Optimisation of nutrient budget in agriculture

D1.2 Quantified measure-impact relationship of selected measures - initial version

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	(iii) Chapter 3 "Expected outcomes and potential challenges" was updated with conclusions (impact) of this deliverable and suggested mitigation strategies for the potential risks. The Chapter 3 is now called "Conclusions and next steps"
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Preface

Deliverable (D) 1.2 *"Quantified measure-impact relationship of selected measures - initial version"* is part of outcomes from Task 1.2 in Work Package (WP) 1 of the NutriBudget project, funded by the 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", applicable in various regions across Europe. NutriPlatform will operate as a decision-support tool for farmers, advisors, and regional and national authorities. Before the end of the project, "NutriPlatform" (as a stand-alone or integrated into 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.

WP1, titled *"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. Based on an inventory of effective mitigation measures in Task 1.1, the objective of Task 1.2 is to further quantify the impact of the selected measures on specific indicators from WP2/WP3. This deliverable, as an initial version of the results from Task 1.2, aims to establish a protocol for a meta-analysis to quantify the measure-impact relationship of selected mitigation measures to improve nutrient use efficiency and nutrient budgets on specific agronomic and environmental indicators selected in WP2/WP3. The protocol in this deliverable will guide the development of meta-regression models in a later stage of Task 1.2, which will also serve for the development and application of algorithms in Task 1.3, which will evaluate the spatial applicability of selected measures.

Executive Summary

The intensification of 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 poses risks to water quality, particularly affecting vulnerable populations. Moreover, the 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 an integrated nutrient management platform, called NutriPlatform, as a decision support tool to intensify agriculture sustainably, ensuring optimal yields without compromising the environment or human health. Efforts have been made in WP1 to provide an overview of relevant agronomic mitigation measures contributing to agricultural sustainability and impact-specific information (environmental performance related to nutrient use efficiency and losses, among others), which resulted in a 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, Task 1.2 aims to further quantify the impact of the measures on selected indicators from WP2/WP3. These impact indicators will be selected based on interactions with WP2 and WP3, as well as WP4 for measures experimentally investigated in the project's pilot cases. Long-term field experimental data across Europe will be collected from existing research publications and databases for the selected measures. By generating a meta-analysis of the selected measures, this task will evaluate their impact response in terms of selected indicators that reflect the relationships between agriculture and the environment regarding nutrient balances, flows, and losses.

Deliverable D1.2, presented in this document, is divided into four Chapters. **Chapter 1** introduces the nutrient challenge in agriculture 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 a methodology to perform meta-analyses based on existing research data. A more detailed protocol is presented in **Chapter 3** with the main focus on three steps: i) defining the research questions and indicators to quantify the measure-impact relationship; ii) defining criteria for data collection; iii) developing the meta-regression models. Finally, **Chapter 4** describes the expected outcomes, potential risks and mitigation strategies.

The rigorous and comprehensive methodology established in this deliverable offers valuable insights for both the NutriBudget project and the wider field of sustainable agriculture. The initial outcomes, encapsulated in D1.2, establish the methodological foundation for the development of meta-regression models to assess the impact of various farm practices and agronomic measures on nutrient balances, flows, and losses. This approach elaborates the mitigation measures identified in Task 1.1, the selected indicators from WP2 and WP3, as well as the collected data in Task 1.4, providing a quantified assessment on the impact of these measures. Linkage between these tasks underscores the iterative nature of this research, where each deliverable builds upon the previous ones to progressively refine our understanding of the measure-impact relationships. By systematically quantifying the impact of mitigation measures, this methodology could facilitate further understanding and optimisation of nutrient management in agriculture, meanwhile supporting the spatial evaluation of the measures in Task 1.3. Beyond the immediate project scope, these methodologies could be adapted and applied to future studies or initiatives with similar aims.

The final output of Task 1.2, i.e. the D1.3 - Quantified measure-impact relationship of selected measures, will present the detailed results and conclusions of the meta-regression models, providing a

robust foundation for future research and practical applications in sustainable agriculture. The insights gained from these deliverables (D1.2 and D1.3) can directly inform the calibration and validation of measure-impact evaluation using empirical and process-based models in WP2.

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List of Abbreviations

AB	Abstract
AIC	Akaike information criterion
CO_2	Carbon dioxide
CH_4	Methane
D	Deliverable
DoA	Description of the Action
EU	European Union
GHG	Greenhouse gas emissions
lnRR	Log-transformed response ratio
MD	Mean difference
MMC	Mitigation Measures Catalogue
N_2	Nitrogen gas
N_2O	Nitrous oxide
NH_4	Ammonium
NH_3	Ammonia
NO	Nitric oxide
NO_2	Nitrite
NO_3	Nitrate
NUE	Nutrient use efficiency
RQ	Research question
SD	Standard deviation
SMD	Standard mean difference
SOC	Soil Organic Carbon
TI	Title
TS	Topic
WP	Work package

1. Introduction

Agricultural management practices play a pivotal role in shaping crop production, soil quality, and related environmental impacts (Girardin et al., 2000; Schulte et al., 2017; Young et al., 2021). Numerous practices have been demonstrated to positively impact crop yield and soil fertility, with examples like crop covers enhancing crop yields (Young et al., 2021), and organic amendments increasing soil pH and crop yield in strongly acidic, sandy soils that have a low acid buffer capacity (Zhang et al., 2023). However, these practices may also have negative consequences, including decreased nutrient use efficiencies and increased emissions of greenhouse gases (GHG) such as CO_2, CH_4, and N_2O (Bathaei & Štreimikienė, 2023; Young et al., 2021). Animal management practices, like manure application, contribute to elevated NH_3 emissions, exacerbating environmental concerns (Montes et al., 2013; van der Weerden et al., 2021). The nutrient losses to air and water remain significant challenges in agricultural systems, leading to issues such as air pollution, water pollution, eutrophication, biodiversity loss, and soil degradation.

