availability, using the right fertiliser type, with the right rate, at the right time, and at the right place. Examples of the right fertiliser type include enhanced efficiency fertilisers as well as smart combinations of inorganic and organic fertilisers. Crop management can increase NUE by exploiting differences in N uptake efficiencies between crop sequences, and includes diversity in crop rotations, use of cover crops and recycling of crop residues. In addition, soil management has often focused on tillage to reduce soil carbon decomposition, cultivation methods to enhance crop yields, soil biodiversity, and structural stability, and management of organic residues to enhance soil nutrient levels to avoid nutrient deficiencies limiting crop yield.

Using this model we can also estimate the impact of management on the nitrogen surplus, since the N surplus is defined as the N input multiplied by the N fraction not taken up by crops (1 – NUE). For the current report, we therefore describe the impact of agronomic measures on the NUE (Figure 6), where we finally assess its impact on the gap between the current and desired N surplus (Figure 7).

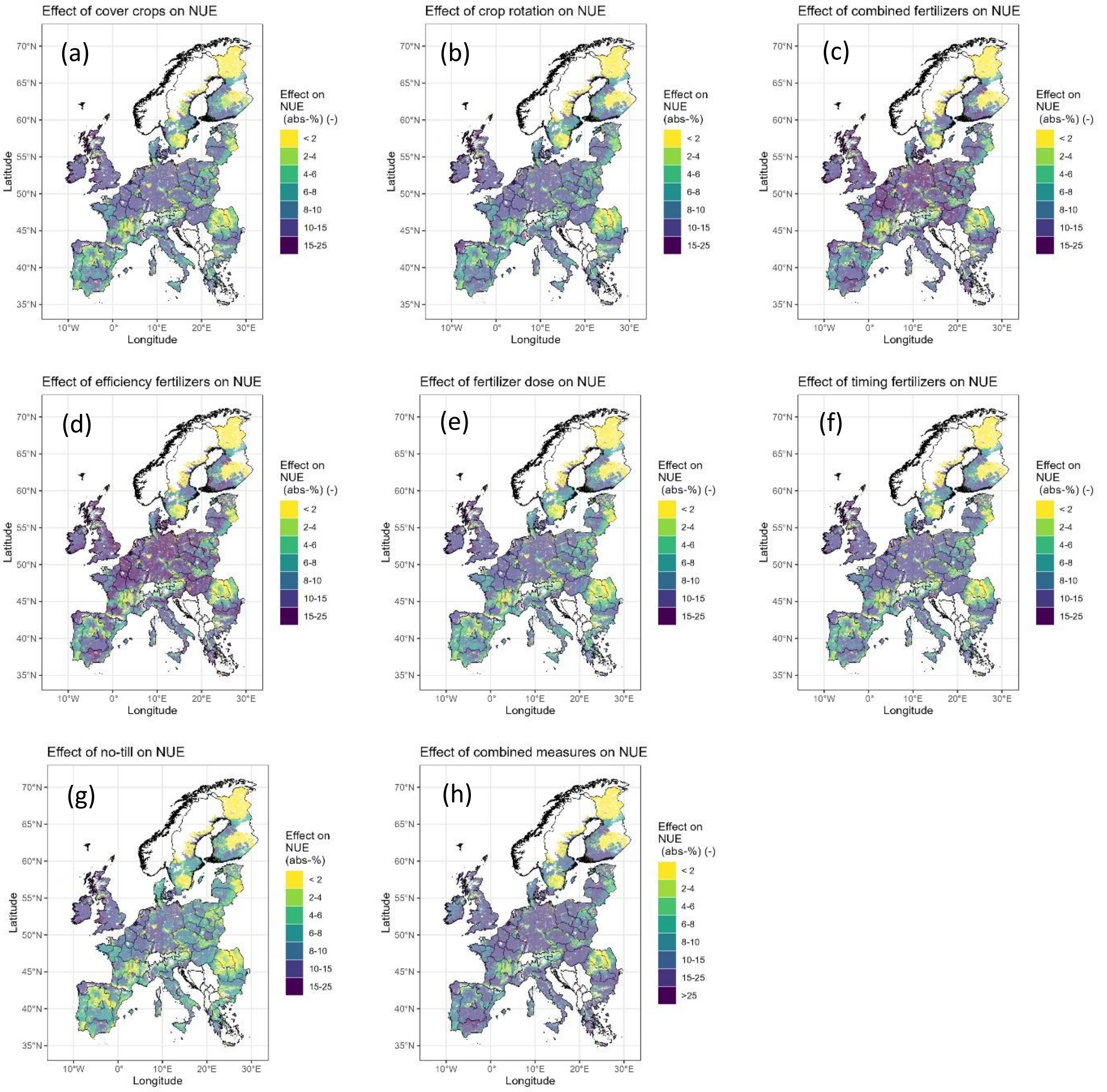

Figure 6. *Spatial variation in the impact of crop (a, b), fertiliser (c, d, e, f), soil (g) and combined practices (h) on NUE in agricultural fields across Europe. The maps show the absolute change in NUE.*

On average, the majority of the management measures had a positive impact on the NUE, with an increase varying from 8.6% for no-tillage up to 13.1% when enhanced efficiency fertilisers are applied (often slow release fertilizers or fertilisers with inhibitors, Figure 6). Across all sites in Europe, the combined practices ranged from 2% up to 24% (Figure 6 g), showing that there is certainly potential to further increase the NUE, thereby reducing the nitrogen surplus and associates losses.

The illustrated impacts of crop, soil and fertiliser measures reveal the potential impact of improved management practices on increasing NUE, in particular when site conditions are accounted for. As expected, sustainable fertiliser strategies had strong and positive effects on NUE, as these practices ensure that crops receive adequate inputs for N during critical crop yield. Applying the right fertiliser rate is an effective measure to reduce excess volatilization, runoff and leaching since the N uptake per unit N applied decreases when N availability is not limiting crop yield. Right timing of fertilisation (e.g., split application and weather-dependent application events) can improve the synchronization of the supply of applied N with crop requirements, in particular in the beginning and final phase of crop growth. Precise placement (e.g., fertiliser injection, fertiliser banding) can increase the N uptake in the rhizosphere and reduce ammonia volatilization, in particular for urea or ammonia-based fertilisers. Similarly, higher NUE values were observed after application of enhanced efficiency fertilisers (Figure 6 d), which can slow N transformation rates to reactive N forms and thereby reduce potential losses. The positive effect of partial substitution of mineral fertilisers with organic fertilisers on NUE agrees with field observations from long-term experiments given the positive impacts of manure on the structure and nutrient retention capacity.

