Optimisation of nutrient budget in agriculture

D1.6 Data/measurement matrix

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Preface

This deliverable was drafted as a part of the outcomes from work package 1 (WP1) in 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", 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 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.

Within the frame of WP1, aiming to develop a Mitigation Measures Catalogue (MMC) consisting of more than 50 mitigation measures, Task 1.4 (T1.4) specifically focuses on the measures requiring more research and that will be investigated at lab and pilot scale in WP4. From the literature inventory in the first draft of deliverable (D) 1.1 "*Mitigation Measures Catalogue"* and the selected measures in D4.1 *"Results of focus groups and explanation of final selection of mitigation measures"*, T1.4 will generate a matrix of data/measurement, i.e. D1.6, which describes qualitatively and quantitatively the effect of the available farm-practices and agronomic measures and the data gaps still to be collected/validated. The outcome will be a full description of the state-of-art and matrix data useful to acquire new information and will have a direct impact on the experimental work to be performed in the five pilots (WP4).

Summary

Deliverable (D) 1.6 *"Data/measurement matrix"* is part of the NutriBudget work package 1 (WP1). The aim of WP1 *"Design Opportunity Map for Effective Measures"* is 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 (T) 1.4 "*Compilation of measures state-of-art related to the five experimental pilots*" is to provide targeted data on the existing state-of-the-art of the measures to be investigated at lab and pilot scale in WP4. This involves the pre-identified mitigation measures for which the existing background information at the relevant scale is limited and/or fragmented requiring further experimental investigation within NutriBudget.

During the project preparation stage, the NutriBudget consortium already pre-identified 21 mitigation measures (see Description of the Action (DoA) part B Table I) whose performance will be experimentally assessed in five NutriBudget pilot regions covering four distinct climate zones in Europe: Atlantic, Boreal, Continental, and Mediterranean. Before the start of the experimental work in WP4, the state-of-the-art of these pre-identified mitigation measures on agri-environmental impact was evaluated in WP1 using data collected from literature, available "best practices databases" and long-term field experiments based on the soil fertility indicators, nutrient budgets, and related environmental indicators identified in WP3. The first run of data collection in T1.1 resulted in an updated list of 22 mitigation measures (see first draft of D1.1 "*mitigation measures catalogue"* submitted in June 2023) with 19 of them (see D4.1 *"Results of focus groups and explanation of final selection of mitigation measures"* submitted in October 2023) needing further experimental work in WP4 to obtain updated information to fill the knowledge gaps regarding implementation at higher Technology Readiness Levels (TRLs, from lab to pilot in relevant environment). Based on the literature inventory in D1.1 and the selection of measures in D4.1, T1.4 aims to identify the knowledge gaps for the 19 selected mitigation measures and provide suggestions for WP4 experimental work. Therefore, this deliverable will provide a summary of the state-of-the-art of the selected mitigation measures and the data gaps still to be collected/validated in WP4.

This deliverable is divided into four Chapters. **Chapter 1** presents an introduction to the selected mitigation measure requiring further experimental investigation within NutriBudget project. **Chapter 2** describes the methodology to identify the knowledge gaps between i) the existing data collected during the first nine months of the project implementation with a focus on the pre-identified mitigation measures, and ii) the pre-listed key performance indicators (KPIs) to evaluate the agronomic and environmental impacts. This includes a preliminary analysis of the collected data in the first draft of MMC and several interaction meetings with pilot leaders to determine the targeted KPIs. Alignments between the data availability and the targeted KPIs are presented and discussed in **Chapter 3**. Finally, **Chapter 4** provides a summary of the knowledge gaps and recommendations for experimental work in WP4.

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List of Abbreviations

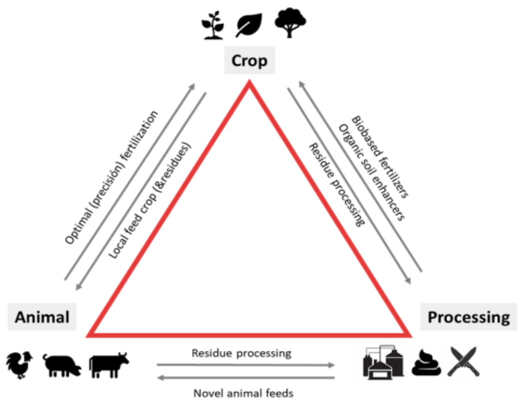
AAS	Atomic Absorption Spectrometer
BBF	Biobased fertiliser
CEC	Cation Exchange Capacity
C, CO_2	Carbon, Carbon Dioxide
DoA	Description of the Action
EU	European Union
GA	Grant Agreement
GHG	Greenhouse Gas
ISO	International Standard Organization
ICP-OES	Inductively Coupled Plasma Optical Emission Spectroscopy
ICP-AES	Inductively Coupled Plasma Atomic Emission Spectroscopy
KPI	Key Performance Indicator
M	Month since the project kick-off
MMC	Mitigation Measures Catalogue
MS	Milestone
N, NH_3, NH_4, NO_3, N_2O	Nitrogen, Ammonia, Ammonium, Nitrate, Nitrous Oxide
NUE	Nutrient Use Efficiency
P, PO_4	Phosphorus, Phosphate
SOC	Soil Organic Carbon
WP	Work package

1. Introduction

Understanding the state-of-the-art in a particular field is paramount for identifying knowledge gaps in research. A comprehensive review of existing literature and the current status of scientific knowledge allows researchers to delineate the boundaries of what is known and, more importantly, what remains to be explored. By assimilating the latest advancements, methodologies, and findings, researchers gain valuable insights into the existing gaps and limitations in the current body of knowledge. This not only provides a foundation upon which new studies can build but also facilitates the formulation of precise research questions aimed at addressing these gaps.

WP1 "Co-creation of the Mitigation Measures Catalogue (MMC)" aims to gather existing data for more than 50 mitigation measures from available literature and datasets, among other sources, in order to populate the databases contributing to the NutriDesign tasks and, later, to the development of the NutriModels. This effort centres on best available measures that can be assessed based on existing data, and this data will be used to plan an optimised nutrient management in different farming systems, regions and countries with the use of the NutriPlatform and Models. Moreover, there are particularly innovative measures for which there is not sufficient data and further experimental investigation is foreseen in WP4.

During the project preparation stage, 21 innovative mitigation measures (DoA – part B, Table I) have been pre-identified by the NutriBudget consortium in five pilot regions covering four distinct climate zones in Europe: Atlantic, Boreal, Continental, and Mediterranean. These pre-identified mitigation measures were categorised among three agricultural pillars (crop production, animal husbandry, and agro-processing industries) and six agricultural management categories (Figure 1). The focus of the pre-identified measures is linked specifically with the regional environmental problems that are expected to be addressed, such as nutrient losses to water, nutrient imbalances, ammonia emissions, nutrient use efficiency, air quality, and soil health.



I. Tools, techniques, and systems for higher-precision fertilization
II. Innovative management systems, tools and practices for optimised nutrient and GHG management in animal husbandry
III. Novel feeds produced from agro-residues
IV. Innovative soil, fertilization and crop management systems and practices for enhanced N, P, efficiency and increased soil OC content
V. Substituting primary nutrient resources by biobased products in practice
VI. Nature-based solutions

Figure 1 *The six agricultural management categories and three agricultural pillars in the NutriBudget project.*

As explained in the first draft of D1.1, *"Mitigation measures catalogue"*, the initial list of the pre-identified mitigation measures was revised by pilot region leaders according to the focus of the mitigation measures, category of agricultural management, type of agricultural system and agricultural pillars. The revision led to an updated list (see D1.1 first draft Table 3) with a final count of 22 mitigation measures, amounting to 21 pre-identified (DoA, part B, Table I) and 1 additional measure added by the Boreal pilot to reach the aim of having precision fertilisation as a common mitigation measure across the five pilot regions. Through a four-pillar strategy consisting of joint meetings, WP1 state-of-the-art outputs, national co-creation workshops, and internal pilot-level discussions (specified in D4.1 "*Results of focus groups and explanation of final selection of mitigation measures"*), 19 of the pre-identified mitigation measures were selected for further experimental work in WP4, which are also the main focus of this deliverable.

Among the 19 mitigation measures to be tested in WP4, 15 are categorized in the crop production pillar, 6 in the animal husbandry pillar, and 4 in the agro-processing industries pillar, and some of them are involved in more than one pillar. The three agricultural pillars concern different perspectives of the nutrient flow and environmental impact, revealing distinct requirements for quantitative data. Therefore, this deliverable employed a two-step approach starting with the identification of the focused agricultural pillar and the targeted indicators for each of the selected mitigation measures, based on interactive discussion with pilot leaders. Meanwhile, a literature review was conducted to collect the existing research data in the MMC. The knowledge gap is identified by matching the existing data collected from literature with the targeted indicators to evaluate the agronomic and environmental impacts. This leads to a qualitative data-measurement matrix suggesting the necessary data to be collected through WP4 experimental work.

2. Methodology

The methodology in T1.4, outlined in Figure 2, commences with the identification of focus and targeted monitoring indicators, conducted simultaneously with a literature review to gauge data availability for each of the 19 active mitigation measures. This process includes a preliminary analysis of the compiled data in the MMC, bolstered by interactive discussions with the five NutriBudget pilot leaders. The identified knowledge gaps reveal a scarcity or fragmentation of necessary information in existing literature for the qualitative and quantitative assessment of these mitigation measures, necessitating further research via experimental or modelling approaches.