Preventing the adverse effects of nutrient pollution depends on the judicious use of agricultural practices, which requires a focus on the effects and improvements in the efficiency of nutrient use, especially nitrogen (N) and phosphorus (P). Optimizing agricultural practices involves considering trade-offs and co-benefits between agronomic, soil fertility, and environmental indicators based on site-specific properties. Significant research efforts have been made in quantifying the impact of different agricultural practices on a spectrum of indicators, such as crop yields and nutrient uptake (Abalos et al., 2014; Cheng et al., 2023), soil fertility indicators spanning carbon (Lessmann et al., 2022) and phosphorus status (Daryanto et al., 2017), and soil acidity (Zhang et al., 2023), but also environmental indicators encompassing nutrient losses or surplus and GHG emissions (Maaz et al., 2021; De Vries et al., 2023). Nevertheless, the existing body of research often presents a notable limitation — it tends to be confined to individual agricultural practices and single indicators. The consequence is a gap in our comprehension of the intricate relationship between potential trade-offs and co-benefits that might unfold across a tapestry of indicators. Moreover, there is a noticeable gap in studies exploring the impact of measures designed to enhance nutrient use efficiency in animal husbandry and mitigate environmental consequences in the agro-processing systems, which is a limitation that the project seeks to transcend.

Furthermore, the impacts of agricultural practices are highly contingent on site-specific properties (Velthof & Rietra, 2018; Zhang et al., 2023), 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 influencers on the outcomes of agricultural interventions. For instance, a practice like minimal tillage might cause higher emissions of N_2O in tropical climates compared to subtropical ones, underlining the significance of climate considerations (Young et al., 2021). Similarly, the emission patterns of N_2O might diverge between arable croplands in wet Scottish sites and drier English sites due to climate disparities (Velthof & Rietra, 2018). These variations underscore the necessity of accounting for these site-specific factors to bolster the predictive accuracy of the impacts of agricultural practices across diverse locations.

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 1.2, quantifying measure-impact relationships, emerges as the natural progression, delving deeper into the evaluation of the measures identified in Task 1.1. This includes the quantification of their impact on specific indicators from subsequent WPs (WP2 and WP3). What unfolds in Task 1.2 is a meticulous meta-analysis of long-term field experimental data, a sophisticated approach with proven advantages in summarizing and comparing various quantification results. To this end, the data collected in the MMC (D1.1) during the primary stage of Task 1.1 provides the necessary stat-of-the-art and research database for the pre-identified measures in this project. Moreover, the outcome of Task 1.4, i.e. *D1.4 “A matrix of data/measurement”* specifically focuses on the innovative measures that were selected for experimental test in WP4, ensuring that the meta-analysis conducted in Task 1.2 is informed by the latest data and measurement techniques, thus enhancing the accuracy and relevance of the impact quantification.

The initial version of the outcomes from Task 1.2, encapsulated in D1.2, is primarily concerned with laying the methodological foundation for the meta-analysis. It serves as a precursor, establishing the framework for the comprehensive quantification of measure-impact relationships anticipated in D1.3. The expected outcome of Task 1.2 is a quantified elaboration on the measures that indicate quantified impact response in terms of selected indicators that reflect the (algorithmic) relationship between agriculture and the environment regarding nutrient balances, flows and losses. Building on the established methodology in this deliverable and the database in Task 1.1 and Task 1.4, D1.3 will present the meta-regression models developed to quantify the agronomic and environmental impact of a broad range of available farm-practices and agronomic measures on the selected indicators from WP2/3. The insights from Task 1.2 (including D1.2 and D1.3) not only contribute to a refined understanding of how these measures impact selected indicators, but also offer a granular perspective, considering site-specific properties across diverse agricultural systems, regions, and countries. This perspective is further explored in Task 1.3, which assesses the applicability and efficiency of measures based on agro-ecological site-specific factors, aiming to align with sustainable agriculture objectives.

2. Methodology

Meta-analysis is a statistical methodology that integrates information from numerous independent studies to conduct a comprehensive and amalgamated examination of the overall effect or relationship between variables. It entails the systematic collection and analysis of data across multiple studies, facilitating the derivation of robust conclusions and the formulation of generalizations.

In essence, a meta-analysis consistently concentrates on the analysis of the influence of a given treatment, denoted as X, on a specific variable, denoted as Y. The primary inquiry revolves around elucidating how variable Y undergoes changes attributable to the application of treatment X. The quantified alteration is commonly referred to as an "effect size," representing either a relative or absolute change. Analogous to conventional regression models, meta-analysis enables the estimation of the impact of covariates such as site properties through the amalgamation of effect sizes.

The procedural sequence of a meta-analysis encompasses **eight distinct steps**:
1. Defining the research question of interest
2. Defining the study selection criteria
3. Collecting data from literature, and extend with open data where needed
4. Selecting and computing the effect size
5. Aggregating effect sizes per main factor
6. Executing meta-regression analyses to quantify the influence of main factors and their interactions
7. Visualising impact of main factors and interactions
8. Applying the regression model on a new dataset

In this deliverable, a protocol is established to tailor the 8 steps of meta-analysis for the quantification of measure-impact relationships of selected measures in the NutriBudget project. Commonly applied and studied mitigation measures will be selected from the literature to build the meta-regression models. These models will be conceptualised based on the selected mitigation measures in crop, soil, or animal/processing systems to evaluate their impact on crop and animal productivity, soil quality and environmental sustainability. Additionally, the pre-identified mitigation measures in the MMC (see D1.1 first draft) will be analysed using the data collected in Task 1.1. Up to date, there are 22 pre-identified mitigation measures, among which 16 fall under the crop production pillar, 9 under animal husbandry and 4 under agro-processing, with some measures included in two or three pillars. Within each pillar, the measures differ in the focus and therefore have different baselines and indicators to quantify the impact of treatments.