Currently, the majority of croplands had N surpluses exceeding the critical ones needed to sustain and improve good water quality for surface water and groundwater (Figure 7 a). When an optimum combination of measures is applied, the N surpluses will stay below the critical surpluses in 78% of the agricultural land (Figure 7 b).

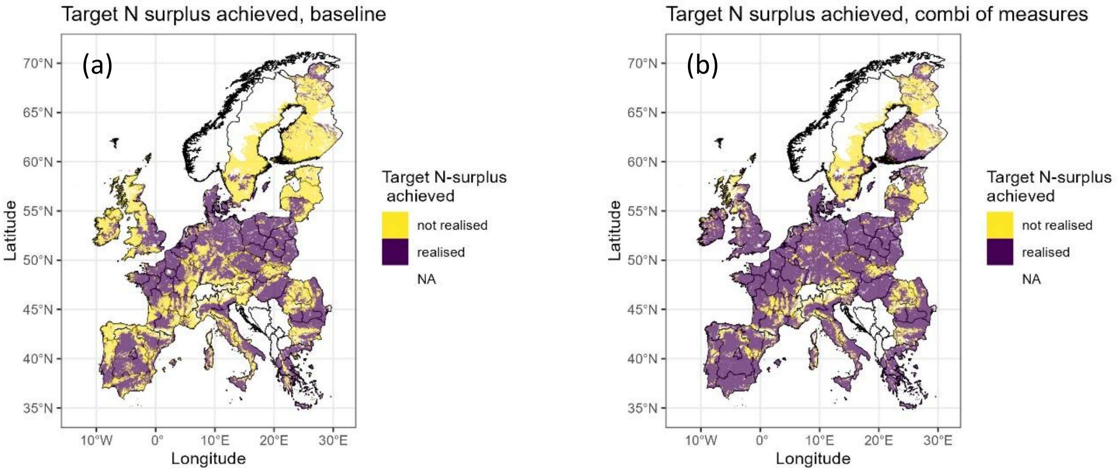

Figure 7. *Spatial variation in the performance of soil N surplus across Europe in view of the desired target for leaching and runoff or nitrogen (being realised or not) for the current situation (a) as well the situation after application of a combination of measures (b).*

3.4. Impacts of measures on SOC

Agricultural soils are under considerable threat due to unsustainable cultivation practices. Excessive fertilisation, intensive tillage and monocultures have led to negative impacts on soil quality, in particular regarding the levels of SOC (Chemnitz & Weigelt, 2015). On global scale, it is estimated that the SOC pool of arable soils is depleted by 25%-75% (Goulding et al., 2013). This loss, which also represents the potential sink capacity to store carbon, indicates that arable soils might have the potential to mitigate climate change by carbon sequestration (Haddaway et al., 2017). In addition, carbon has important functions in moderating soil quality, such as improving water holding capacity and increasing soil biological and physical properties (Goulding et al., 2013). In order to improve the quality of arable soils, agronomic practices such as green manuring and cover crops, substitution of mineral with organic fertilisers, crop residue incorporation and reduced tillage, have been increasingly promoted (Han et al., 2016; Zavattaro et al., 2017).

Using a meta-analysis, it could be identified that SOC variabilities between studies were attributed to the type of tillage management, soil properties and climatic conditions (Haddaway et al., 2017; Virto et al., 2012). The study by Lessmann et al. (2021) showed that fertiliser management could have a pronounced effect on SOC stocks compared to reduced tillage, crop rotation, and residue incorporation. The highest potential for additional carbon storage was found in regions with low crop production, low initial SOC levels, and in regions where livestock manure and crop residues are only partially recycled. Note that soils being low in carbon contents can still be carbon saturated when the maximum saturation potential is reached. In these cases adding more carbon above these thresholds does not make sense since the added carbon will be easily decomposed. When applying the appropriate measures to stimulate carbon sequestration, one should account for the distance to target (as illustrated in Figure 3B).

For the Nutribudget project, we collected data focussing on soil tillage, since the net impact of crop and fertiliser measures on the C fluxes can be well tackled with the processed based models in WP2. Data for changes in SOC under different tillage management practices and a range of agricultural practices and site conditions were collected from 30 different studies in Europe, providing 329 distinct observations. Expectedly, SOC responds positively and significantly to reduced tillage and no-tillage treatments (See D1.3 section 3.2 (under review)). However, stronger and significant estimates are found for residue management, the use of fertiliser, the maintenance of cover crops and the choice of crop. Surprisingly, climatic and soil conditions do not seem to correlate with the tillage and fertiliser induced changes in SOC, being the main management measures included in the database, except for soil bulk density which has a small but significant effect. This implies that the management impacts are rather consistent over the different climate zones.

The impact of these soil tillage practices on SOC are shown in Figure 8. Applying reduced till on all cropland locations where this is appropriate resulted in an averaged increase of 2.4 g kg^{-1}, where it could vary from a decline of 3.5 up to an increase with 6.6 g kg^{-1}. The impact of reduced till had a comparable impact as well the combination of both measures. Note that areas that are currently under reduced tillage can be potentially converted to no tillage, but the other way around is not desirable.