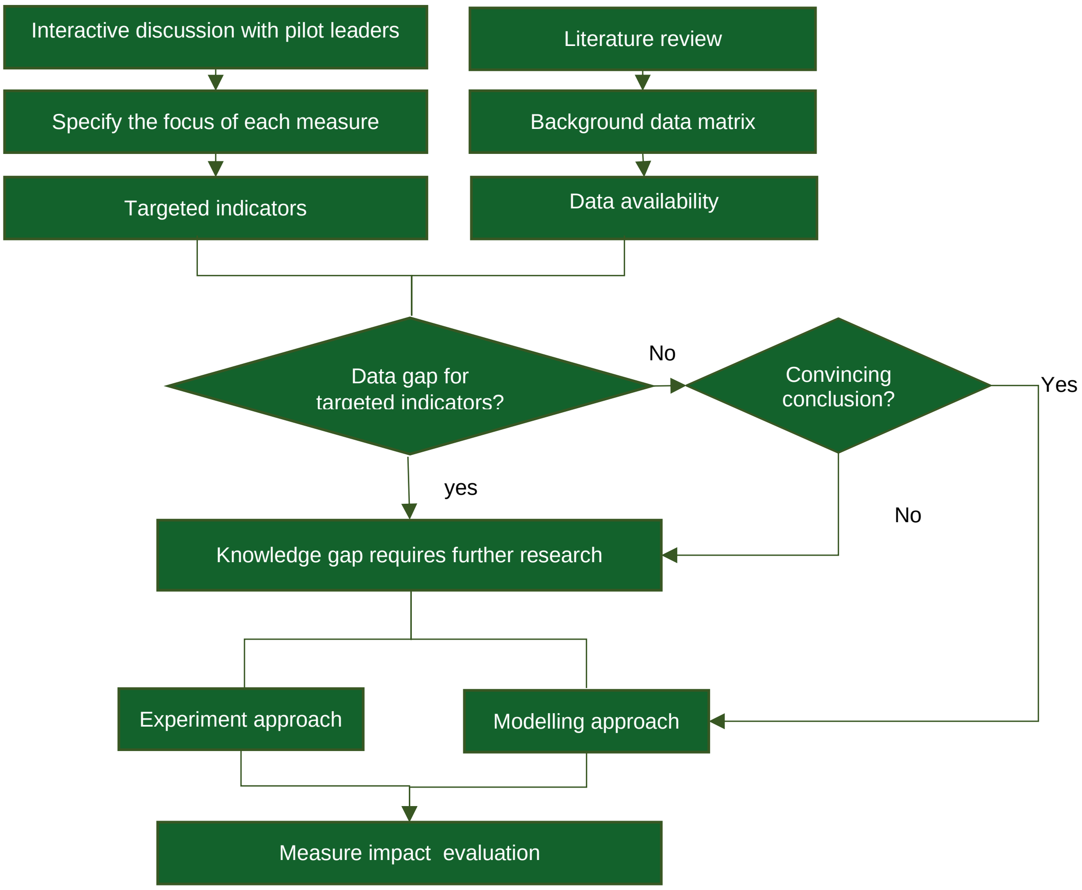


Figure 2 *The proposed approach for Task 1.4 "Compilation of measures state-of-art related to the five experimental pilots".*

2.1 Selection of evaluation and monitoring indicators

Relevant impact-specific information, termed key performance indicators (KPIs), were delineated by WP3, aligning with various parameters inherent in models designated for implementation/development within the NutriBudget project. A comprehensive inventory of pertinent indicators was formulated in Annex 1 Table A1, including experimental conditions, ecosystem properties, pressure (driver), and effect indicators, supplemented by precise guidelines for data collection, encompassing indicator descriptions, associated measuring methods, and data units. Selection of the KPIs to evaluate the impact of the mitigation measures was based on the involved agricultural pillars and the main focus of the mitigation measures. Accordingly, a pack of indicators was selected from the full list (Annex 1, Table A1) as the minimum datasets to be collected either from further literature review in WP1 or from the experimental work planned in WP4.

2.2 Inventory of existing research

Due to a tight timeline for the design of the experimental work for the selected measures to be tested in WP4 (*D4.2 "Description of experimental set-up and methods used in each pilot",* submitted in January 2024), the first stage of data collection for the MMC started with an inventory of the existing research data for the 22 pre-identified mitigation measures, which also fit with the objective of T1.4 to produce *D1.6 "Data /measurement matrix"*. Desk research on the existing results (published papers, reports or database, etc.) was conducted to collect the impact-specific information (environmental performance related use efficiency, nutrient losses, etc.), leading to a comprehensive inventory of available data providing insights on current state-of-knowledge for each of the pre-identified mitigation measures.

The MMC was drafted in excel format and shared among the project consortium through Microsoft SharePoint project drive. It is continuously updated with newly added mitigation measures and associated data collection during the project implementation. To identify the knowledge gaps, a data matrix of the 19 selected mitigation measures (to be tested in the five pilot regions) was extracted from the MMC. Data availability of the included indicators was checked for each measure.

2.3 Identification of knowledge gaps

There are three scenarios that can be identified as knowledge gaps:

i) Absence of research data:

One significant knowledge gap pertains to the outright absence of research data for the implementation of the identified mitigation measures. In several instances, there is a dearth of empirical evidence or documented studies related to the practical application and outcomes of these measures. This lack of foundational research data poses a challenge in comprehending the real-world impact and effectiveness of the mitigation strategies.

The knowledge gap concerning the outright absence of research data is best addressed through targeted experimental work. Conducting field trials, controlled experiments, and empirical studies can generate essential data points that directly capture the practical implications and outcomes of the mitigation measures. These experiments can provide foundational insights into the real-world effectiveness and impacts of these measures.

ii) Limited data at preliminary implementation stage:

Another facet of the knowledge gap involves the availability of research data that is confined to the preliminary stages of implementation. While some information exists, it is often limited to lower Technology Readiness Levels (TRLs), rendering it insufficient for guiding high-level, practical applications. This limitation hampers the ability to extrapolate findings to real-world scenarios, hindering the seamless transition of mitigation measures from conceptualization to robust, field-level implementation.

To bridge the gap resulting from limited data at preliminary implementation stages, a dual approach might be suitable. Initiating experimental work that mimics real-world scenarios can yield practical evidence. Meanwhile, modelling can complement this by extrapolating existing data and incorporating theoretical insights to simulate higher TRL scenarios, thus enhancing the practical applicability of the measures.

iii) Conflicting and inconclusive existing data:

The third knowledge gap arises from the multifaceted nature of existing data. Numerous factors contribute to data inconsistencies and conflicts, making it challenging for end-users to derive conclusive insights regarding the impact of mitigation measures. Variability in methodologies, diverse experimental conditions, and contradictory results across studies create a landscape where obtaining a unified and convincing conclusion becomes elusive. This lack of consensus in the existing data further accentuates the need for targeted research to clarify and resolve these discrepancies.

3. Results and discussion

3.1 Inventory of the specific focus and existing research

Recognising the specific focus of the selected mitigation measures is the first crucial step for making an inventory of the existing research to identify the knowledge gaps and advance our collective understanding of the impact of a given measure. This section encapsulates a concise overview of the precise emphasis placed on the selected mitigation measures and the pertinent research data acquired in the initial phase of data collection within Task 1.1. It furnishes indispensable information aimed at discerning pivotal data gaps (Section 3.3) on the basis of identified target indicators (Section 3.2).

In the NutriBudget project, the selected mitigation measures have been categorised in three agricultural pillars (Figure 1), which was adapted from the Nutri2Cycle H2020 project. The basic understanding is to re-connect the intensified crop production and animal husbandry pillars via optimised management and technologies that result from the agro-processing industries pillar. While the three agricultural pillars are interlinked, each of them focuses on different management units, thus showing distinct impact on the nutrient flows and environmental impact:

- **Crop production pillar** has as major challenge in maintaining high productivity and quality of the crop at low environmental impact. The involved mitigation measures mainly focus on crop management (e.g. crop rotation, 4R - right source, rate, time, and place - fertilisation strategy, irrigation, straw return) and soil management (e.g. liming, tillage, drainage systems).
- **Animal husbandry pillar** varies dramatically between regions and countries as influenced by local legislative frameworks and environmental parameters. The main focus is animal and manure management including feeding strategy (type and rate), housing structure, manure storage and treatment.
- **Agro-processing industries pillar** has emerged as an agricultural activity on its own over the last decades and has provided added value to the conventional agro-activities. The focused management practices include manure separation, composting of agro-residues, generation of renewable energy via anaerobic digestion (AD), and post-treatment of manure or digestate using nutrient recovery technologies such as stripping and scrubbing, membrane concentration, duckweed or microalgae cultivation, among others.

3.1.1 Crop production pillar

Among the 19 selected mitigation measures to be tested in WP4, 13 of them are involved mainly in the crop production pillar. There are 5 measures in the management category "*Tools, techniques, and systems for higher- precision fertilisation*", 3 from the category "*Innovative soil, fertilisation, and crop management systems and practices for enhanced N, P, efficiency and increased soil OC*", 4 from the category "*Substituting primary nutrient resources by biobased products in practice*" and 1 from the category "*Nature-based solutions*".

As stipulated in the DoA, "precision agriculture tools will be a common measure to be implemented in all pilots, providing the opportunity to compare measure effectiveness in nutrient budget optimization among regions distributed along a latitudinal gradient" (DoA Part B, pages 10-11). Precision fertilisation is a technique that aims to apply the optimal amount and type of fertiliser to each specific location in a field, based on the spatial variability of soil and crop conditions. This technology aims to improve the nutrient use efficiency, crop yield and quality, and reduce the environmental impact of fertiliser application. The advances in precision fertilisation are mainly related to the development and application of various sensors, models, and algorithms that can measure, predict, and control the fertiliser input and output in a field. Consequently, five mitigation measures are selected, one for each pilot region and all fall in the **crop production pillar**, focusing on different tools, techniques and systems for precision fertilisation:

- **Advanced sensor technologies for the application of liquid biobased fertilisers (e.g., pig urine, ammonium sulphate, liquid fraction of digestate, mineral concentrate) to address nutrient variability in fields and products**: this mitigation measure focuses on the judicious application of variable rates of synthetic or biobased N fertilisers. Traditional farm management usually uses a whole-field approach, i.e. fertilisers are applied uniformly across the field, regardless of the fact that most of the agricultural soils are highly heterogenous. Uniform management of fields often results in over-application of inputs in areas with high nutrient levels and under-application in areas with low nutrient levels (Ferguson et al., 2002; Zhao et al., 2023). Site-specific management of nutrient, generally via variable rate fertiliser application, has been acknowledged as one means for addressing this problem (Cahn et al., 1994; Guerrero et al., 2021).
- **Precision fertilisation of bio-based fertilisers and/or mineral fertilisers through multilevel data integration**: this mitigation measure demonstrates the precision fertilisation strategy for mineral fertilisers and BBFs based on the in-season plant monitoring and multilevel data integration technologies. The ability of vegetation indices, such as the normalized difference vegetation index (NDVI), to assess and monitor the crop status allows a field to be divided into homogeneous zones for variable application of inputs (Gozdowski et al., 2020; Ileri et al., 2022; Rehman et al., 2019; Seo et al., 2019). The application of multispectral data derived from different sources such as satellite and ground sensors has become increasingly popular due to the decreased cost of satellite imagery and computing (Panek et al., 2020; Roznik et al., 2022).
- **Updating precision injection system to reduce NH_3 emission by using BBFs (digestate from organic agro-food waste and sludge)**: this measure is related to use a new device designed to enhance the efficiency and environmental sustainability of BBF (digestate from sludge) distribution with reference to ammonia emission. Previous works have demonstrated that the proper use of anaerobically digested sludge through injection led to the complete replacement of chemical fertilisers while maintaining the same productivity and ammonia emissions levels as chemical fertilisers (Zilio et al., 2022, 2021). The experimental work will test by distribution trials an improved system for precision injection of BBF to reduce ammonia emissions. This mitigation measure is relevant for the territory as the Po Valley faces issues with ammonia emissions and air quality.
- **Sensor technologies for correcting potential nitrogen deficiency for achieving optimal yields:** this measure will also provide new information about the potential of sensor technologies for improving yields and nutrient utilization originating from BBFs in grass production. As a BBF with high N/P ratio, liquid fraction of pig slurry is commonly applied at the beginning of the growing season (Pedersen et al., 2020). However, availability of N may limit yield production as the growing season advances (Luo et al., 2021). Sensor technologies can be used to optimise N fertilisation

during growing season but there are knowledge gaps about the potential of sensor technologies in grass production, and field testing is required to validate their effectiveness.