2.1 Defining the research question of interest

On the basis of Task 1.1 - MMC and Task 1.4 - State-of-the-art of the innovative measures, Task 1.2 evaluates the identified measures contributing to the nutrient budget within and between the three agro-pillars, i.e. crop production, animal husbandry, agro-processing industries. These measures encompass a spectrum of practices spanning fertiliser, soil, crop, animal feeding and housing, as well as manure processing management. The focus is on unravelling the nuanced impact of these measures on specific indicators outlined in subsequent work packages (WP2 and WP3).

As stated in D1.1 Mitigation Measures Catalogue - first draft version, indicators relevant to the agronomic and environmental impact of mitigation measures have been categorized as follows: agro-ecosystem properties, pressure indicators, effect indicators, and performance indicators. Among them, four of the key performance indicators (KPIs, listed in Table 1) are selected as the main focus of the quantification in Task 1.2, which will also be simulated by the NutriModels that will be developed in WP2 based on the existing process-based models, e.g. MITERRA-Europe and MITERRA-Farm from the Nutri2Cycle project.

Table 1 *Key performance indicators selected as the main focus in Task 1.2 Quantification of measure-impact relationship*

Class	Key Performance Indicator	Description	Relevant agro-pillars
P3	Nutrient Surplus Gap	Gap between current and target/critical nutrient surplus, derived as the soil C and nutrient status gap (indicator P1) divided by a target time plus unavoidable or critical losses.	• Crop production • Animal husbandry • Agro-processing
P5	Nutrient Use Efficiency (NUE)	The ratio of nutrient uptake divided by the nutrient inputs	• Crop production • Animal husbandry
P8	Farmgate C, N and P Efficiency Gap	Gap between current and target farm gate balances for C, N and P.	• Crop production • Animal husbandry • Agro-processing
P9	Soil Quality Index (focus on SOC and pH)	An index reflecting the distance to target for optimum soil health given the OSI framework (or adapted version of it)	• Crop production

- **P3_Nutrient Surplus Gap:**

This KPI serves as a linchpin in gauging the disparity between the existing and target/critical nutrient surplus. It holistically encapsulates the nutrient budget, derived from the soil carbon and nutrient status gap, further divided by a target time plus critical losses. The Nutrient Surplus Gap is of paramount importance across the agro-pillars—crop production, animal husbandry, and agro-processing— offering a comprehensive view of nutrient imbalances.

- **P5_Nutrient Use Efficiency (NUE):**

NUE, another focal KPI, stands as a vital metric capturing the efficiency with which crops and animals utilize nutrients. For crop production and animal husbandry, this KPI represents the ratio of nutrient uptake to nutrient inputs, offering critical insights into resource utilization and the risk of ecosystem loading and losses to the environment. It is instrumental in discerning the efficacy of mitigation measures in optimizing nutrient use of crop or animal systems.

- **P8_Farmgate C, N, and P Efficiency Gap:**

This KPI, tailored for the farming system integrating crop production, animal husbandry and agro-processing industries, emphasizes the disparity between the current and target farm gate balances for carbon (C), nitrogen (N), and phosphorus (P). It provides a nuanced perspective on nutrient efficiency at the farm level, acknowledging the broader implications of nutrient management strategies in the context of sustainability.

- **P9_Soil Quality Index:**

The Soil Quality Index, focusing on soil organic carbon (SOC) and pH, serves as a comprehensive measure reflecting the proximity to optimum soil health. Aligned with the NutriBudget project's emphasis on sustainable soil management, this KPI provides a robust indicator of soil health, vital for sustaining crop production.

Accordingly, the research questions (RQs) are defined as followings:

RQ1: What is the impact of the selected mitigation measures (e.g. **crop, soil and fertiliser management**) on **nutrient surplus (P3) and nutrient use efficiency (P5) by crop?**

RQ2: What is the impact of the selected mitigation measures (e.g. **crop, soil and fertiliser management**) on **soil quality (P9)**?

RQ3: What is the impact of the selected mitigation measures (e.g. **animal feed management**) on the **nutrient use efficiency by animals (P5)?**

RQ4: What is the impact of the selected mitigation measures (e.g. **manure processing technologies**) on the **farmgate C, N and P efficiency (P8)**?

The selected mitigation measures for each research question are specified in the subsequent steps.

2.2 Defining selection criteria

In order to ensure a rigorous and comprehensive meta-analysis, a set of stringent criteria is established for screening individual studies. This may include research focus, data availability of KPIs, spatial coverage, duration of studies, geographic locations and other basic site properties. In essence, the specified selection criteria embody the contemporary relevance and innovative nature of the identified management practices, underscoring their pivotal role in addressing the intricacies of nutrient management within diverse agricultural systems.

Therefore, a series of criteria is meticulously designed to refine the selection process and enhance the reliability of the synthesized data:

- **Research Focus**: Studies must explicitly incorporate one or more of the identified management practices outlined in Table 2 and Table 3. Each selected study should address at least one of the KPIs corresponding to the relevant research question.
- **Data Availability**: Inclusion of studies necessitates the availability of mean values (with unit) and standard deviation for both the treatment and control (as listed in Table 2 and 3). The number of replicates for both treatment and control groups should be preferably known, ensuring robust statistical analysis.
- **Spatial Coverage**: Emphasis is placed on studies conducted within Europe or comparable climate zones. This criterion ensures a contextual relevance to the NutriBudget project's focus on European agricultural systems.
- **Type and Duration**: For the crop production pillar, exclusive consideration is given to field experiments. These experiments should span a defined duration to capture the temporal dynamics of the impact of management practices. In the context of animal production and agro-processing pillars, studies conducted at the farm level are included, and it is required that these studies encompass at least one complete life cycle to account for comprehensive impact assessment. Note that the desired duration also depends on the turnover time / fate of the element in the agroecosystem, e.g. the desired duration is assumed to be longer for C than P and N.
- **Site properties**: Studies selected for meta-analysis should provide essential information regarding basic site properties. This includes but is not limited to details such as soil characteristics, climatic conditions, and other relevant experimental settings.