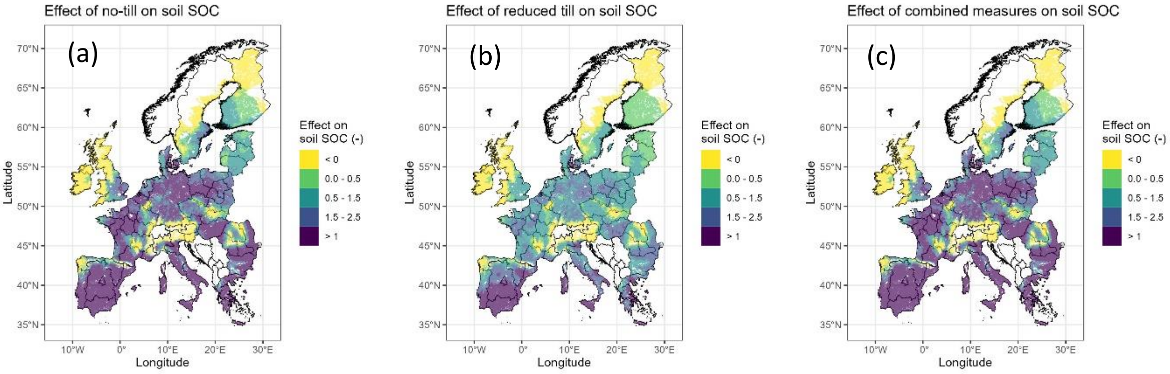

Figure 8. *Spatial variation in the impact of no tillage (a) and reduced tillage (b) practices and a combination of organic manuring and tillage (c) on SOC contents in agricultural soils across Europe. The maps show the absolute change in SOC (in g kg^{-1}).*

Given the fact that the majority of the soils (65%) had already a SOC level being higher than the target value (1%-1.5%, Figure 9 a), the adoption of tillage could allow almost bring all soils (90%) to that target level by changing the soil management (Figure 9 b).

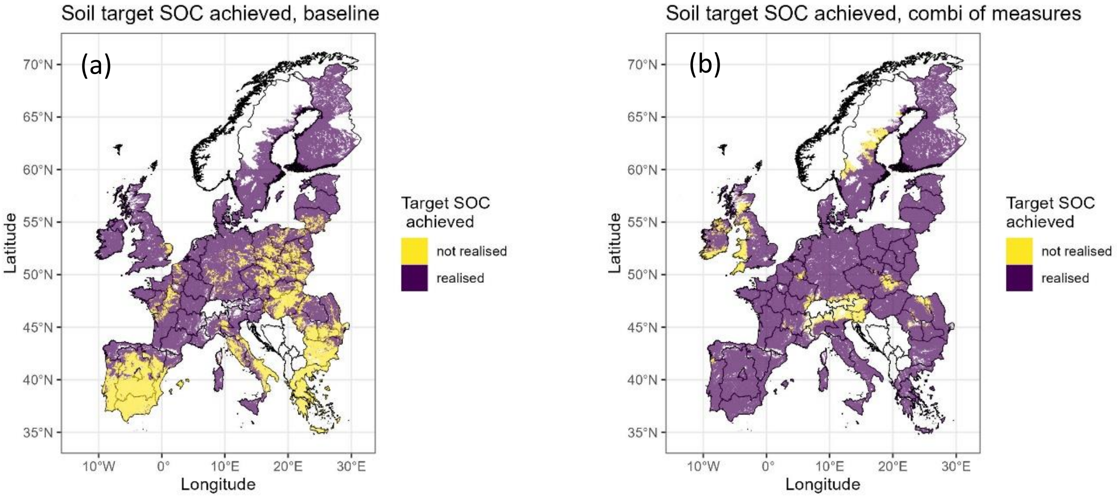

Figure 9. *Spatial variation in the performance of SOC across Europe in view of their desired target SOC levels (being realised or not) for the current situation (a) as well the situation after application reduced and no-till practices (b).*

3.5. Impacts of measures on soil pH

Soil acidification, defined as a decrease in the acid neutralization capacity of the soil (De Vries & Breeuwsma, 1987) is a major issue all around the world. In calcareous soils with a high natural buffer capacity, there is little concern as the pH remains stable and slightly alkaline until all the carbonates are depleted, which depends on their dissolution rate. However, in non-calcareous soils with a low buffer capacity that are sensitive to acidification, especially sandy soils with low organic matter content, soil acidification may cause a relatively fast decline in soil pH and base saturation. Soil pH is an important parameter for soil health as it affects the availability of nutrients and toxic elements (e.g. aluminium, cadmium and other heavy metals). As a consequence, it affects primary productivity and the quality of surrounding water bodies by increasing or reducing, and it affects the habitat function for soil organisms and hence biodiversity (Siciliano et al., 2014).

Soil amendments, including lime, biochar, industrial by-products, manure, and straw are used to alleviate soil acidification. Quantitative insight in the effect of these amendments on soil pH across Europe is limited, hampering their appropriate use. Until now, there is no comprehensive evaluation of the effects of soil amendments on soil acidity, accounting for differences in soil properties. The meta-regression model developed in Nutribudget was derived from 55 observations from 28 unique locations across Europe (See D1.3 Section 3.2 (under review)). Accordingly, the impact of biochar addition (BC), cover crops, no-till, zonation and reduced tillage, lime, and inorganic and organic fertilisation on the change in soil pH was determined in view of the site conditions controlling their effects (Figure 10).