- **Foliar application based on plant analysis**: this measure focuses on the use of in-season plant analysis and subsequent application of foliar fertilisers, with specific focus on Mg fertilisation and its effect on crop nutrition. It raises from the fact that, in the Switzerland pilot region, farms with high organic inputs and greater proportions of grass-clover leys in the crop rotation had stronger deficits of Mg. Careful evaluation of pre-existing soil data collected in 2017 suggests Mg deficits on at least one third of the fields. Additional plant sap and plant dry matter analyses in a wheat field revealed a surplus of Mo and B, imbalances of cations, Zn deficiencies as well as partly deficiencies of S and N. A previous study (Potarzycki et al., 2022) reported that Mg applied to wheat resulted in a significant yield gain with respect to the effect of NPK, with a slightly higher increase in the yield caused by foliar fertilisation. However, the inconsistent results with respect to Mg concentrations in plant dry matter and the combination of other nutrient deficiency/imbalance request further investigation.

The other 8 mitigation measures in crop production pillar are listed as follows:

- **Deep-rooted nutrient cycling with Kernza perennial cereal to mitigate nutrient losses to surface water and groundwaters**: this measure emphasizes the use of the perennial cereal variety Kernza (*Thinopyrum intermedium*) to amplify nutrient cycling and minimize nutrient losses to both surface and groundwater bodies. Kernza has demonstrated a superior capability to capture and utilize a larger proportion of soil solution NO_3^--N, thus mitigating nutrient leaching and greenhouse gas emissions (Culman et al., 2013; Reilly et al., 2022). The perennial nature of the root systems of Kernza® and its analogous intermediate wheatgrass (IWG) provides several advantages over annual crops, notably enhanced and stable carbon sequestration as root biomass, heightened resilience to environmental stressors, reduced N requirements, improved carbon fixation, and augmented below- and above-ground biodiversity leading to elevated ecosystem services (Huddell et al., 2023).
- **Enhanced and optimized fertilisation with upgraded pig manure products to avoid nutrient excess in soil**: this measure evolved from previous experiments in the H2020 project FERTIMANURE, with the aim to evaluate the application of BBFs derived from manure as substitutes for synthetic mineral fertilisers. Initial tests presented challenges, with field conditions exhibiting high nutrient concentrations that may have overshadowed the positive effects of BBF on wheat. This, combined with Catalonia's prolonged drought period, necessitated a reconsideration of the experimental approach. Research demonstrates the critical role of long-term trials in assessing the sustainability of agricultural systems and understanding the intricate effects of fertilisers on soil quality over extended periods (Kurniawati et al., 2023). As a result, the team decided to prolong the experiment by two additional years, allowing for the exploration of the performance nuances of BBF in a long-term setting.
- **The effect of biological stability degree on carbon and nitrogen:** this mitigation measure aimed to assess the fate of N and C in the soil originating from materials with different degrees of biological stability in various incubation trials and to explore potential correlations. Literature inventory and past research data revealed that crops primarily utilize the mineral components of digestate (that is subject to leaching and emissions), while the organic fraction, including organic N, being well stabilized, does not result in further N emissions (Tambone et al., 2019; Zilio et al., 2023, 2022). Nevertheless, there was a gap in systematic research concerning the role of biological stability in governing the turnover and fate of N and C.
- **Mineral fertiliser replacement using digestate and derived products (ammonium sulphate)**: Previous data (Zilio et al., 2023, 2022, 2021) showed that digestate and digestate-derived ammonium sulphate reduced nitrate leaching and nitrous oxide emissions, compared to mineral fertilisers, indicating a lower environmental impact. The study was performed measuring N (nitrate, ammonia) and P in bulk soil at a 1 m depth. This data will be updated by measuring N (and P) in the water table using piezometric devices over at least two crop seasons.
- **Reduction of nutrient losses with deep rooted crops (faba bean) in a no-till system**: this measure aims to validate the effect of faba bean cultivation in the leaching field with a long history of previous cultivation practices on nutrient losses. Growing N-fixing faba beans can not only

enhance the self-sufficiency of animal feed protein in Finland but also reduce the need for N fertiliser. Also, as a deep-rooted crop, faba bean is expected to enhance soil structure by providing a higher C input to the soil than the annual cereals typical in the target area (Ali et al., 2019; Karkanis et al., 2018). Limited research has focused on faba bean cultivation, with none investigating erosion and nutrient losses.

- **Effect of soil properties on mineralisation of organic matter**: this measure aims to explore the potential to adjust N fertilisation based on soil clay/C ratio. In Southwest Finland, the productivity of agricultural fields with heavy clay texture depends on soil organic matter content. High soil organic matter enhances soil porosity, reduces erosion risk through improved aggregate stability, and releases N through organic matter mineralisation, potentially allowing for reduced fertilisation, increased nutrient use efficiency, and lower environmental impact (Soinne et al., 2021).

- **Mineral fertiliser replacement potential of biobased fertilisers with high N/P ratio**: this measure concerns the use of liquid fraction of pig slurry as recycled fertiliser. The solid-liquid separation process provides means for optimizing the use of N and P from manure and consequently reduce nutrient losses through imbalanced fertilisation (Pantelopoulos and Aronsson, 2021). Liquid fraction of digestate with a high N/P ratio can be used as a N-fertiliser at a close vicinity of the production sites, without further increasing soil P status (Meade et al., 2011). Notably, manure-derived fertilizers exhibit considerable diversity in both their properties, leading to varied agronomic efficacy in field application. Consequently, to ensure acceptance of this product among farmers, there is a requisite for additional inquiry to substantiate their potential as replacements for mineral fertilizers and to elucidate the influencing factors at the levels of crops, soil, and the environment.
- **Adapted and balanced fertiliser inputs based on diagnosis by a combination of farmgate balances, soil and plant analysis:** this measure aims to fill the knowledge gap with strip experiments to test recycled nutrient sources that could help to balance inputs of N, P and K together with those of other macro- and micronutrients such as S, Mg and/or Zn. On organic farms, in particular, N is known to be the main yield-limiting factor (Reimer et al., 2023), but farmers lack experience with new recycled sources of N. Supplementing rotational N inputs from biological N fixation with recycled organic sources can increase the productivity of organic farms (Udvardi et al., 2021), but there is a gap of knowledge regarding the effect this can have on overall plant nutritional status. Therefore, all nutrients besides N will also be monitored in the treatment with recycled N sources, and an additional treatment with a combination of recycled N inputs and supplementation of other deficient elements will be installed as well.

3.1.2 Crop production and animal husbandry pillars

The mitigation measure titled **“Advanced NH_3 emissions mitigation using zeolites”** is relevant to both the crop production and animal husbandry pillars. The focus is on the emission of NH_3 from storage and field application of animal manure, which is a key issue in livestock manure management because it represents a loss of fertiliser value and it can negatively impact the environment. Existing data is available for the NH_3 emission mitigation using zeolites during manure storage and separation in pig beds (Cao 2019; Lamkaddam et al., 2021; Li et al., 2018; Portejoie et al., 2003). With this mitigation measure, UVIC-UCC directed the focus towards a broader scientific contribution beyond the pig stable. Past research showed that the majority of the N losses occur during the first days after the application of fertiliser and the NH_3 emission have been reported up to 75% of the applied N within the first 24h. Therefore, finding new methodologies that can delay N losses may increase the efficiency of fertilisers and reduce their environmental impacts.

3.1.3 Animal husbandry pillar

The mitigation measure titled **“Grass and faba bean as novel protein sources for pig and poultry”** mainly concerns the nutrient flows in the animal husbandry pillar. Efforts are actively underway to identify alternative protein sources for pigs and poultry, aiming to reduce the reliance on imported soybean products as feed ingredients. Under Finnish climatic conditions, grass is one of the most productive crops with efficient nutrient utilization (Keto et al., 2021). Earlier studies have indicated that both faba bean and grass are potential protein sources in poultry and pig production (Nyende et al, 2023; Perz et al., 2021; Stødkilde et al., 2021; Tampio et al., 2019), which contribute to a reduced dependency on imported protein sources. This mitigation measure will further evaluate the nutrition potential of these novel protein sources through feeding trials with both poultry and pigs.

3.1.4 Animal husbandry and agro-processing industries pillars

The following 3 mitigation measures are selected to assess the nutrient management bridging the animal husbandry and agro-processing industries pillars:

- **Duckweed cultivation on agricultural wastewater (pig manure and aquaculture) as alternative protein source for animal feed:** this mitigation measure addresses the regional issue of surplus in nutrient-rich aqueous waste streams from agriculture whereas a need for imported protein for animal feed exists. The provided approach is of high interest to local stakeholders, however the associated research is currently at a preliminary stage (e.g., laboratory scale and initial pilot studies) (Devlamynck et al., 2021 a, b; Lambert et al., 2022; Petersen et al., 2021), therefore, additional research is warranted at the pilot scale to gather comprehensive data.
- **Microalgae cultivation on digestate as alternative protein source for animal feed:** the rationale of this mitigation measure is similar to duckweed cultivation. Addition to the demand of upscaling research, there is also a concern about algae production at a constant quality when using digestate and also the market for such product is not clear. In previous projects and research, the maximum digestate concentration that could be used for microalgae cultivation was around 2% (Papadopoulos et al., 2023). This leads to a need of a significant amount of freshwater and it is seen as a drawback when seeing microalgae cultivation as not only a novel bioprocess for protein production, but also as an alternative for the treatment of excess digestate. Moreover, when growing algae in recycled nutrients, there is a concern by the market on the quality and homogeneity of the produced biomass.
- **Constructed wetlands: tertiary treatment of pig manure towards discharge water**: this mitigation measure falls under the category of nature-based solutions, as it is not only useful to process surplus manure in regions suffering from manure excess but can also contribute to ecosystem services like increased biodiversity. Previous studies (Borin et al., 2013; Meers et al., 2005, 2008; Terrero et al., 2020) have highlighted the treatment efficiency of constructed wetlands at different loading rates, scales and climate regions. Despite its emphasis within the EU framework, the majority of farmers exhibit minimal awareness and enthusiasm for harmonizing natural ecosystem services with the agricultural imperative of maximizing crop productivity. Moreover, in NutriBudget, the association of constructed wetlands with duckweed cultivation will be assessed to increase the treatment capacity of constructed wetlands while enabling nutrient recovery from manure.