2.2.1 Crop and soil management

For RQ1 and RQ2, the targeted management practices are pivotal in shaping nutrient dynamics in crop production systems, including crop, soil, and fertiliser management. Table 2 lists the selected management practices in categories:

- **CROPB**: refers to the crop management practices aiming for biomass production, including crop rotation in the manner of multi-cropping (MCR, referring to cultivation of two or more crops in the same field during one year, see Table 2) or inter-cropping (INC, referring to cultivation of two or more crops simultaneously on the same field), cover cropping or catch cropping (CC, referring to cultivation of non-cash crops to cover the soil rather than for the purpose of being harvested). The associated control is mono-cropping without cover crop.
- **CROPE**: refers to the crop management practices aiming for reducing nutrient emissions, including legume cultivation (LG), deep-rooting crop (DRC), crop residual retention (RR, referring to mulching, retaining or incorporating crop residues after harvest, see Table 2). The associated control is conventional practice, e.g. without legume, cultivated with shallow-rooting crop, residual removed after harvest, respectively.
- **STILL:** refers to the soil management practices, i.e. reduced tillage (RT) or no tillage (NT), for which the control is conventional tillage used by local farmers.
- **SIMP:** refers to the soil management practices using soil improvers such as biochar or compost derived from agro-waste (crop residual, livestock manure, sewage sludge, etc.).
- **FTYPE:** refers to the fertiliser management practices with various types of fertilisers, including organic fertilisers (OF) in comparison to mineral fertilisers, or enhanced efficiency (EE) fertilisers with additives such as nitrification/urease inhibitors (most frequent), and biofertilisers (BF) in comparison to control without any additional fertilisers.
- **FDOSE:** refers to the fertiliser management practices at various doses, including improved/optimized or reduced fertiliser rate (OFR) in comparison to conventional rate, or supplement of specific nutrient (N, P, micronutrient such as Mg, Ca, S, Zn, etc.) in comparison to no supplement.
- **FTIME:** refers to the fertiliser management practices with improved/optimized timing of fertiliser application (OFT) in comparison to conventional timing, i.e. one time fertilisation before or at sowing.
- **FLOC:** refers to the fertiliser management practices with improved/optimized placement of fertiliser (OFP) such as injection, subseed placement, deep placement, foliar application in comparison to conventional placement, i.e. broadcasting.

2.2.2 Animal and manure management

For RQ3 and RQ4, the targeted management practices are pivotal in shaping nutrient dynamics in animal husbandry and agro-processing industries, which are usually closely interlinked. Table 3 lists the selected management practices in categories:

- **MTREAT:** refers to the alternative manure treatment using anaerobic digestion (AD), manure separation technology (MST), membrane filtration technology (MFT), stripping and scrubbing technology (SST), duckweed cultivation (DC), microalgae cultivation (MC), and constructed wetland (CW), in comparison to conventional manure treatment using nitrification denitrification (NDN) system.
- **AFEED:** refers to the alternative animal feed using local production of duckweed, microalgae, grass, and faba bean as novel proteins (LCP), in comparison to imported soybean meal, which makes up 14% of EU feed and has a high carbon footprint due to its long distance transportation.

Table 2 *Management practices for research question 1 (crop) and research question 2 (soil)*

Management practice name	Man_category	Man_code	Man_treatment	Man_control
Rotation or multi-cropping	CROPB	MCR	cultivation of two or more crops in the same field during one year	monoculture
	CROPB	INC	cultivation of two or more crops simultaneously on the same field	one crop monoculture
Cover crop	CROPB	CC	cultivation of non-cash crops to cover the soil rather than for the purpose of being harvested	no cover crop
Legume	CROPE	LG	including a legume in rotation and addition effects of N fixation	no legume in rotation
Deep-rooting crop	CROPE	DRC	deep-rooting crop such as faba bean and kenza	shallow-rooting crops such as wheat and barley
Residue retention	CROPE	RR	retaining or incorporating crop residues after harvest, mulching	removing crop residues after harvest
Reduced tillage	STILL	RT	reduced or minimal tillage practices such as strip till, zone till ridge till, reduced tillage passes, medium intensity non-inversion tillage up to 40 cm depth	conventional tillage
No tillage	STILL	NT	no tillage	conventional tillage
soil improver	SIMP	IMP	application of biochar (most frequent) or compost	no soil improver applied
Organic VS mineral	FTYPE	OF	organic fertiliser, namely from animal waste or compost	mineral fertiliser
Enhanced efficiency	FTYPE	EE	application of enhanced efficiency fertilisers with additives such as nitrification or urease inhibitors (most frequent) or zeolites	no enhanced efficiency fertiliser applied

Management practice name	Man_category	Man_code	Man_treatment	Man_control
Biofertilisers	FTYPE	BF	application of biofertilisers (microbial inoculant)	no biofertiliser applied
N fertilisation	FDOSE	NF	specific fertiliser rate assessed by levels or continuous data	no fertiliser
P fertilisation	FDOSE	PF	specific fertiliser rate assessed by levels or continuous data	no fertiliser
Micronutrients fertilisation	FDOSE	MIF	in-season supplementing of micronutrients, e.g. B, Mn, Cu, Zn, Fe	no fertiliser
Right rate	FDOSE	OFR	improved/optimized or reduced fertiliser rate	conventional rate
Right timing	FTIME	OFT	improved/optimized timing of fertiliser application	conventional timing
Right placement	FLOC	OFP	improved/optimized placement of fertiliser	conventional placement

Table 3 *Management practices for research questions 3 (animal) and research question 4 (animal and agro-processing)*