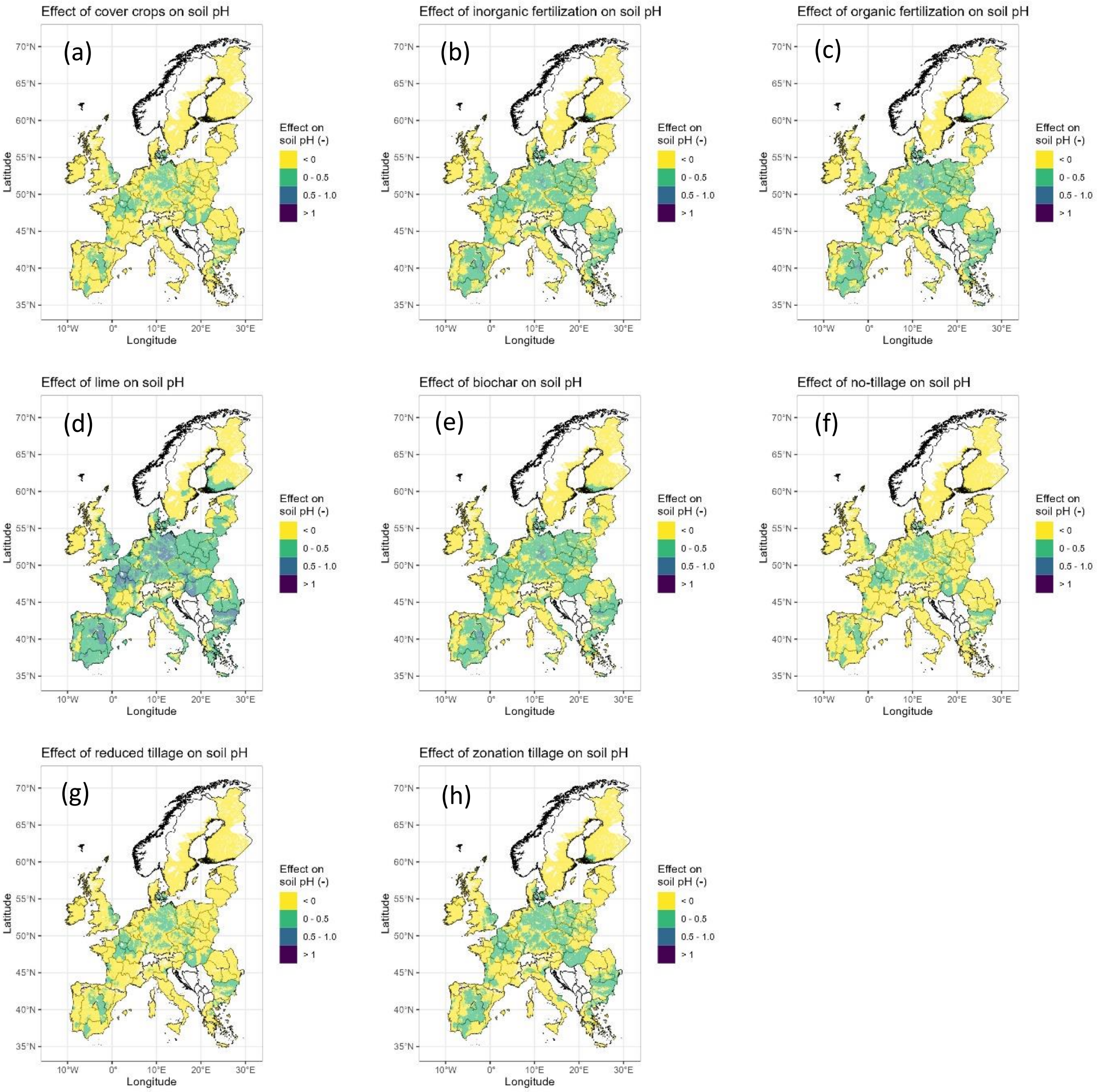

Figure 10. *Spatial variation in the impact of cover crop (a) inorganic (b) and organic fertiliser (c), and soil practices (including liming (d), biochar (e), conventional tillage (f), reduced tillage (g), zonation tillage (h)) on soil pH in agricultural soils across Europe. The maps show the absolute change in soil pH.*

Surprisingly all measures except for lime application (Figure 10 d) had a negative impact (i.e. acidification) on soil pH levels on average but in particular for tillage (Figure 10 f, g, h) and cover crops (Figure 10 a). This might be explained by the low statistical power of the meta-regression model due to the limited number of observations covering the variation in soil, land use and climatic conditions across Europe. The effects of management practices on pH were generally not strongly regulated by site conditions within our dataset, except for initial pH which correlates negatively and significantly with the pH response (higher initial soil pH correlates with weaker response to treatment). Soil organic matter, bulk density, cation exchange capacity and clay content have virtually no significance for the response of soil pH to the implemented measures. The highest response in soil pH was as expected after the soil amendment with lime.

Given the fact that the majority of the soils (96%) had already a pH level being higher than the target value of 5.5 (Figure 11), the addition of lime could allow almost bring all soils (97%) to that target level by changing the soil management. Since the majority of the soils is already above the target level, there is currently only limited lime requirement. Note that this is valued on the resolution of 1 x 1 km^2, thereby averaging the soil properties of individual fields. Surprisingly the pH could not increased up to the target level in the Scandinavian countries, likely due to limited data observations in this region.

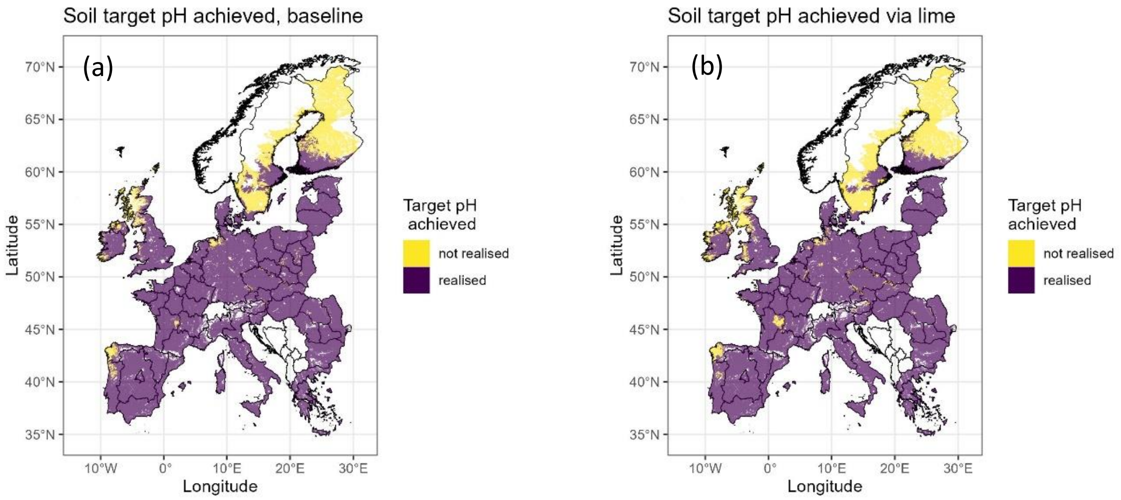

Figure 11. *Spatial variation in the performance of soil pH across Europe in view of the desired target for cropland (being realised or not) for the current situation (a) as well the situation after application of lime (b).*

As mentioned in D1.3 section 3.2 (under review), it was surprising that the meta-regression model did not highlight the role of liming as strongly, which could be due to the low number of liming experiments included in the meta-analysis compared to the relatively large variance of the observed KPI changes. The results therefore indicate that the use of measures to mitigate pH should be adapted to site conditions and consider the strong buffering processes that regulate the long-term responses of soil pH.