3.1.5 Crop production, animal husbandry and agro-processing industries pillars

Above from all, the mitigation measure titled “**Dual purpose Lemna cultivation: green manure production and alternative protein potential**” highlights a connection between the three agricultural pillars. As stated in the *section 3.1.4*, research on duckweed cultivation is still at the preliminary stage, and the lab scale experiments underscored the need for optimal conditions for *Lemna* cultivation on pig manure, especially under real conditions. Besides, the insights shed light on the limited existing knowledge regarding the valorization of the *Lemna* biomass, e.g. exploring the potential as an alternative protein source for animal feed, or as green manure for soil improvement and crop production. Therefore, this mitigation measure encompasses the meticulous study and fine-tuning of duckweed cultivation in both laboratory settings and outdoor conditions. Moreover, the study will evaluate the potential of the biomass for use as green manure through pot experiments and field trials. These findings can then be compared and potentially combined with other organic amendments. In addition, this mitigation measure will include a general characterization of *Lemna* biomass to preliminarily delineate its potential as an alternative protein source for animal feed.

3.2 Identification of targeted indicators

Targeting the agronomic and environmental impact, namely soil quality, water quality, GHG emission, and agricultural production, WP3 proposed four types of indicators to be included in the MMC: agro-ecological site properties (A), driving (pressure) indicators (D), effect indicators (E) and performance indicators (P), which are specified in *D1.1 "Mitigation Measures Catalogue-first draft version".* Site properties and driving indicators are part of the experimental design. Among the effect indicators, 10 indicators were defined to describe the change of variables due to the impact of altering nutrient inputs and/or management strategies, such as nutrient uptake, surplus, losses and pools that can be measured or modelled. Moreover, 9 performance indicators were selected to describe the gaps between a current and a targeted status with respect to nutrient inputs, surpluses, losses or contents/pools that cannot be measured but only calculated from effect indicators. Accordingly, Table 1 lists the link between the performance and effect indicators as well as the targeted agronomic and environmental impact.

***Table 1** Performance indicators and the associated effect indicators to evaluate the main impact of selected mitigation measures*.

Class*	Performance Indicator	Effect indicators (class)	Main Impact
P1	Soil carbon and nutrient** status Gap***	Changes of Soil C and nutrient contents/pools (E5)	Soil quality
P2	Losses Gap for C, N and P	N & P losses (E7) GHG emissions (E8)	Water quality; GHG emission
P3	Nutrient Surplus Gap	Soil C and nutrient contents/pools (E5) N & P losses (E7) Nutrient surplus soil (E3) and farm (E4)	Soil quality; Water quality; GHG emission
P4	Nutrient Input Gap	Crop/biomass/animal yield (E1) Nutrient uptake(E2)	Agricultural production
P5	Nutrient Use Efficiency (NUE)	Nutrient uptake(E2) Nutrient surplus soil (E3) and farm (E4)	Agricultural production
P6	NUE Gap	NUE (P5)	Agricultural production
P7	Emission Fraction Gap	N & P losses (E7) GHG emissions (E8)	Water quality; GHG emission
P8	Farm-gate C, N and P Efficiency Gap	Nutrient uptake(E2) Nutrient surplus farm (E4)	Agricultural production
P9	Soil Quality Index	Changes of Soil C and nutrient contents/pools (E5) Soil acidity (E6)	Soil quality

** Indicators and class are listed in Annex 1 Table A1 and defined in D1.1 Mitigation Measures Catalogue-first draft version*

***Nutrient refer to N, P, K, Ca, Mg, Na, S, Cu and Zn, possibly Cd.*

**** The "gap" refers to the difference between the current status and the desired status to be defined in WP3.*

The targeted performance and effect indicators are differentiated for the three agricultural pillars:

- For measures involved in the **crop production** pillar, the main target is to enhance the crop productivity while reducing the environmental impact. The soil health status is critical for the capacity of the farming system to maintain the crop productivity and quality as human food, animal feed within natural or managed ecosystem boundaries. Soil pH is a crucial and commonly monitored soil quality index as it influences the nutrient availability and microbial activity. Meanwhile, reducing the risk of N and P losses through leaching and emissions (N_2O and/or NH_3) is a key focus in the NutriBudget project. Therefore, all the listed performance indicators are identified as KPIs for the evaluation and modelling. The associated effect indicators include the **crop/biomass yield (E1) and nutrient uptake (E2), soil nutrient surplus (E3), soil C and nutrient status (E5), soil acidity (E6), N and P losses (including N & P leaching, runoff or NH_3 emissions) (E7) and GHG emissions (E8)**.

- For measures involved in **animal husbandry** and **agro-processing industries** pillars, the focus is mainly on the agricultural production and GHG emissions, involving 7 listed KPIs (except P1 and P9). It is also highlighted that insight understanding of the farm-gate nutrient flows is required to mitigate the NH_3 emission and improve the nutrient budget. Therefore, the associated effect indicators include **crop/biomass yield (E1, optional for some measures), nutrient surplus farm (difference between farm nutrient inputs and outputs) (E4), N and P losses (E7) via NH_3 emissions, and GHG emissions (E8).**

Additionally, the agro-ecological site properties (indicator class A1-A7 in Annex 1 Table A1) encapsulate the comprehensive physical, chemical, and biological attributes of an experimental site, exerting a profound influence on nutrient dynamics within the entire farming system. While these indicators play a pivotal role in delineating the spatial applicability of management practices, their data may not always be available in existing studies. This could be attributed to factors such as these indicators not being the primary focus of the publication or data being accessible only upon request. The absence of data for agro-ecological site properties poses challenges for utilizing these datasets in model calibration and validation. Consequently, it becomes imperative to gather pertinent information for the selected mitigation measures tested in WP4. For example, crucial data regarding climate conditions (precipitation, potential evaporation, mean temperature, sunlight) and basic soil properties (texture, clay and sand content, cation exchange capacity (CEC), bulk density, rootability (soil available water and filtration capacity), groundwater depth, slope, Al and Fe oxides are vital for mitigation measures in crop production pillar. These can be acquired either through on-site measurements or retrieved from open-access databases using the longitude and latitude of the experimental site.

Furthermore, data gaps have been identified for certain driving indicators (indicator class D2, D6, D7, D10 in Annex 1 Table A1) representing animal or processing management practices. These indicators are instrumental in calculating farm-gate nutrient use efficiency and surplus. Of the six mitigation measures associated with animal husbandry, data on manure properties, specifically concentrations of K, S, Ca, Mg, Cu, and Zn, are rarely reported. Addressing these data gaps is crucial for a comprehensive understanding of nutrient dynamics and the effectiveness of proposed mitigation strategies.

Considering the targeted KPIs in each agricultural pillar and the specific focus of each mitigation measure, Table 2 suggests the most relevant effect indicators (marked with an "x") to be monitored for each of the selected mitigation measures. Note that among the listed effect indicators, nutrient surplus in soil (E3) and farm (E4) are usually calculated from the nutrient inputs (driving indicators), nutrient uptake (E2) by crops and animals, N & P losses via leaching (E7) and NH_3 or GHG emissions (E8), therefore they are not included in Table 2 as monitoring indicators.

Note that the mitigation measure **Grass and faba bean as novel protein sources for pig and poultry** focuses mainly on the animal husbandry pillar, therefore the effect indicators E1 and E2 refer to the associated indicators for animals as meat or milk production and nutrient intake by animals.

In summary, impact on soil quality and the associated effect indicators (E5 soil C and nutrient status, E6 soil acidity) are targeted in all the 15 mitigation measures related to crop (13 in crop production pillar, 1 in crop production and animal husbandry pillars, and 1 in crop production, animal husbandry and agro-processing industries pillars). Impact on agricultural production is targeted in 15 mitigation measures in the sense of crop or biomass yield (E1), while Nutrient uptake(E2) is targeted in 12 of the selected mitigation measures. Referring to the impact on N & P losses through runoff, leaching or NH_3 emissions (E7), 6 out of the 19 selected mitigation measures showed specific focus on N & P runoff to surface water, 8 on N & P leaching while 3 on NH_3 emissions. There are also 2 mitigation measures in the crop production pillar targeted to evaluate the impact on GHG emissions (E8).

Table 2 *The targeted effect indicators to be included (marked with an "x") for the evaluation of the selected mitigation measures involved in the three agricultural pillars, i.e. crop production, animal husbandry, and agro-processing industries. Note: the listed mitigation measures are differentiated by the inclusion of agro-pillars: crop production (cells in green); crop production and animal husbandry (cell in light yellow); animal husbandry (cell in dark yellow); animal husbandry and agro-processing industries (cells in light orange); crop production, animal husbandry and agro-processing industries (cells in orange).*

Title of selected mitigation measure	Pilot region	Measure code	crop/biomass /animal yield (E1)	nutrient uptake (E2)	SOC (E5)	soil nutrient status (E5)	soil acidity (E6)	N & P surface runoff (E7)	N & P leaching (E7)	NH_3 or GHG emissions (E8)
Advanced sensor technologies for the application of liquid biobased fertilisers (e.g., pig urine, ammonium sulfate, liquid fraction of digestate, mineral concentrate) to address nutrient variability in fields and products	BE	1	x		x	x	x		x	
Precision fertilisation of bio-based fertilisers and/or mineral fertilisers through multilevel data integration	ES	2	x		x	x	x			
Updating precision injection system to reduce NH3 emission by using BBFs (digestate from organic agro-food waste and sludge).	IT	3	x			x	x			x
Foliar application based on plant analysis	CH	4	x	x		x	x			
Sensor technologies for correcting potential nitrogen deficiency for achieving optimal yields	FI	5	x	x	x	x	x			
Reduction of nutrient losses with deep rooted crops (faba bean) in a no-till system	FI	14	x	x	x	x	x	x	x	
Effect of soil properties on mineralisation of organic matter	FI	15	x	x	x	x	x			
The effect of biological stability degree on carbon and nitrogen	IT	16			x	x	x			
Adapted and balanced fertiliser inputs based on diagnosis by a combination of farmgate balances, soil and plant analysis	CH	17	x	x		x	x			
Mineral fertiliser replacement using digestate and derived products (ammonium sulphate)	IT	18	x	x	x	x	x		x	
Enhanced and optimized fertilisation with upgraded pig manure products to avoid nutrient excess in soil	ES	19	x	x	x	x	x		x	
Mineral fertiliser replacement potential of biobased fertilisers with high N/P ratio	FI	20	x	x	x	x	x			
Deep-rooted nutrient cycling with Kernza perennial cereal to mitigate nutrient losses to soils and groundwaters	ES	22	x	x	x	x	x	x	x	
Advanced NH3 emissions mitigation using Zeolites	ES	7	x	x	x	x	x			x
Grass and faba bean as novel protein sources for pig and poultry	FI	13	x	x						
Duckweed cultivation on agricultural wastewater (pig manure and aquaculture) as alternative protein source for animal feed	BE	10	x	x				x		
Microalgae cultivation on digestate as alternative protein source for animal feed	BE	11	x	x				x		
Constructed wetlands: tertiary treatment of pig manure towards discharge water	BE	21						x		
Dual-purpose Lemna cultivation: green manure production and alternative protein potential	ES	9	x	x	x	x	x	x	x	