Management practice name	Man_category	Man_code	Man_treatment	Man_control
Anaerobic digestion	MTREAT	AD	application of anaerobic digestion in manure treatment	NDN
Manure separation technology	MTREAT	MST	application of separation technology (including centrifuge, screw, band or press separation) in manure treatment	NDN
Membrane filtration technology	MTREAT	MFT	application of membrane filtration (including MF, UF, NF, OR) in manure treatment	NDN
Stripping and scrubbing	MTREAT	SST	application of stripping & scrubbing (with acid or not) in manure treatment	NDN

Management practice name	Man_category	Man_code	Man_treatment	Man_control
Duckweed cultivation	MTREAT	DC	cultivation of duckweed using waste streams from manure treatment	NDN
Microalgae cultivation	MTREAT	MC	cultivation of duckweed using waste streams from manure treatment	NDN
Constructed wetland	MTREAT	CW	constructed wetland as the post-treatment for manure	NDN
Local novel protein	AFEED	LNP	local production of duckweed, microalgae, grass, faba bean as novel protein	imported Soybean

2.3 Data collection

Implementing a meticulous and systematic data collection strategy is paramount to the success of a comprehensive meta-analysis. With defined research questions and specific selection criteria, data collection in this task is tailored to the following aspects:

2.3.1 Data source

There are several open data sources that can be employed to collect research data for meta-analysis, such as Web of Science (WOS), Scopus, and Google Scholar. These renowned academic databases provide a wealth of literature spanning diverse disciplines. Utilizing all three ensures a comprehensive coverage of relevant studies. Among them, WOS is widely accepted as data source for meta-analyses, given that:

- WOS is renowned for its comprehensive coverage across various disciplines, including agriculture, environmental science, and nutrition. This is crucial for the NutriBudget project, which operates at the intersection of these diverse fields.
- WOS curates high-quality academic content from reputable journals, conferences, and scholarly publications. This ensures that the studies included in the meta-analysis meet rigorous academic standards, enhancing the reliability of the findings.

There are also some additional databases specialized in the research questions identified in this deliverable, for example:

a) Within the overarching goal of developing a MMC for agronomic practices across the European Union (EU), Task 1.1 has collected background research data for the 22 pre-identified mitigation measures, each of them falling into the frame of one or more research questions defined above. During the continuous updating period of the MMC, more data is foreseen to be provided by responsible partners.

b) Partners from WU have conducted several meta-analyses on crop management practices:

- 832 observations (n = 142 papers) for impact of crop yield, soil pH and soil properties following soil amendment with lime, biochar, by-products, manure, straw. (Zhang et al., 2023)> 200 studies for impact of SOC levels following fertilisation, manuring, tillage, crop diversity and crop residue incorporation. (Lessmann et al., 2021)
- 2068 observations (n = 144 papers) to explore impact of N addition on N2O emissions and role of N functional genes. (You et al., 2022)
- 2436 observations (n = 407 studies) to explore impact of management (crop, soil, fertiliser management) on NUE (You et al., 2023).

c) Additional datasets can be extracted from existing meta-analyses through inventory of the supplemental materials containing raw data and references to individual studies.

d) In some case, the required raw data is only available by contacting the corresponding authors. However, this is not guaranteed, and it may require more time than expected, therefore it is only used as an alternative approach when the collected data from online data sources are not adequate or incomplete.

2.3.2 Searching approach

The searching of relevant studies is initiated by filtering studies based on the advanced search offered by WOS, enabling a preliminary relevance screening tailored to specific criteria. For example, complex queries can be constructed using Boolean operators (AND, OR, NOT) to combine or exclude terms in the titles (TI), topic (TS), abstracts (AB) and more. Queries are suggested for each RQ to initiate the searching:

- **RQ1**: TS=((enhanced efficiency fertili*er) OR (combined fertili*er) OR (organic fertili*er) OR (fertili*er placement) OR (fertili*er rate) OR (fertili*er timing) OR biochar) OR (residue retention) OR (cover cropping) OR (crop rotation) OR (zero tillage) OR (reduced tillage)) AND ((N loss*) OR (N_2O emission) OR (NH_3 volatili*ation) OR (N runoff) OR (N leaching) OR (Nutrient Use Efficiency (NUE)))
- **RQ2**: TS=((enhanced efficiency fertili*er) OR (combined fertili*er) OR (organic fertili*er) OR (fertili*er placement) OR (fertili*er rate) OR (fertili*er timing) OR biochar) OR (residue retention) OR (cover cropping) OR (crop rotation) OR (zero tillage) OR (reduced tillage)) AND ((soil pH) OR (soil acidity) OR (soil organic carbon) OR (SOC) OR (C sequestration)
- **RQ3**: (TI=((livestock OR pig OR cattle OR chicken) AND (feed* OR protein))) AND (TS=((ammonia OR nitrogen OR phosphorus OR nutrient))) AND (AB=((alternative protein) OR (novel feed) OR duckweed OR microalgae OR grass OR faba*bean))
- **RQ4**: (TI=((livestock OR pig OR cattle OR chicken) AND (manure OR slurry OR sludge OR digestate))) AND (TS=(ammonia OR nitrogen OR phosphorus OR nutrient)) AND (AB= (solid-liquid separation) OR (anaerobic digestion) OR (ammonia stripping) OR (air scrubbing) OR (membrane filtration) OR (duckweed cultivation) OR (microalgae cultivation) OR (struvite crystalli*ation))

In a subsequent stage, a more extensive approach might involve evaluating the entire content of selected studies. This includes examining the full texts, methodology, and results sections to extract nuanced information.

2.3.3 Contextual factors

Specifically, impacts of agricultural management practices are affected by contextual factors including site properties in experimental design and implementation of non-targeted management practices.

The site properties can be considered the crop type, the soil properties, such as clay content and soil pH, and climatic variables such as precipitation and temperature (Table 4). Given that the NutriBudget project focuses on European agricultural systems, data collection is prioritized to studies conducted in European regions or those with comparable climates to ensure contextual relevance.