3.6. Identification of appropriate measures

This deliverable makes use of meta-regression models which development is being described in deliverables D1.2 and D1.3 without further explanation and elaboration in this report. Shortly, using numerous observations from field trials done in Europe, empirical algorithms have been developed quantifying the change in crop yield, NUE, soil organic carbon content, and soil pH due to the adoption of agronomic management measures. Since the impact of these measures depends on site conditions and the actual crop, soil and water management, we corrected for these controlling factors while applying these empirical algorithms to all agricultural land in Europe. The exact procedure for the application of these models has been underpinned and explained in D1.4, being shortly summarized in section 2.

Given the differences between actual and desired status for crop yield, SOC, soil pH and N surplus, it is not surprising that the best measures (showing the highest improvements) are focusing on reducing the N surplus. The measure having the biggest impact on N surplus is the adaptation of fertiliser type where the use of controlled release fertilisers or inhibitors have the highest potential to reduce the N surplus.

Considering the variation in management impacts as well as targets and limits for crop yield, SOC, pH, and N surplus, it is logical that management predictions show distinct trends or influences by climate, crop and soil type combinations. The heterogeneity in management recommendation outcomes indicates that not one site property acts as a single predictor of management performance. This shows that holistic approaches, capturing the variation in best recommendations for management as a function of many site properties, are preferred above one-dimensionally solutions. Similar to the results of Young et al. (2020) who analysed six farming systems across Europe, we conclude that the use of combined and optimised fertiliser strategies is the best overall practice due to its large reduction of N surplus and its neutral to positive effects on SOC and crop yield. This is logical when considering the synergistic effects of combined sources on crop yield and nutrient use efficiency (macro- and micronutrients from mineral and organic sources, respectively) and SOC (additional organic matter, which is approximately 50% organic carbon, is added from organic sources) (Hijbeek et al., 2017; Janssen, 2002; Pribyl, 2010).

Considering current tools and decision frameworks for agriculture (see D3.1), we find that there is a need for an integrated assessment of synergies and trade-offs of multiple maps on various indicators related to crop yield, soil quality and environmental quality. Such an analysis is relevant to choosing practices that stimulate sustainable agricultural intensification. The meta-analytical regression models illustrated here will further improve the modelled measure-impact relationships and associated roadmaps to improve sustainability of farming systems across Europe (in WP2). The developed algorithms in this deliverable, and their applicability across various farming systems in Europe, show that these data-driven approach can easily be implemented in or used to parameterise other tools such as Nutrifarm to enhance their applicability across multiple farms, soils and regions. Note that data reliability regarding site properties and management controls the estimated impacts in this study. In combination with the process based models the current insights will guide the identification and selection of appropriate measures.

Our developed KPI framework (see D3.1) in combination with the meta-regression models developed (see D1.3 (under review)) highlights the relevance and importance of agricultural measures and allows practitioners and scholars to increase insights into the best management to improve soil and ecosystem functioning, to identify effective measures over multiple environmental objectives, and to quantify the overall environmental performance of agricultural ecosystems. The novelty of the illustrated approach here lies in its simple and reproducible approach, which integrates meta-analytical regression models to quantify synergies and trade-offs among Key Performance Indicators that have traditionally been analysed separately.

.

4. Conclusions and future perspectives

In this deliverable, algorithms were developed to assess the impact of crop-related measures on the response KPIs including crop yield, NUE, SOC and soil pH across various regions in Europe. This approach integrated site-specific data, including soil type, climate, and agricultural practices, to evaluate the impact of management measures on these indicators. By leveraging a comprehensive meta-regression model derived from extensive scientific observations, the study categorized management practices into crop (e.g., rotation, cover cropping), soil (e.g., reduced tillage, biochar application), and fertilisation strategies. The main conclusions are:

- For crop yield, crop management (crop rotation, cover crop, intercropping, and ley) showed a negative effect of 18% while soil management (reduced tillage, biochar application, residue retention, drilling and mulching) led to averagely 7.5% yield increase. A combination of the crop, soil and fertiliser practices was identified as the most effective management, showing an average yield increase of 33%, with the highest effectiveness observed in Southern and Eastern Europe. The optimized practices are supposed to increase the areas achieving targeted yield from 7% to 52% of the NCUs.
- For NUE, both crop and fertiliser management showed a positive effect, ranging from 3.6% to 11%, while soil management (reduced tillage) showed no signifiant impact on NUE. Using enhanced efficiency fertilisers and precision timing increased NUE by up to 13.1%. With optimized practices, 78% of EU agricultural land can achieve the target of N surpluses below critical levels.
- For SOC, soil management practices like reduced tillage positively boost the levels by up to 6.6 g kg^{-1}. Residue management and reduced tillage resulted in significant increases in SOC, particularly effective in low SOC regions. Given that currently 65% of soils are above the target SOC level, the ratio can reach 90% of soils with the implementation of improved management practices.
- For soil pH, most crop, soil and fertiliser measures showed a negative impacted, with liming as the only practice consistently increasing soil pH, particularly in acid-prone soils. Since 96% of soils at EU regions are above the critical pH level of 5.5, application of lime can improve 97% of soils towards the target pH level.