3.3 Data gaps to be filled by experimental work

The inventory of the existing research provides a time-based overview of the current state of knowledge about a mitigation measure and suggest directions for future research. During the first stage of data collection in T1.1, a comprehensive inventory of the existing research for the 22 pre-identified mitigation measures resulted in extensive data compilation from 107 existing references, reflecting a broad spectrum of research efforts, publications, and reports. Background research data for the 19 selected mitigation measures was extracted from the first draft of MMC (D1.1) as a separate data matrix to indicate the data availability. Table 3 provides an overview of the data collected in MMC (marked with an "x") or to be collected (highlighted in Yellow) for the relevant effect indicators targeted in the 19 selected mitigation measure.

Table 3 Summary of data collected in the mitigation measures catalogue for the 19 selected mitigation measures. Measures are presented in the same order and color code as in Table 2. Note: E = existing, M = missing. Indicators marked with "E" are available from the Mitigation Measures Catalogue, while indicators marked as "M" and highlighted in yellow are knowledge gaps that need to be filled with WP4 experimental work.

Indicator_categories	Indicator_name	1	2	3	4	5	14	15	16	17	18	19	20	22	7	13	10	11	21	9
Crop/biomass/animal yield (E1)	fresh yield	E	E	M	E					M	M	E		E	M	E	E			E
	dry yield		E		M	E				E		E	E	E	M		E	E	E	E
	grain yield		E	E	E	E	E	E	E	E	E		E	E	M					
Crop/animal nutrient uptake (E2)	N uptake		E	E	M	E	E			M	E	E	E	E	M	M	E	E	E	E
	P uptake				M	E	E			M	M	E	E	M	M	M	E	E	E	E
	K uptake				M	E				M	M	M	E	M	M		E	M	M	M
	S uptake				M	M				M			M				E	M		M
	Ca uptake				M	M				M			M				E	M		M
	Mg uptake				M	M				M			M				E	M		M
	Cu uptake				M	M				M			M				E	M	M	M
	Zn uptake				M	M				M			M				E	M	M	M
soil C and nutrient status (E5)	total C	E	M	M		E	M	E	M		M		E	E	M					M
	Total N	E		M		E	M	E	M		M	E	E	E						
	Total P	E							M					E						
	Total K	E												E						
	Total S																			
	Total Ca	E																		

Indicator_categories	Indicator_name	1	2	3	4	5	14	15	16	17	18	19	20	22	7	13	10	11	21	9
	Total Mg	E																		
	Total Cu																			
	Total Zn																			
	Total Cd																			
	available N	M	M	M	M	E	M	M	M	M	M	M	E		M					M
	available P	M	M		M	E	E	E	M	M	M	M	E		M					M
	available K					E		E					E							
	available Ca					E		E					E							
	available Mg					E		E					E							
	available S																			
	available Zn																			
	available Cu																			
	available Cd																			
Soil acidity (E6)	soil pH	E	E	M	M	E	E	E	E	E	E	E	E	E	E					M
N and P losses /GHG emissions (E7, E8)	cumulated N_2O	E				E					E		E							
	cumulated NH_3			E					E		E				E				E	
	cumulated CH_4			E							E									
	Cumulated CO_2							M	M											
	N load in surface water						M							M			E	E	E	E
	P load in surface water						M							M			E	E	E	E
	NO_3 leaching towards groundwater	M		E							E	E		E						M
	PO_4 leaching towards groundwater										M			M						M
Other	Data available at higher TRL																M			M
	Data available on mechanism insights					M					M	M	M	M						M

It is worth noting that the first version of MMC was a result of data collection at the preliminary stage of the project when the selection of mitigation measures was under processing. The final selection of mitigation measures to be tested in WP4 was only ready by M14, therefore, two scenarios surfaced where the collected information did not seamlessly align with the mitigation measures' focus:

- Certain references for measures lacked relevance;
- Insufficiency or inconsistency in representative references.

To bridge these gaps, targeted meetings with pilot leaders were held to refine the specific focus and identify the challenges pertaining to each mitigation measure. This leads to a more detailed and precise evaluation on the knowledge gap regarding data availability specified for each mitigation measure:

- **Advanced sensor technologies for the application of liquid biobased fertilisers (e.g., pig urine, ammonium sulfate, liquid fraction of digestate, mineral concentrate) to address nutrient variability in fields and products:** Data is available in MMC for crop yield (E1), total nutrients as soil nutrient status (E5), soil acidity (E6), cumulated N2O as GHG emissions (E8), however, there is data gap for plant-available nutrients in soil (N, P, K) and the risk of NO3 leaching towards groundwater.
- **Precision fertilisation of bio-based fertilisers and/or mineral fertilisers through multilevel data integration:** data is available in MMC for crop yield (E1), nutrient uptake (E2) and soil acidity (E6), while data gaps exist in soil C and nutrient status (E5), particularly for the plant-available nutrients (N, P, K). It is worth noting that this mitigation measure implements advanced sensor technologies to detect the crop growth at canopy level, therefore, data for vegetation indices such as normalized difference vegetation index (NDVI) is available.
- **Updating precision injection system to reduce NH3 emission by using BBFs (digestate from organic agro-food waste and sludge:** the collected data in MMC focus on the crop yield (E1), nutrient uptake (E2), soil acidity (E6), NH_3 and GHG emissions (E8) as main impacts, further research should investigate the effect of optimizing digestate distribution device on NH3 emissions (E8) comparing with the results obtained from old distribution device.
- **Foliar application based on plant analysis:** previous data showed main impact on crop yield (E1), further monitoring is needed on the nutrient uptake (E2), soil acidity (E6), soil C and nutrient status (E5), particularly on the total and available fractions of macronutrients (S, Ca, Mg) and trace elements (Cu, Zn).
- **Sensor technologies for correcting potential nitrogen deficiency for achieving optimal yields:** data is available in MMC for crop yield (E1), nutrient uptake(E2), soil C and nutrient status (E5) regarding N, and soil acidity (E6), while data gap exists in the crop uptake of other nutrients (including P, K, Mg, Ca, S), and trace elements (Cu, Zn) and heavy metals (e.g. Cd). There is also a knowledge gap in the effects of additional fertilisation on the yield of grassland as determined by sensor technology.
- **Reduction of nutrient losses with deep rooted crops (faba bean) in a no-till system:** previous research revealed data for crop yield (E1) and nutrient uptake (E2). Data of plant-available P as soil nutrient status (E5), soil acidity (E6) and P load in surface water (E7) is available for cereals. However, this mitigation measure uses deep rooted, N-fixing crop. Therefore, experiments in WP4 it is important to collect data of N and P losses through runoff and leaching (E7), soil C and nutrient status (particularly N) (E5) and acidity (E6).
- **Effect of soil properties on mineralisation of organic matter:** data is available in MMC for crop yield (E1), soil C and nutrient status (E5) and soil acidity (E6), while data collection in WP4 experiment is needed to verify the potential to reduce fertilisation rates based on the clay/C ratio in various soils to prevent yield reduction and nutrient losses. **The effect of biological stability degree on carbon and nitrogen mineralisation:** the publication included in MMC provided data for crop yield (E1), soil C status (E5), soil acidity (E6), NH_3 and GHG emissions

as main impacts, further research in WP4 is needed to explore the impact on the effect of biological stability of organic matter on N mineralization, confirming previous finding.

- **Adapted and balanced fertiliser inputs based on diagnosis by a combination of farmgate balances, soil and plant analysis:** the publications included in MMC provided data for crop yield (E1) and soil acidity (E6), while data gap exists in the impact on nutrient uptake (E2), soil C and nutrient status (E5), in particularly the plant-available nutrients (N, P, K).
- **Mineral fertiliser replacement using digestate and derived products (ammonium sulphate):** previous data revealed impact on crop yield (E1), nutrient uptake (E2), soil acidity (E6), NH_3 and GHG emissions as well as the risk of NO_3 leaching towards groundwater (E7, E8). Further research needs to consolidate data measuring nitrate and P leaching directly in table water (E7). Apart from the already included indicators, it is also suggested to investigate the impact on soil C and nutrient status (E5).
- **Enhanced and optimized fertilisation with upgraded pig manure products to avoid nutrient excess in soil:** previous research included in MMC provided data for crop yield (E1), nutrient uptake (E2), soil total N (E5), soil acidity (E6), as well as NO_3 leaching towards groundwater. It is suggested to further validate these effect indicators in WP4 experimental work, preferably including measurements for the soil C and plant available nutrients.
- **Mineral fertiliser replacement potential of biobased fertilisers with high N/P ratio:** collected data in MMC showed impact of this mitigation measure on crop yield (E1), nutrient uptake (E2), soil C and nutrient status (E5) and soil acidity (E6). To reach a convincing conclusion for the impact, this measure will be tested on grass, having both different growth cycle and fertilisation practices than with cereals. Relevant effect indicators indicated in Table 2 will be monitored to provide new data for grass production.
- **Deep-rooted nutrient cycling with Kernza perennial cereal to mitigate nutrient losses to soils and groundwaters**: previous research provided data for crop yield (E1), nutrient uptake (E2), soil C and nutrient status (E5), soil acidity (E6) and NO_3 leaching towards groundwater (E7), however, given this mitigation measure focus on using deep rooted crops to mitigate the nutrient losses to soils and groundwater, it is important to collect data for N and P loads in surface water and assess the risk of PO_4 leaching towards groundwater.
- **Advanced NH3 emissions mitigation using zeolites:** the publications included in MMC provided the effect of zeolites on mitigation NH_3 emissions from the manure storage phase, while no data is available for the impact regarding the application of zeolite-amended manure on soil and crop. Therefore, the experiment in WP4 should also provide data for crop yield (E1) and nutrient uptake (E2), soil C and nutrient status (E5), soil acidity (E6) and NH_3 emissions.
- **Grass and faba bean as novel protein sources for pig and poultry:** as this mitigation measure focuses mainly on animal husbandry, data is available in MMC for the animal productivity and the nutrient excreted in animal manure, however, there is knowledge gap regarding the nutrient use efficiency of these animals when fed with grass and faba bean as alternative protein. Therefore, WP4 experiment should provide data for the digestibility of these novel feeds to pig and poultry, as well as the nutrient intake by these animals.
- **Duckweed cultivation on agricultural wastewater (pig manure and aquaculture) as alternative protein source for animal feed:** data collected from previous research revealed the impact on the biomass yield (E1) and nutrient uptake (E2) as well as the nutrient loads in effluent which is discharged to surface water (E7). However, these impacts were observed mainly in lab and pilot scale experiments, it is suggested to perform long-term and upscaling investigation on these indicators in WP4.
- **Microalgae cultivation on digestate as alternative protein source for animal feed:** similar to the mitigation measure using duckweed cultivation, previous research focusing on microalgae cultivation revealed impact on the biomass yield (E1) and nutrient uptake (E2) as well as the nutrient loads in effluent which is discharged to surface water (E7). Further validation of these impact in pilot scale is suggested for WP4 experimental work.