Note that some of the missing data can be retrieved from other available datasets. For example, in most studies the crop yield is known; in the case that no nutrient uptake is measured, it can be determined by multiplying the yield with a given crop composition. However, these calculated values should be used with caution as they will have a direct impact on the determination of NUEs. Based on the applied nutrient from fertilisers and the measured or calculated nutrient uptake, one can also estimate the nutrient surplus from the crop system. Also, given the longitude and altitude, soil texture and climate data over specific period can be extracted from open-access databases (e.g. LUCAS - https://esdac.jrc.ec.europa.eu/projects/lucas, Climate Data Online - https://www.ncei.noaa.gov/cdo-web/datasets).

Acknowledging the complexity of agricultural systems, studies implementing non-targeted management practices will also be considered. These could include practices that unintentionally impact the variables under investigation, providing a more comprehensive understanding of the agricultural landscape.

Table 4 lists the variables (excluding KPIs) to be included in the database to guide the data collection from individual studies.

Table 4 *Contextual variables to be included in the database*

Group	Variable	Unit	description	Additional information
dataset	dataset_ID	-	unique ID for each dataset	
study	study_ID	-	unique ID for individual research papers	
	reference	-	paper reference: firstauthor_year_firstwordoftitle	
location	lat	-	if present: x coordinate of site	Latitude (N/S)
	lon	-	if present: y coordinate of site	Longitude (W/E)
duration	term		short (1 growing season), long (> 3 years), mid (1-3 years)	
	year	-	experimental year	for KPIs highly affected by short-term management, data should be listed from each growing season if available
climate	mat	ºC	mean temperature	if unknown, can be derived from existing databases using X and Y
	map	mm	annual precipitation	if unknown, can be derived from existing databases using X and Y
site properties	soc	g/kg	soil organic carbon level	if soil organic matter is given, estimate soc = 0,5 x soil organic matter, if unknown, can be derived from existing databases using X and Y
	pH	-	soil acidity	if unknown, can be derived from existing databases using X and Y
	pH_method	-	method used to measure pH	classify: water, CaCl2, KCL or soil solution
	clay	g/kg	clay content	if unknown, can be derived from existing databases using X and Y
	cec	$mmol^+/kg$	buffered cation exchange capacity	if unknown, can be derived from existing databases using X and Y
	phosphorus	mg/kg	available phosphorus content	if unknown, can be derived from existing databases using X and Y
	phosphorus_method	-	method used to determine available P	classify: $CaCl_2$, Olsen, MEHLIG, OXALATE, ...
	nitrogen	mg/kg	total and mineral nitrogen content	if unknown, can be derived from existing databases using X and Y

Group	Variable	Unit	description	Additional information
Managemant practice	Man_code	-	Abbreviations for the management practice in treatment	See Table 2 and Table 3
crop management	crop_type	-	crop	maize, rice, wheat, barley, potato, grass, …
	crop_residue		if crop residue is incorporated back to the field	yes/no
	cover_crop		if cover crop is used	yes/no
	crop_rotation		if there is crop rotation	classify: the number of crops in the rotation (1 = monocropping, 2 or more)
soil management	tillage		which tillage method is used	conventional or reduced/no-tillage
fertiliser management	fertiliser_type		type of fertilisers	mineral, organic, combined, enhanced, biofertiliser
	n_dose	kg N/ha	total N input from fertilisers and manure	
	n_dose_eff	kg N/ha	total effective N input from fertilisers and manure	
	p_dose	kg P_2O_5/ha	total P input	
	k_dose	kg K_2O/ha	total K input	
Animal management	animal_type	-	Species of animal involved in the study	Mainly focus on pig, cow, poultry
	farm_capacity	head/year	Scale of the livestock farm	
Manure treatment	manure_type	-	Type and fraction of livestock manure being treated	
	treat_capacity	Tonne/year	The annual capacity of the installation/pilot for mannure treatment	

The dataset will be summarized in a row-based csv or excel file where each row represents an unique case with a mean, standard deviation (SD) and number of replicates for both control and treatment as well all kind of site properties being a column in the database.

Existing open datasets and aggregation procedures to estimate the current adoption of management measures are outlined in Deliverable 1.4.

2.4 Selecting and computing an effect size

The selection and computation of an appropriate effect size are critical components in meta-analysis. Three type of effect sizes are commonly employed for meta-analyses:

- **Log-transformed response ratio (lnRR)**: a statistical measure used to express the proportional change in the outcome variable (response) between two groups, typically a treatment group and a control group. It is calculated as the natural logarithm of the ratio of the mean of the treatment group to the mean of the control group. A positive lnRR indicates an increase in the outcome variable in the treatment group compared to the control group, while a negative value suggests a decrease. The log transformation is applied to make the measure symmetrical, facilitating its use in statistical analyses.

- **Mean difference (MD):** a straightforward measure that quantifies the absolute difference between the means of two groups. In the context of meta-analysis, it is used to represent the average effect size across studies. A positive MD indicates that the treatment group has a higher mean than the control group, while a negative value suggests the opposite. MD is often expressed in the original units of the outcome variable.
- **Standardized Mean Difference (SMD)**: a dimensionless metric that standardizes the mean difference by dividing it by the pooled standard deviation. The resulting value represents the effect size in standard deviation units. SMD provides a standardized measure of the effect size, allowing for comparisons across different studies and variables. A positive SMD indicates that the treatment group has a higher mean in standardized units compared to the control group.

The computation of effect size can be efficiently performed using meta-analysis toolboxes like MetaWin or Metafor, with Metafor being the tool of choice in this instance. This method necessitates the mean, SD, and number of replicates for both the control and treatment groups. It is important to note that this process is executed separately for each KPI, treating the KPI as the response variable of interest.