To improve crop yield, NUE, SOC, and soil pH simultaneously, an integrated approach combining nutrient management, diversified cropping systems, and strategic soil management is recommended. Fertiliser practices synchronized with crop demand, such as the use of smart fertilisers and organic amendments, enhance NUE and SOC while supporting crop productivity. Reduced tillage and cover cropping foster SOC sequestration and soil health. Liming should be prioritized in areas prone to acidification to maintain soil pH. By applying these combined measures, it is estimated that target yields could be achieved in 52% of European croplands, with significant improvements in soil quality and nutrient management.

The findings of this deliverable provide critical insights for guiding sustainable farming practices across the EU. By illustrating the spatial variation in agricultural performance and identifying effective management strategies, the study underscores the importance of tailoring practices to regional conditions. Implementing these recommendations can help bridge the gap between current and target yields, improve nutrient management, and enhance soil health, ultimately contributing to the EU's sustainability goals. This data-driven approach in this deliverable supports policymakers and farmers in making informed decisions that optimize agricultural productivity while minimizing environmental impacts, promoting a resilient and sustainable agricultural sector in Europe.

List of references

Abdalla, K., Chivenge, P., Ciais, P., Chaplot, V., 2016. No-tillage lessens soil CO2 emissions the most under arid and sandy soil conditions: Results from a meta-analysis. Biogeosciences, 13, 3619–3633.

Antonopoulos, I. -S., Canfora, P., Dri, M., Pierre, G., Styles, D., Williamson, J., … Price, M., 2018. Best environmental management practice for the agriculture sector -crop and animal production, Brussels, Belgium: Official Journal of the European Union.

Bolinder, M.A., Crotty, F., Elsen, A., Frac, M., Kismanyoky, T., Lipiec, J., Tits, M., Tóth, Z., Kätterer, T., 2020. The effect of crop residues, cover crops, manures and nitrogen fertilisation on soil organic carbon changes in agroecosystems: a synthesis of reviews. *Mitigation and Adaptation Strategies for Global Change,* 25, 929–952.

Camargo, J.A., Alonso, Á., 2006. Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: a global assessment. *Environment international,* 32, 831–849.

Chemnitz, C., & Weigelt, J. (2015). Soil Atlas. Facts and figures about earth, land and fields (pp 1–68). Heinrich-Böll Stiftung, Institute for Advanced Sustainability Studies (IASS). https://www.boell.de/sites/ default/files/soilatlas2015_ii.pdf

Deines, J. M., Guan, K., Lopez, B., Zhou, Q., White, C. S., Wang, S., & Lobell, D. B. (2023). Recent cover crop adoption is associated with small maize and soybean yield losses in the United States. Global change biology, 29(3), 794-807.

De Vries, W. & A. Breeuwsma, 1987. The relation between soil acidification and element cycling. Water, Air, and Soil Pollution 35, 293-310.

De Vries, W., Cellier, P., Erisman, J.W., Sutton, M.A., 2011a. Assessment of nitrogen fluxes to air and water from site scale to continental scale: an overview. *Environmental Pollution* 159, 3143–3148.

De Vries, W., Leip, A., Reinds, G.J., Kros, J., Lesschen, J.P., Bouwman, A.F., 2011b. Comparison of land nitrogen budgets for European agriculture by various modeling approaches. *Environmental Pollution,* 159, 3254–3268.

De Vries, W., Schulte-Uebbing, L., 2020. Required changes in nitrogen inputs and nitrogen use efficiencies to reconcile agricultural productivity with water and air quality objectives in the EU-27., *Proceedings International Fertiliser Society,* 842.

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.

De Vries, W., Schulte-Uebbing, L.S., Kros, H., Voogd, J.C., Louwagie, G., 2021. Spatially explicit boundaries for agricultural nitrogen inputs in the European Union to meet air and water quality targets. *Science of the Total Environment,* 786, 147283.

Djodjic , F., Montas, H., Shirmohammadi, A., Bergstrom,L., Ulen, B. 2002. A decision support system for phosphorus management at a watershed scale. Journal of Environmental Quality, 31 : 937 – 945

Eagle, A.J., Christianson, L.E., Cook, R.L., Harmel, R.D., Miguez, F.E., Qian, S.S., Diaz, D. A.R., 2017a. Meta-analysis constrained by data: recommendations to improve relevance of nutrient management research. *Agronomy Journal*, 109, 1–9.

Eagle, A.J., Olander, L.P., Locklier, K.L., Heffernan, J.B., Bernhardt, E.S., 2017b. Fertiliser management and environmental factors drive N2O and NO3 losses in corn: a meta-analysis. *Soil Science Society of America Journal,* 81, 1191–1202.

EC, 1991. Council Directive of 12 December 1991 Concerning the Protection of Waters against Pollution Caused by Nitrates From Agricultural Sources (91/676/EEC). European Commission, Brussels.

EC, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy. European Commission, Brussels

Eurostat, 2016. Agri-environmental indicator - livestock patterns, available at https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agri-environmental_indicator_-_livestock_patterns, last accessed on 25th July 2024.

Eurostat, 2020. Statistical regions in the European Union and partner countries — NUTS and statistical regions 2021, available at https://ec.europa.eu/eurostat/web/products-manuals-and-guidelines/-/KS-GQ-20-092, last accessed on 25th July 2024.

FAO, 2024. Crop and livestock products. Faostat, available at http://www.fao.org/faostat/en/#data/QC/visualize

Ghassemi B, Dujakovic, A., Zoltak, M., Immitzer, M.,Atzberger C., Vuolo, F., 2022. Designing a European-Wide Crop Type Mapping Approach Based on Machine Learning Algorithms Using LUCAS Field Survey and Sentinel-2 Data. *Remote Sensing,* 14, 541.

Goulding, K., Powlson, D., Whitmore, A., & Macdonald, A., 2013. Food security through better soil carbon management. In R. Lal, et al. (Eds.), *Ecosystem services and carbon sequestration in the biosphere*, (63–78). Dordrecht: Springer.

Groenendijk, P., van Boekel, E., Renaud, L., Greijdanus, A., Michels, R., & de Koeijer, T. (2016). *Landbouw en de KRW-opgave voor nutriënten in regionale wateren: het aandeel van landbouw in de KRW-opgave, de kosten van enkele maatregelen en de effecten ervan op de uit-en afspoeling uit landbouwgronden* (No. 2749). Wageningen Environmental Research. 150 pp. In Dutch.