- **Constructed wetlands: tertiary treatment of pig manure towards discharge water:** the mitigation impact of constructed wetlands is mainly reflected on the nutrient loads in effluent which is discharged to surface water (E7), either with or without plant or biomass growing. This has been done mainly for N and P, while nutrients such as K, Cu and Zn have been overlooked. The WP4 pilot will monitor these elements besides N and P, providing a more long-term view of the system. Moreover, the implementation of a duckweed pont for nutrient recovery and efficiency increase of constructed wetlands is a novel approach not explored before.
- **Dual-purpose Lemna cultivation: green manure production and alternative protein potential:** this mitigation measure includes two stages of management practice, being the manure processing using Lemna cultivation and the soil application of Lemna biomass as green manure. Therefore this mitigation measure reveals potential impact on crop/biomass yield (E1), nutrient uptake (E2), soil C and nutrient status (E5), soil acidity (E6), N & P load to surface water and leaching towards groundwater (E7). Existing data collected in MMC focus mainly on the impact of Lemna cultivation, while data gaps exist in the impact of Lemna biomass as green manure in soil application. The experimental work in WP4 is supposed to collect data on the crop/biomass yield (E1), nutrient uptake (E2), soil C and nutrient status (E5), soil acidity (E6), N & P leaching towards groundwater (E7).

In addition to these identified knowledge gaps, depending on the focus of the mitigation measures, more measurements on soil, crop and fertiliser properties are planned in each pilot region to provide necessary data for the agro-ecological site properties (indicator class A1-A7 in Annex 1 Table A1) and driving indicators (indicator class D2, D6, D7, D10). Detailed experimental plan is explained in D4.2 *Description of experimental set-up and methods used in each pilot* as submitted in January 2024.

3.4 Knowledge gap in standardised analytical methods

Upon cross-checking the compiled data in the catalogue, it becomes evident that the knowledge gaps extend beyond the mere impact of the mitigation measures. Notably, there are substantial disparities in the evaluation methodologies applied across the five pilot regions, introducing a potential knowledge gap due to the heterogeneity of analytical methods. This heterogeneity is exemplified by:

- the determination of available nutrient fractions in soil and fertilising products, which is crucial for assessing plant availability and the risk of nutrient leaching to groundwater, exhibits significant variations in definition and analytical methods. According to the discussion with the five pilot regions, mainly three forms of nutrients can be defined as bioavailable (i) water soluble; (ii) extractable by certain salt solutions, e.g. 1M KCl or 0.01M $CaCl_2$ solutions; (iii) mineralisable after certain period of aerobic or anaerobic incubation (mainly for N);
- for P and metals in soil samples, one often distinguishes extraction methods in plant available (extracted by weak salt solutions or water), reactive (extracted by HNO_3, including the pool that is sorbed, buffering the actual metal concentration in solution) and total (extracted by Aqua regia, a 1:3 mixture of concentrated nitric and hydrochloric acids);
- disparate protocols for measuring Cation Exchange Capacity (CEC). The most commonly used methods are (i) Ammonium Acetate method of Schollenberger and Dreibelbis (1930) buffered at pH 7; (ii) barium chloride-triethanolamine method of Mehlich (1938) buffered at pH 8.2; (iii) Compulsive exchange ($MgSO_4$/$BaCl_2$) at soil pH described by Houba et al. (1989); (iv) Cobalt (III) hexamine chloride method at soil pH (Cohex) as described by Ciesielski et al. (1997). The different CEC protocols vary differ in the type and concentration of the exchanging cation, the soil to solution ratio, single or multiple extractions, the contact time, phase separation, and analytical detection methods. The efficiency of the different analytical methods may also be affected by the soil properties such as pH, clay and organic matter contents given the wide geographic distribution of these pilot regions;

- the inability to universally adapt protocols in all pilot regions, primarily due to equipment limitations, exacerbates this issue. For example, colorimetric analysis, atomic absorption spectrometer (AAS) or inductively coupled plasma (ICP) facilitated with optical emission spectrometry (OES) or atomic emission spectrometry (AES) are commonly used to quantify the concentration of elements after extraction process; however, the accuracy and efficiency of the measurements may differ due to the detection limits of each equipment.

These discrepancies yield diverse results across individual studies, posing challenges in the comparison and evaluation of findings across different farming systems, studies, and regions. The current literature, therefore, lacks concrete conclusions due to these methodological disparities. To address this, a pressing need arises to establish a standardised protocol with common analytical methods for the effect indicators targeted in WP4 experimental work. After interactive discussions between five pilot regions and WP2/3 leaders, a list of preferred analytical methods has been established (Table 4) for effect indicators related to soil, plant and fertiliser measurements, which have been included in the experimental plan of all pilot regions. Such standardisation would not only facilitate comparability between countries, climate regions, and agricultural systems but also provide results directly applicable to models in WP2 for comprehensive evaluation.

Table 4 *Preferred analytical methods for soil, plant and fertiliser analysis in the five pilot regions.*

	Indicators	Analytical methods	Additional remark
Soil analyses	pH	Soil solution (both deionized water and 0.01 M $CaCl_2$) suspension in a ratio of 1:5 (w/v). pH is measured from the suspension using a glass electrode.	Soil sample is air-dried and sieved through a mesh (< 2 mm)
	Dry matter (moisture content)	Oven drying (105°C), gravimetric method	
	Plant available/easily soluble pools	Olsen-P following the method by Olsen and Somers (1982). Soil is extracted with 0.5 M $NaHCO_3$ (pH 8.5) at 1:20 soil:extractant (w/v) ratio and measured colorimetrically.	Widely used as one of the soil fertility indicators, not appropriate for soils which are mild to strongly acidic (pH <6.5)
		NH_4-N and NO_3-N is extracted with 1M KCl at 1:5 w/v, colourimetric determination.	Alternatively, NH_4-N and NO_3-N can be measured from 0.01 M $CaCl_2$ or water extracts.
	Total elements (P, K, S, Ca, Mg, Cu, Zn, Cd)	Aqua regia digestion by microwave and measured by ICP-OES or ICP-AES	Soil samples from top soil (0-30 cm) should be characterised for total elements.
	Total C and N	Dry combustion and CHN elemental analyser	Results of total N measured by dry combustion and Kjeldahl method are comparable (Oxenham et al., 1983)
	Total N	Kjeldahl method	
	Soil organic carbon (SOC)	Walkley and Black method	SOC results obtained from these two methods are comparable (Richardson and Bigler 1982)
		Dry combustion and elemental analyser	
	Cation exchange capacity (CEC)	Ammonium-saturation method using 1 M ammonium acetate at pH =7 (Van Ranst et al., 1999, Räty et al. 2021)	Results from different methods can be comparable depending on the soil pH (Hendershot and Duquette 1986; Ngewoh et al. 1989)
		Barium chloride solution (pH = 8.1) extraction method (Rhoades 1982, ISO 13536: 1997-04)	
		Cobalt hexamine trichloride extraction method (ISO 23470, 2007)	

	Indicators	Analytical methods	Additional remark
	Soil texture	Sieving and sedimentation method (Elonen 1971, Gee and Bauder 1986).	Soil texture is identified through USDA Classification System based on the particle size distribution of sand, silt and clay fractions.
Plant material and biomass (e.g. duckweed) analyses	Dry matter	Gravimetric after oven dry at 60°C or 65°C	Temperature depending on the type of plant or biomass samples
	Total elements (P, K, Ca, Mg, S, Cu, Zn, Cd)	Microwave digestion with HNO_3 and measured by ICP-OES or ICP-AES	
	Crude protein content	Calculated from total N measured by Kjeldahl method	Total N content is converted to crude protein by multiplying with 6.25 (Devlamynck, et. Al., 2021)
	Total C and N	Dry combustion and elemental analyser	
BBF analyses	Dry matter	Gravimetric after oven dry at 105 °C	
	Total elements (P, K, Ca, Mg, S, Cu, Zn, Cd)	Aqua regia digestion in a microwave oven and measured by ICP-OES or ICP-AES	When BBFs are used as C and/or nutrient inputs, full characterisation of the total elements should be performed in order to evaluate the impact.
		Microwave digestion with HNO_3 and measured by ICP-OES or ICP-AES	
	Total N	Kjeldahl method	

3.5 Additional remarks for modelling

There are also some indicators that are of high relevance to soil quality and water quality but facing challenges in on-site monitoring.

- Along with the climate change, extreme weather events (e.g. flooding) are observed worldwide at a higher frequency, leading to an increasing concern on the risk of N and P run-off from arable farms to surface waterbodies. However, this can highly depend on the climate conditions and regulations in each pilot region. For example, in Flanders, there is usually quite much precipitation during summer, so the crop is rainfed and no irrigation is allowed during the growing season (to reduce the N and P leaching risk); consequently the risk of nutrient run-off will probably be low and undetectable. In regions with low precipitation during the growing season (e.g. Spain and Italy), irrigation or fertigation is applied, therefore it is reasonable to assess the N and P run-off risk. Considering a higher impact of regional situations over the agricultural management, a modelling approach may be a better option to fill the knowledge gap regarding the risk of N and P run-off in specific regions.

- The risk of N and P leaching towards groundwater is another indicator relevant to the EU Nitrates Directive (91/676/EEC). Again there are various methods to determine the N and P leaching risk, for example, pre-set lysimeters are widely used to capture the water lost through the soil where the N and P concentrations are measured; another method measures N and P concentrations in soil samples taken from certain depth. Moreover, in some regions (e.g. Finland), it is difficult to take lysimeter or soil samples until the depth of groundwater level, leaving a knowledge gap in precisely determining the leaching risk towards groundwater. In this case, a modelling approach can be a back-up for the experimental results and simulate the water and nutrients flow towards unsampled soil depth.