2.5 Aggregating effect sizes per main factor

Following the acquisition of data regarding the change in an indicator (effect size) resulting from the application of a treatment (management practice) across multiple papers, we proceed to estimate the mean effect across various categorical factors. This process is akin to a "main factor analysis", focusing on factors such as land use, soil types, climate zones, and soil health categories as well the observed numeric variables such as soil organic carbon, pH, clay content, precipitation, temperature, and so on. The analysis provides a mean impact for each category along with its associated uncertainty. The approach can be represented mathematically as $Y = A * X + error$, where A quantifies the effect of a treatment for specific groups or factors affecting the change in the indicator (Y) due to the main factor (X), where X represents the explanatory variable controlling the variation in Y.

At least the following moderator variables (the X variables mentioned above) are included: crop type, nitrogen dose (as linear and quadratic term), pH, clay content, soil organic carbon content, soil N and P status, mean annual precipitation, and the mean annual transpiration. As management practices we include the crop rotation, the ploughing system (no-till, conventional till and shallow till), crop residue incorporation, and cover cropping. Optionally, one can include composite indices from weather data (derived from earlier studies where data driven statistical models were developed to assess the crop N response to fertilizer addition).

Meta-analytical models assume independence between observed effects among studies. In practice, dependencies arise due to multiple treatment studies (e.g.,multiple fertiliser doses are compared with a common control group), multiple endpoint studies (e.g., multiple crop parameters are determined on the same sample) or other forms of clustering (e.g., observations derived from the same research group) (Gleser and Olkin, 2009). We account for this non-independence by using multivariate meta-modelling with restricted maximum-likelihood estimation, as implemented in Metafor (Viechtbauer 2010). Paper numbers will be used to specify the random-effects structure of the model.

2.6 Performing Meta-regression in R

Building on the main factor analysis, a meta-regression model is constructed to consider interactions among site conditions and management practices that together control the impact of a measure. The impact of site properties and management (variables) on the selected indicators Y_i can be evaluated for all main and two-way interactions between variables affecting Y_i as follows:

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \beta_3 x_{i1} x_{i2} + \cdots + u_i + e_i, \quad (5)$$

where y_i indicates the observed effect size for the ith study; x_{i1} and x_{i2} indicate the value of the first and second moderator variables for the ith study, respectively; β_0 indicates a regression coefficient representing the intercept; β_1 and β_2 indicate the regression coefficients indicating how the average true effect size changes for one unit increase in x_{i1}, and x_{i2}, respectively; u_i indicates the variance of the true effect (residual heterogeneity) of study i; e_i indicates the sampling error of study I; $x_{i1}x_{i2}$ indicates the interaction term with coefficient β_3. The following moderator variables (site factors) are at least included: crop type, nitrogen dose (as linear and quadratic term), soil pH, soil clay content, soil organic carbon, mean annual precipitation, and the mean annual transpiration.

The implementation of this meta-regression is seamlessly executed through meta-analysis toolboxes like MetaWin or Metafor, leveraging R for the analysis. Note that the main factor analysis described in 2.5 is a simplified version of the meta-regression described here.

The forward selection method will be used for model fitting, which means management practices and site factors are added one by one to the meta-regression model. AIC and likelihood ratio test are used to compare the goodness of fit of meta-regression models. The lower AIC value and higher log-likelihood ratio, the better the model fitting. . In addition, one has to check the amount of residual heterogeneity based on the Q_E value, which is included in the default output of the *rma.mv* function. Q_E represents the heterogeneity that cannot be explained by the meta-regression model. Thus, the smaller the Q_E, the more explanatory variability and the better the performance of the model. In evaluating the fit of the meta-regression models, we followed the concept of parsimony (that is, a well-fitted model with less variables are preferred above a model with more variables), to achieve a balance between complexity and performance.

In summary, the following steps need to be taken:

Data Preparation:

1. Data Loading: Data is read from an Excel file and converted into a data table.
2. Handling Missing Data: Missing SD values are estimated from the coefficient of variation of other studies. All moderator variables are checked and converted to a single unit. Missing values are retrieved from open datasets based on the longitude and latitude.
3. Data Cleaning: Column names are cleaned to remove special characters (e.g. dashes, comma, etc.) and make everything lower case.
4. Variable Scaling: Selected variables are scaled to unit variance.
5. Effect Size Calculation: Effect sizes are calculated using the log-transformed response ratio or one of the other effect sizes being more appropriate for the indicator selected.

Main Factor Analysis:

1. Treatment Analysis: A main factor analysis is performed for each treatment category, estimating the overall mean with a random error structured by study ID (as listed in Table 4).
2. Forest Plot: Forest plots are generated to visualize the impact of each treatment on each KPI.
3. Publication Bias Tests: Begg's and Egger's tests are conducted to assess publication bias.

Meta-regression for main and interaction effects:

1. Main Factor Analysis: Meta-regression models are run to evaluate the impact of selected variables (i.e. management practices in Table 2 and Table 3) on the selected KPI.
2. Summary Stats Collection: Summary statistics such as the AIC, log-likelihood improvement, and p-values are collected for each meta-regression model.

Optionally, one can assess the importance of moderator variables (*X*) to explain the variation in the response variable *Y* (the selected indicator) using simple machine learning algorithms like random forest or XGBoost.

2.7 Visualizing the impact of main factors and interactions

Various visualizations can effectively communicate the performance of the meta-regression model and highlight the main factors controlling the impact of measures. Graphical representations may include regional maps illustrating the geological distribution of individual studies, scatter plots illustrating the range of effect size, forest plots illustrating the relationships between the factors and the impact of measures, bar or box plots illustrating the absolute value of the KPI changes and model estimates. These plots can be generated through statistical software packages such as R (with the "metafor" or "meta" package). Besides, sensitivity analyses can be conducted in R to assess the consistency of the effect sizes across studies. High heterogeneity suggests variability in the study outcomes, which may require removing outlier studies or using subgroup analysis as alternative effect size metrics. These visualizations and analyses aid in conveying the nuances of the model and contribute to a comprehensive understanding of the study's findings.