Haddaway, N.R., Söderström, B., Hedlund, K., Jackson, L.E., Kätterer, T., Lugato, E., Thomsen, I.K., Bracht Jørgensen, H., 2014. What are the effects of agricultural management on soil organic carbon (SOC) stocks? *Environmental Evidence*, 3, 2.

Haddaway, N. R., Hedlund, K., Jackson, L. E., Kätterer, T., Lugato, E., Thomsen, I. K., … Isberg, P. E., 2017. How does tillage intensity affect soil organic carbon? A systematic review. *Environmental Evidence*, 6, 1-48.

Haddaway, N.R., Rytwinski, T., 2018. Meta-analysis is not an exact science: Call for guidance on quantitative synthesis decisions. *Environment international*,114, 357–359.

Han, P., Zhang, W., Wang, G., Sun, W., & Huang, Y. (2016). Changes in soil organic carbon in croplands subjected to fertilizer management: A global meta-analysis. *Scientific Reports*, *6*, 27199.

Heuvelink, G. B. M., Kros, J., Reinds, G. J., de Vries, W., 2016. Geostatistical prediction and simulation of European soil property maps. *Geoderma Regional*, 7, 201–215

Körschens, M., Weigel, A., & Schulz, E., 1998. Turnover of soil organic matter (SOM) and long-term balances - tools for evaluating sustainable productivity of soils. *Zeitschrift für Pflanzenernährung und Bodenkdunde*, 161, 409–424.

Kros, J., Heuvelink, G.B.M., Reinds, G.H., Lesschen, J.P., Loannidi, V. , de Vries W., 2011. Assessment of uncertainties in nitrogen and greenhouse gas fluxes from agro-ecosystems in Europe, 1–2.

Kros, H., Cals, T., Gies, E., Groenendijk, P., Lesschen, J.P., Voogd, J.C., Hermans, T., Velthof, G., 2024. Region oriented and integrated approach to reduce emissions of nutrients and greenhouse gases from agriculture in the Netherlands. *Science of the Total Environment*, 909, 168501.

Kunkel, R., Herrmann, F., Kape, H.E., Keller, L., Koch, F., Tetzlaff, B., Wendland, F., 2017. Simulation of terrestrial nitrogen fluxes in Mecklenburg-Vorpommern and scenario analyses how to reach N-quality targets for groundwater and the coastal waters. *Environmental Earth Sciences,* 76, 1–19

Laane, R.W.P.M., 2005. Applying the critical load concept to the nitrogen load of the river Rhine to the Dutch coastal zone. *Estuarine, Coastal and Shelf Science*,62, 487–493.

Lessmann, M., Ros, G.H., Young, M.D., De Vries, W., 2021. Global variation in soil carbon sequestration potential through improved cropland management. *Global Change Biology,* 28, 1162-1177.

Liu, C., Kroeze, C., Hoekstra, A.Y., Gerbens-Leenes, W., 2012. Past and future trends in grey water footprints of anthropogenic nitrogen and phosphorus inputs to major world rivers. *Ecological indicators*, 18, 42–49.

Liu, C., Zhang, Q., Tao, S., Qi, J., Ding, M., Guan, Q., Wu, B., Zhang, M., Nabil, M., and Tian, F., 2021. A new framework to map fine resolution cropping intensity across the globe: Algorithm, validation, and implication, *Remote Sensing of Environment*, 251, 112095

Loveland, P., Webb, J., 2003. Is there a critical level of organic matter in the agricultural soils of temperate regions: A review. *Soil and Tillage Research*, 70, 1–18.

Lu, C., & Tian, H. 2017. Global nitrogen and phosphorus fertiliser use for agriculture production in the past half century: shifted hot spots and nutrient imbalance. *Earth System Science Data*, *9*(1), 181-192..

Lugato, E., Bampa, F., Panagos, P., Montanarella, L., Jones, A., 2014. Potential carbon sequestration of European arable soils estimated by modelling a comprehensive set of management practices. *Global change biology*, 20, 3557–3567.

Luo, Z., Wang, E., Sun, O. J., 2010. Soil carbon change and its responses to agricultural practices in Australian agroecosystems: A review and synthesis. *Geoderma,* 155, 211–223.

Meurer, K. H. E., Haddaway, N. R., Bolinder, M. A., Kätterer, T., 2018. Tillage intensity affects total SOC stocks in boreotemperate regions only in the topsoil—A systematic review using an ESM approach. *Earth-Science Reviews*, 177, 613–622.

Oldfield, E. E., Bradford, M. A., Wood, S. A., 2019. Global metaanalysis of the relationship between soil organic matter and crop yields. *Soil*, 5, 15–32.

Peel, M. C., Finlayson, B. L., Mcmahon, T. A., 2007. Hydrology and Earth System Sciences Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences*, 11(5), 1633–1644.

Porwollik, V., Rolinski, S., Heinke, J., Müller, C., 2019. Generating a global gridded tillage dataset. *Earth System Science Data Discussions*, 2015, 1–28.

Qin, W., Hu, C., Oenema, O., 2015. Soil mulching significantly enhances yields and water and nitrogen use efficiencies of maize and wheat: A meta-analysis. *Scientific Reports*, 5, 1–13.

Ros, G.H., Verweij, S., Quist, N., Van Eekeren, N., 2020. BedrijfsBodemWaterPlan. Maatwerk voor duurzaam bodem en waterbeheer. NMI, Wageningen, Rapport 1805.N.20, 34 pp. In Dutch. Available at https://www.nmi-agro.nl/wp-content/uploads/2021/01/1805.N.20-BedrijfsBodemWaterPlan-20201205.pdf, last accessed on 25th July 2024.

Ros, G.H., Verweij, S. E., Janssen, S. J.C., De Haan, J., Fujita, Y., 2022. An open soil health assessment framework facilitating sustainable soil management. *Environmental Science and Technology*, 56, 17375–17384.