- The challenge existing for GHG emissions reveals a different angle: the complex nature of agricultural systems resulted in inherent variability and dynamics of emission in response to the type of crop, animal, soil, and environmental conditions. Data from direct GHG flux measurements is usually limited to controlled laboratory conditions or covers only a short period, leaving gaps to evaluate the climate-induced impact over a longer observation period. Modelling provides a systematic framework to simulate and understand the intricate processes influencing GHG emissions. It allows researchers to integrate diverse data sources, account for spatial and temporal variations, and estimate emissions under different scenarios, without solely relying on direct measurements. Furthermore, models provide a cost-effective means to explore various scenarios and predict the outcomes of different interventions, enabling the evaluation of the effectiveness of mitigation strategies and the identification of optimal management practices to minimize GHG emissions.

It is noteworthy that updated data pertaining to the tested mitigation measures will only become available towards the conclusion of the project. Consequently, modelling of the nutrient flows (dynamics of leaching and emissions) will be initially based on literature data. Based on the currently existing dataset for the selected measures, a meta-analytical approach is employed in Task 1.2 - Quantify measure-impact relationships and Task 1.3 - Develop algorithms for the spatial applicability of measures, which aim to assess the applicability and efficiency of measures depending on agro-ecological site-specific factors at European scale. The outcomes of these tasks will contribute to the calibration and validation of predicted measure impacts by the empirical and process-based models in WP2. Simultaneously, the results of measurements in WP4 will serve to further validate the modelling assessments under specific conditions. However, the absence of continuous monitoring for nutrient flows such as run-off, leaching, or greenhouse gas emissions in either literature or the planned pilot studies may introduce assumptions or limitations in modelling simulations. Consequently, the interpretation of the estimated impact should be accompanied by an elucidation of the implementation conditions for both the measure and the modelling work.

4. Conclusions and recommendations

On the basis of interactive discussion with pilot leaders and the inventory of existing research for the 19 selected mitigation measures to be tested in WP4, three types of knowledge gap are identified:

1) Data gap is identified by matching the existing data in MMC with the targeted indicators to evaluate the agronomic and environmental impact. Within the crop production pillar, data gaps are notable on soil C and nutrient status, particularly the plant-available nutrients in soil (N, P, K) and N leaching towards groundwater. For mitigation measures involved in the animal husbandry and agro-processing pillars, the data gap exists mainly on the farm-level nutrient flow which limits the evaluation of the farm-gate nutrient use efficiency.
2) Several innovative mitigation measures such as duckweed and microalgae cultivation exhibit knowledge gaps at higher TRLs, especially when moving from lab to pilot scale.
3) Knowledge gaps also arise from conflicting and inconclusive existing data due to the variation in the agro-ecosystem properties such as climate conditions and soil properties, or the heterogeneity of measurement methods between studies.

To fill the knowledge gaps associated with the implementation and evaluation of mitigation measures, there is a need for combination of experimental work and modelling approaches to collect more convincing evidence for the impact of the selected mitigation measure. Moreover, a standardised protocol is highly recommended for measurement of the relevant indicators, leading to a more nuanced understanding of their real-world impact and effectiveness.

Annexes

Annex 1 Summary of the effect indicators included in the data matrix

Table A1 List of the relevant indicators in the first version of mitigation measures catalogue (MMC).

Indicator_category	Indicators		Indicator_name	Commonly used unit ("-" represents "undefined")	Remark
	Type (See D1.1 first draft)	Class			
General Experimental Data	experimental conditions	GE1	measure code	-	e.g. 001, 002, 003
	experimental conditions	GE1	treatment code	-	BS= baseline, T1 = treatment 1, T2 = treatment 2; etc.
	experimental conditions	GE1	treatment details	-	specify the material used in the treatment
	experimental conditions	GE1	technological or nature-based measure	-	fill in TES (technological) or NBS (nature-based)
	experimental conditions	GE1	category	-	choose from six categories defined in DoA
	experimental conditions	GE1	subcategory	-	choose from the pre-defined shortlist
	experimental conditions	GE1	institute	-	name of institute
	experimental conditions	GE1	data entry	-	name of the responsible person (confidential)
	experimental conditions	GE1	contact	-	email of the responsible person (confidential)

Indicator_category	Indicators		Indicator_name	Commonly used unit ("-" represents "undefined")	Remark
	Type (See D1.1 first draft)	Class			
	experimental conditions	GE1	Time frame	-	Period of the experimental work: dd/mm/yyyy- dd/mm/yyyy
	experimental conditions	GE1	Spatial frame	-	GPS location including longitude and latitude
Farming system type	ecosystem property	A1	farm system	-	choose a category: conventional, agro-ecological, biological
Basic soil property	ecosystem property	A2	soil type	-	Specify the classification system, WRB or USAD
	ecosystem property	A2	groundwater depth	cm	in cm
	ecosystem property	A2	slope	-	in degree
	ecosystem property	A2	SOM content	%	0-30cm. Specify measuring method, e.g. Walkley Black
	ecosystem property	A2	Fe oxide content	-	extraction of soil via oxide extraction
	ecosystem property	A2	Al oxide content	-	extraction of soil via oxide extraction
	ecosystem property	A2	Cation exchange capacity (CEC)	-	specify measuring method, e.g. BaCl2-compulsive exchange procedure
	ecosystem property	A2	clay content	-	specify measuring method, e.g. pipette method
	ecosystem property	A2	sand content	-	specify measuring method, e.g. pipette method

Indicator_category	Indicators		Indicator_name	Commonly used unit ("-" represents "undefined")	Remark
	Type (See D1.1 first draft)	Class			
	ecosystem property	A2	silt content	-	specify measuring method, e.g. pipette method
	ecosystem property	A2	bulk density	kg/m3	specify measuring method, e.g. gravimetry
Optional Soil Properties	ecosystem property	A3	Particulate organic matter (POM) content	-	0-30cm. Specify measuring method, e.g. Walkley Black
	ecosystem property	A3	dissolved organic matter (DOM) content	-	0-30cm. Specify measuring method, e.g. Walkley Black
	ecosystem property	A3	light fraction organic matter (LFOM) content	-	0-30cm. Specify measuring method, e.g. Walkley Black
	ecosystem property	A3	soil organic carbon (SOC) content	%	specify evaluation method, e.g., Walkley-Black chromic acid wet oxidation method. (0-30 cm)
	ecosystem property	A3	C-stock (topsoil)	kg/ha	0-30 cm (specify evaluation method, e.g., how is the bulk density measured?)
	ecosystem property	A3	C-stock (subsoil)	kg/ha	30-60 cm (specify evaluation method, e.g., how is the bulk density measured?)
	ecosystem property	A3	Soil biological activity (soil respiration)	kg CO2 per day	specify measuring method, e.g. Aerobic incubation
	ecosystem property	A3	Potential Mineralizable Nitrogen (PMN)	%	specify measuring method, e.g. Aerobic incubation
	ecosystem property	A3	bacterial biomass	g/kg FW	specify measuring method, e.g. Plate culture
	ecosystem property	A3	Fungal Biomass	g/kg FW	specify measuring method, e.g. Plate culture

Indicator_category	Indicators		Indicator_name	Commonly used unit ("-" represents "undefined")	Remark
	Type (See D1.1 first draft)	Class			
	ecosystem property	A3	Biodiversity (total number of taxa)	copies/g FW	specify measuring method, e.g. Plate culture
	ecosystem property	A3	C, N microbial biomass	g/kg FW	specify measuring method, e.g. Chloroform fumigation
	ecosystem property	A3	infiltration capacity	m/day	
	ecosystem property	A3	water field capacity	% water in soil DW	
	ecosystem property	A3	wilting point	% water in soil DW	Measure soil water retention pF-curve
	ecosystem property	A3	available water capacity	-	water field capacity minus wilting point
Climatic conditions	ecosystem property	A4	precipitation	-	annual, growing season
	ecosystem property	A4	evapotranspiration	-	annual, growing season
	ecosystem property	A4	mean temperature	-	annual, growing season
	ecosystem property	A4	mean radiation	-	annual, growing season
	ecosystem property	A5	climatic zone	-	choose a category: Atlantic, Continental, Mediterranean, Boreal
bioprocessing system	ecosystem property	A6	treatment capacity	-	specify the treated volume of feedstock

Indicator_category	Indicators		Indicator_name	Commonly used unit ("-" represents "undefined")	Remark
	Type (See D1.1 first draft)	Class			
	ecosystem property	A6	production	-	specify the type and volume of final products
	ecosystem property	A6	operating expense (OPEX)	-	specify in Euro
	ecosystem property	A6	Capital expenditures (CapEx)	-	specify in Euro
livestock system	ecosystem property	A7	manure storage	-	choose a category: open, closed, …
	ecosystem property	A7	ammonia strippers	-	yes/no
System Nutrient inputs (note: nutrient input at the beginning point of the whole system, e.g. for animal system and for combined animal-bioprocessing system, it refers to the animal feed; for field system and combined bioprocessing-field system, it refers to fertilisers; and for bioprocessing system it refers to the feedstock treated)	driver	D1	total N input	kg/ha or kg/farm	specify measuring method
	driver	D1	total P input	kg/ha or kg/farm	specify measuring method
	driver	D1	total K input	kg/ha or kg/farm	specify measuring method
	driver	D1	total S input	kg/ha or kg/farm	specify measuring method
	driver	D1	total Ca input	kg/ha or kg/farm	specify measuring method
	driver	D1	total Mg input	kg/ha or kg/farm	specify measuring method
	driver	D1	total Cu input	kg/ha or kg/farm	specify measuring method
	driver	D1	total Zn input	kg/ha or kg/farm	specify measuring method
	driver	D1	total Cd input	kg/ha or kg/farm	specify measuring method