2.8 Applying the regression model at the European scale

Once a robust meta-regression model is developed, its application extends beyond the original dataset. The model can be employed for diverse situations, provided spatially explicit data for independent *X* variables are available. This versatility allows for the extrapolation of model outcomes to novel scenarios, enhancing the practical applicability of the findings. This step ensures that the insights gained from the meta-regression model can be effectively utilized in different contexts, thereby maximizing the utility of the research outcomes.

The analysed impact for the various management practices can be upscaled to determine the impact of measures on selected indicators on field, farm and regional level (in % of the current practice) by multiplying the predicted change with the potential area where the practice in theory could be applied, corrected for the areas where it is already practiced. This will be done by applying the meta-regression model on high resolution spatial maps (depending on the availability of soil properties and management data), using European or country specific datasets of the aforementioned data for climate conditions, soil properties, and local traditional farming practices.

Since the impacts strongly depend on the actual management practices being applied, we first derived global maps of current practices, following the procedures outlined by Lessmann et al. (2022). In summary, they combined spatially explicit data from the Koeppen Geiger classification map, the spatial production allocation model (SPAM) for land use and technology level, maps on N fertilizer application rates, N manure production and application rates on cropland and grassland, the global tillage system dataset and Food and Agriculture Organization databases on cropping systems, crop residue retention, and crop residue burning. The study of Young et al. (2022) elaborated on the earlier work of Lessman et al. (2022) and improved this dataset for European upscaling by inclusion of European datasets that are available online. Both analyses resulted in a spatial dataset, allowing one to assess the potential areas for application of the agronomic measures evaluated here in changing the selected indicators (selected to assess the agronomic and environmental performance of field, farms and regions).

The exact procedures to apply these meta-analytical models on European scale are outlined in Deliverable 1.4 (entitled “Quantifying impact of measures for EU agriculture - initial version”), together with their use in optimisation procedures to identify the most effective measure to move farming systems from the current up to the desired status for a series of indicators.

3. Conclusions and next steps

This deliverable outlines the methodology and approach developed to quantify the impact of agronomic mitigation measures on selected indicators from WP2/WP3. The focus is on generating a meta-analysis of long-term field experimental data to evaluate the measure-impact relationships concerning nutrient balances, flows, and losses in agricultural systems. In summary:

- A comprehensive protocol is established to perform meta-analyses, which includes defining research questions and indicators, criteria for data collection, and developing a minimum of four meta-regression models. The established methodology enables the estimation of agronomic and environmental impacts of the selected measures on carbon and nutrient budgets of crop, soil and animal systems, include indicators linked to crop yield, soil health (e.g., soil pH and organic carbon content), air quality (e.g., GHG and ammonia emissions), and water quality (e.g., nutrient surplus and nutrient use efficiency).
- Building on the established methodology, meta-regression models will be developed on the measures and data collected in Task 1.1 MMC as well as existing database for a broad range of farming practices. Additionally, the outcome of Task 1.4 (*D1.4 A data/measurement matrix*). supplies insights to the innovative measures being selected for experimental test in WP4, ensuring the meta-analysis in Task 1.2 is informed by the latest data and measurement practices.
- The protocol facilitates us in understanding and optimizing nutrient management in agriculture, meanwhile supporting the spatial evaluation of the measures in Task 1.3 (with D1.4 and D1.5 as outcomes). Comprehensive particulars about the amassed databases, and characteristics intrinsic to the involved studies (namely, sample size, typology, and geographical distribution), in conjunction with the algorithms and outcomes of quantification shall be incorporated into the conclusive iteration *of D1.3 Quantified measure-impact relationship of selected measures*, which is anticipated to be finalized and submitted by August 2024.
- The protocol provides a structured approach to quantify the effectiveness of agronomic measures using KPIs identified in WP3. The insights gained from these deliverables will directly inform the calibration and validation of measure-impact evaluations using empirical and process-based models in WP2.
- The methodology established in this deliverable also has far-reaching implications beyond the immediate scope of the NutriBudget project, providing a robust foundation for future studies or initiatives with similar aims. By addressing the complex interplay between agricultural practices and environmental impact, it paves the way for more informed decision-making and policy development aimed at achieving sustainable agricultural systems.

Quantifying the impact of agricultural practices comes with inherent risks that can impact the validity and reliability of the findings. One significant risk lies in the heterogeneity of the datasets sourced from various studies, as differences in experimental designs, geographical locations, as well as meteorological and climatic conditions may introduce variability. Heterogeneity can obscure true effect sizes and lead to misleading conclusions. Employing statistical techniques such as meta-regression allows for the investigation of potential moderating factors, helping to unravel the complexities introduced by variations in experimental conditions. A random-effects meta-analysis may be used to incorporate heterogeneity among studies, intended primarily for heterogeneity that cannot be explained. In general, it is unwise to exclude studies from a meta-analysis on the basis of their results as this may introduce bias. However, if an obvious reason for the outlying result is apparent, the study might be removed with more confidence. Addressing heterogeneity can involve conducting subgroup analyses to explore potential sources of variation, providing a more nuanced understanding of the impact of agricultural practices across different contexts.

Another potential risk is the lack of standardized reporting across studies, leading to variations in the availability of crucial information such as mean, standard deviation, and sample size, hindering the computation of reliable effect sizes. Moreover, publication bias, where studies with significant or positive results are more likely to be published, can skew the synthesized evidence, providing an incomplete representation of the true spectrum of outcomes associated with agricultural practices. It is also imperative to consider the influence of a heterogenous quality of the management skills of the landowner or the individuals executing the trial, which is difficult to quantify but can add an extra layer of noise to the model. The creation of a transparent and reproducible protocol in this deliverable can enhance the study's credibility and facilitate the identification and management of potential risks before the meta-analysis commences in D1.3. Additionally, to minimise the publication bias and ensure a more comprehensive representation of the available evidence, this methodology employed an extensive literature search, including query search on the open data sources such as WoS, the inventory in Task 1.1 of this project, as well as incorporation of the existing databases and unpublished studies.

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Optimisation of nutrient budget in agriculture

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