Ros, G.H, Riechelman, B., Fujita, Y., 2023. Bodemkwaliteit Gelderland. Analyse van knelpunten en oplossingsrichtingen. NMI-report, 73 pp. In Dutch. Available at https://www.nmi-agro.nl/wp-content/uploads/2024/04/1987.N.23-Kwaliteit-Landbouwbodems-in-Gelderland.pdf, last accessed on 25th July 2024.

Rozemeijer, J.C., Van der Velde,Y., van Geer, F.C., Bierkens, M.F.P, Broers, H.P., 2010. Direct measurements of the tile drain and groundwater flow route contributions to surface water contamination: From field-scale concentration patterns in groundwater to catchment-scale surface water quality. *Environmental Pollution*, 158, 3571-3579.

Siciliano, S.D., Palmer, A.S., …, Snape, I., 2014. Soil fertility is associated with fungal and bacterial richness, whereas pH is associated with community composition in polar soil microbial communities. Soil Biology & Biochemistry 78, 10-20.

Sturel, S., Sturel, S, Bampa, F., Sandén, T., Spiegel, H., Madena, K., Brunet, A., Dumontier, A., Berger, C., Fort, J.L., Longueval, C., Barneoud, C., Lombard, M.A., Moulin, J., Henriksen, C.B., Ghaley, B.B., Jones, A., Sullivan, L.O., Vrebos, D., Staes, J., Creamer, R.E., 2018. Report on optimised suites of soil functions, as prioritised by stakeholder groups (D1.2) Available at https://landmarkproject.eu/work-package/work-package-1, last accessed on 25th July 2024.

Tonitto, C., David, M.B., Drinkwater, L.E., 2006. Replacing bare fallows with cover crops in fertiliser-intensive cropping systems: a meta-analysis of crop yield and N dynamics. *Agriculture, Ecosystems and Environment*, 112, 58–72.

Van Doorn, M., van Rotterdam, D., Ros, G.H., Koopmans, G.F., Smolders, E., De Vries, W., 2023. The phosphorus saturation degree as a universal agronomic and environmental soil P test, *Critical Reviews in Environmental Science and Technology*, *54*(5), 385-404.

Van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P. & Z. Hochman, 2013. Yield gap analysis with local to global relevance—A review. Field Crops Research, 143, 4-17. doi: 10.1016/J.FCR.2012.09.009

Velthof, G.L., Oudendag, D., Witzke, H.P., Asman, W.A.H., Klimont, Z., Oenema, O., 2009. Integrated Assessment of Nitrogen Losses from Agriculture in EU-27 using MITERRA-EUROPE. *Journal of Environment Quality,* 38, 402.

Venterea, R. T., Coulter, J. A., Dolan, M. S., 2016. Evaluation of intensive “4R” strategies for decreasing nitrous oxide emissions and nitrogen surplus in rainfed corn. *Journal of Environmental Quality*, 45, 1186–1195.

Virto, I., Barré, P., Burlot, A., & Chenu, C. (2012). Carbon input differences as the main factor explaining the variability in soil organic C storage in no-tilled compared to inversion tilled agrosystems. *Biogeochemistry*, *108*(1–3), 17–26.

WHO, 2011. Nitrate and Nitrite in Drinking-water. Background Document for Development of WHO Guidelines for Drinking-water Quality. Report No. WHO/SDE/WSH/07.01/16/Rev/1. Geneva.

Wood-Sichra,U., Joglekar, A. B., You, L. , 2016. Spatial Production Allocation Model (SPAM) 2005: Technical Documentation. HarvestChoice Working Paper. Washington, D.C.: International Food Policy Research Institute (IFPRI) and St. Paul: International Science and Technology Practice and Policy (InSTePP) Center, University of Minnesota.

Xu, R., Tian, H., Pan, S., Dangal, S. R. S., Chen, J., Chang, J., Lu, Y., Maria Skiba, U., Tubiello, F. N., Zhang, B., 2019. Increased nitrogen enrichment and shifted patterns in the world's grassland: 1860–2016. *Earth System Science Data*, 11(1), 175–187

You, L., Ros, G.H., Chen, Y., Shao, Q., Young, M.D., Zhang, F., de Vries, W., 2023. Global mean nitrogen recovery efficiency in croplands can be enhanced by optimal nutrient, crop and soil management practices. *Nature Communications*, 14, 5747.

Young, M.D., Ros, G.H., de Vries, W., 2020. A decision support framework assessing management impacts on crop yield, soil carbon changes and nitrogen losses to the environment. *European Journal of Soil Science*, 72, 1590-1606.

Young, M.D., Ros, G.H., de Vries, W., 2021a. Impacts of agronomic measures on crop, soil, and environmental indicators: a review and synthesis of meta-analysis. *Agriculture, Ecosystems and Environment*, 319, 107551.

Young, M.D., Ros, G.H., de Vries, W., 2021b. Impacts of agronomic measures on crop, soil, and environmental indicators in European agriculture: a review of meta-analys2s. *IFS Proceedings,* 870, 56 pp.

Zavattaro, L., Bechini, L., Grignani, C., van Evert, F. K., Mallast, J., Spiegel, H., Sandén, T., Pecio, A., Giráldez Cervera, J. V., Guzmán, G., Vanderlinden, K., D'Hose, T., Ruysschaert, G., ten Berge, H. F. M., D'Hose, T., Ruysschaert, G., & ten Berge, H. F. M., 2017. Agronomic effects of bovine manure: A review of long-term European field experiments. *European Journal of Agronomy*, *90*, 127–138.

Zhang, B., Tian, H., Lu, C., Dangal, R. S. S., Yang, J., Pan, S., 2017. Global manure nitrogen production and application in cropland during 1860–2014: a 5 arcmin gridded global dataset for Earth system modeling. *Earth System Science Data*, *9*(2), 667-678.

Zhang, M., Wu, B., Zeng, H., He, G., Liu Ch, Tao, S, …, Liu, Y, 2021. GCI30: a global dataset of 30 m cropping intensity using multisource remote sensing imagery. *Earth System Science Data Discussions* 2021 13, 4799-4817.

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