Indicator_category	Indicators		Indicator_name	Commonly used unit ("-" represents "undefined")	Remark
	Type (See D1.1 first draft)	Class			
System Nutrient outputs (note: nutrient output at the endpoint of the whole system, e.g. for animal system, it refers to animal meat; for bioprocessing system and combined animal-bioprocessing system, it refers to the final and by-products; for field system and combined bioprocessing-field system, it refers to crop)	driver	D1	total N input	kg/ha or kg/farm	specify measuring method
	driver	D1	total P input	kg/ha or kg/farm	specify measuring method
	driver	D1	total K input	kg/ha or kg/farm	specify measuring method
	driver	D1	total S input	kg/ha or kg/farm	specify measuring method
	driver	D1	total Ca input	kg/ha or kg/farm	specify measuring method
	driver	D1	total Mg input	kg/ha or kg/farm	specify measuring method
	driver	D1	total Cu input	kg/ha or kg/farm	specify measuring method
	driver	D1	total Zn input	kg/ha or kg/farm	specify measuring method
	driver	D1	total Cd input	kg/ha or kg/farm	specify measuring method
Manure / feedstock/final product properties	driver	D7	Total C in manure / feedstock/final product	g/kg DW	specify measuring method
	driver	D7	Total N in manure / feedstock/final product	mg/kg	specify measuring method, e.g. Kjeldahl
	driver	D7	total P in manure / feedstock/final product	mg/kg	specify measuring method, e.g. ICP-OES
	driver	D7	total K in manure / feedstock/final product	mg/kg	specify measuring method, e.g. ICP-OES
	driver	D7	total S in manure / feedstock/final product	mg/kg	specify measuring method, e.g. ICP-OES

Indicator_category	Indicators		Indicator_name	Commonly used unit ("-" represents "undefined")	Remark
	Type (See D1.1 first draft)	Class			
	driver	D7	total Ca in manure / feedstock/final product	mg/kg	specify measuring method, e.g. ICP-OES
	driver	D7	total Mg in manure / feedstock/final product	mg/kg	specify measuring method, e.g. ICP-OES
	driver	D7	total Cu in manure / feedstock/final product	mg/kg	specify measuring method, e.g. ICP-OES
	driver	D7	total Zn in manure / feedstock/final product	mg/kg	specify measuring method, e.g. ICP-OES
	driver	D7	total Cd in manure / feedstock/final product	-	specify measuring method, e.g. ICP-OES
Crop management Measures	driver	D8	use of catch crops	-	yes/no or area catch crops / total area cultivated
	driver	D8	use of straw incorporation	-	yes/no or area straw incorporated
	driver	D8	use of strip cultivation	-	yes/no
	driver	D8	use of integrated pest management	-	yes/no
	driver	D3	application technology method	-	choose a category from: broadcasted, injected, banded, satellite based, …
	driver	D4	application type	-	choose a category from: inorganic (nh4, no3, NP, etc), organic, animal manure, compost, etc.
	driver	D5	method used to optimize timing	-	choose a category from: split, weather dependent, etc (exact to be defined)
	driver	D6	area per crop	-	area (ha) per crop
	driver	D6	crop sequence	-	crop sequence order

Indicator_category	Indicators		Indicator_name	Commonly used unit ("-" represents "undefined")	Remark
	Type (See D1.1 first draft)	Class			
	driver	D6	area proportion nature / non-productive	-	calculated form area crops / area farm
Soil Management Measures	driver	D9	soil is frequently limed to optimize pH	-	yes/no
	driver	D9	soil tillage depth	cm	cm
	driver	D9	use of biostimulants	-	yes/no
	driver	D9	use of drainage systems	-	yes/no
Animal and Manure Measures	driver	D10	number of animals (livestock density)	-	livestock density
	driver	D10	grazing period	-	number of days in a year
	driver	D10	animal category	-	choose a category: cattle, pigs, poultry, etc.
	driver	D10	manure treatment technology	-	choose a category: liquid separation, etc
crop/biomass yield	effect	E1	fresh yield	t/ha	Specify crop species
	effect	E1	dry yield	t/ha	Specify crop species
	effect	E1	grain yield	t/ha	Specify crop species
Crop nutrient uptake	effect	E2	N uptake	kg/ha	Specify crop species, on dry weight basis
	effect	E2	P uptake	kg/ha	Specify crop species, on dry weight basis
	effect	E2	K uptake	kg/ha	Specify crop species, on dry weight basis
	effect	E2	S uptake	kg/ha	Specify crop species, on dry weight basis
	effect	E2	Cd uptake	kg/ha	Specify crop species, on dry weight basis

Indicator_category	Indicators		Indicator_name	Commonly used unit ("-" represents "undefined")	Remark
	Type (See D1.1 first draft)	Class			
	effect	E2	Ca uptake	kg/ha	Specify crop species, on dry weight basis
	effect	E2	Mg uptake	kg/ha	Specify crop species, on dry weight basis
	effect	E2	Cu uptake	kg/ha	Specify crop species, on dry weight basis
	effect	E2	Zn uptake	kg/ha	Specify crop species, on dry weight basis
	effect	E2	normalized difference vegetation index (NDVI)	-	specify the measuring method, e.g. UAV-based spectra sensing
	effect	E2	triangular greenness index (TGI)	-	specify the measuring method, e.g. UAV-based spectra sensing
	effect	E2	green leaf index (GLI)	-	specify the measuring method, e.g. UAV-based spectra sensing
	effect	E2	leaf area index (LAI)	-	specify the measuring method, e.g. UAV-based spectra sensing
	effect	E2	Visible Atmospherically Resistant Index(VARI)	-	specify the measuring method, e.g. UAV-based spectra sensing
Nutrient surplus soil	effect	E3	N surplus	kg/ha	calculate soil balance, nutrient surplus as difference between input and crop uptake
	effect	E3	P surplus	kg/ha	calculate soil balance, nutrient surplus as difference between input and crop uptake
	effect	E3	K surplus	kg/ha	calculate soil balance, nutrient surplus as difference between input and crop uptake
	effect	E3	S surplus	kg/ha	calculate soil balance, nutrient surplus as difference between input and crop uptake
	effect	E3	Ca surplus	kg/ha	calculate soil balance, nutrient surplus as difference between input and crop uptake

Indicator_category	Indicators		Indicator_name	Commonly used unit ("-" represents "undefined")	Remark
	Type (See D1.1 first draft)	Class			
	effect	E3	Mg surplus	kg/ha	calculate soil balance, nutrient surplus as difference between input and crop uptake
	effect	E3	Cu surplus	kg/ha	calculate soil balance, nutrient surplus as difference between input and crop uptake
	effect	E3	Zn surplus	kg/ha	calculate soil balance, nutrient surplus as difference between input and crop uptake
	effect	E3	Cd surplus	kg/ha	calculate soil balance, nutrient surplus as difference between input and crop uptake
Nutrient surplus farm	effect	E4	N surplus	kg/farm	calculate farm gate balance, nutrient balance as difference between input and output
	effect	E4	P surplus	kg/farm	calculate farm gate balance, nutrient balance as difference between input and output
	effect	E4	K surplus	kg/farm	calculate farm gate balance, nutrient balance as difference between input and output
	effect	E4	S surplus	kg/farm	calculate farm gate balance, nutrient balance as difference between input and output
	effect	E4	Ca surplus	kg/farm	calculate farm gate balance, nutrient balance as difference between input and output
	effect	E4	Mg surplus	kg/farm	calculate farm gate balance, nutrient balance as difference between input and output
	effect	E4	Cu surplus	kg/farm	calculate farm gate balance, nutrient balance as difference between input and output
	effect	E4	Zn surplus	kg/farm	calculate farm gate balance, nutrient balance as difference between input and output

Indicator_category	Indicators		Indicator_name	Commonly used unit ("-" represents "undefined")	Remark
	Type (See D1.1 first draft)	Class			
	effect	E4	Cd surplus	kg/farm	calculate farm gate balance, nutrient balance as difference between input and output
soil C and nutrient status	effect	E5	total C	mg/kg	specify measuring method
	effect	E5	total N		specify measuring method, e.g. Kjeldahl
	effect	E5	total P	mg/kg	specify measuring method, e.g. ICP-OES
	effect	E5	total K	mg/kg	specify measuring method, e.g. ICP-OES
	effect	E5	total S	mg/kg	specify measuring method, e.g. ICP-OES
	effect	E5	total Ca	mg/kg	specify measuring method, e.g. ICP-OES
	effect	E5	total Mg	mg/kg	specify measuring method, e.g. ICP-OES
	effect	E5	total Zn	mg/kg	specify measuring method, e.g. ICP-OES
	effect	E5	total Cu	mg/kg	specify measuring method, e.g. ICP-OES
	effect	E5	total Cd	mg/kg	specify measuring method, e.g. ICP-OES
	effect	E5	available N (NO3, NH4)	mg/kg	plant available, specify measuring method, e.g. CaCl2 or soil solution (rhizon)
	effect	E5	available P (PO4)	mg/kg	plant available, specify measuring method, e.g. CaCl2 or soil solution (rhizon)
	effect	E5	available K	mg/kg	plant available, specify measuring method, e.g. CaCl2 or soil solution (rhizon)
	effect	E5	available S	mg/kg	plant available, specify measuring method, e.g. CaCl2 or soil solution (rhizon)
	effect	E5	available Ca	mg/kg	plant available, specify measuring method, e.g. CaCl2 or soil solution (rhizon)

Indicator_category	Indicators		Indicator_name	Commonly used unit ("-" represents "undefined")	Remark
	Type (See D1.1 first draft)	Class			
	effect	E5	available Mg	mg/kg	plant available, specify measuring method, e.g. CaCl2 or soil solution (rhizon)
	effect	E5	available Zn	mg/kg	plant available, specify measuring method, e.g. CaCl2 or soil solution (rhizon)
	effect	E5	available Cu	mg/kg	plant available, specify measuring method, e.g. CaCl2 or soil solution (rhizon)
	effect	E5	available Cd	mg/kg	plant available, specify measuring method, e.g. CaCl2 or soil solution (rhizon)
Soil acidity	effect	E6	pH	-	specify measuring method, e.g. pH-water or pH-KCl
N and P losses / GHG emissions	effect	E7	cumulated N2O	-	specify measuring method, e.g. in-situ gas chamber
	effect	E7	cumulated NH3	-	specify measuring method, e.g. in-situ gas chamber
	effect	E7	N-load surface water	-	specify measuring method, e.g. Lysimeters, runoff sampler
	effect	E7	P-load surface water	-	specify measuring method, e.g. Lysimeters, runoff sampler
	effect	E7	NO_3 concentration in groundwater	-	specify measuring depth in cm, using extraction, rhizon, soil centrifugation
	effect	E7	PO4 concentration in groundwater	-	specify measuring depth in cm, using extraction, rhizon, soil centrifugation
	effect	E8	cumulated CH4	-	specify measuring method, e.g. in-situ gas chamber
Biodiversity	effect	E9	crop biodiversity index	-	calculate this from crop (rotation) areas from field monitoring / satellite data
Farm Energy Balance	effect	E10	total energy consumption	KWh/day	in the form of natural gas, coal or electricity, etc.
	effect	E10	total energy generation	KWh/day	in the form of methane, residual heat reuse, etc.

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Optimisation of nutrient budget in agriculture

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