Nutri2Cycle
Nurturing the Circular Economy

Nutri2Cycle

D.4.2 Upscaling and quantifying effects at regional, national and EU level

Deliverable:	Upscaling and quantifying effects at regional, national and EU level
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Abbreviations

AD	Anaerobic Digestion
CAPRI	Common Agricultural Policy Regional Impact Analysis
CAP	Common Agricultural Policy
CH_4	Methane
CNP	Carbon Nitrogen Phosphorus
CO_2	Carbon dioxide
ECAMPA	Economic assessment of GHG mitigation policy options for EU agriculture
EU	European Union
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies
GHG	Greenhouse Gas
GPS	Global Positioning Systems
GWP	Global Warming Potential
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
K_2O	Potassium Oxide
LL	Long List Number
LSU	Livestock Units
N	Nitrogen
N-Surplus	Nitrogen Surplus
NH_3	Ammonia
NH_4NO_3	Ammonium Nitrate
NH4-N	Ammonium nitrogen
NIRS	Near-Infrared Sensors
N_2O	Nitrous Oxide
NO_X	Nitrogen Oxides
NO_3	Nitrate

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NTF	National Task Force
NUTS 2	Nomenclature of Territorial Units for Statistics
OC	Organic Carbon
OM	Organic matter
P_2O_5	Phosphorus pentoxide
P	Phosphorus
PRIMES	Price-Induced Market Equilibrium System
SRL	Sub Research Line
VCS	Voluntary Coupled Support
WP	Work Package

Glossary

Aggregated effects : Total effects integrated across sectors and/or regions.

Anaerobic digestion: A series of biological processes in which microorganisms break down biodegradable material in the absence of oxygen and produce biogas (consisting of methane and carbon dioxide).

Baseline levels: In a scientific study, a value is recorded at the beginning of the study that measures the impact of an intervention.

Calibration: Is the process of configuring an instrument to provide a result for a sample within an acceptable range.

CAPRI model: Is a global partial equilibrium model for the agricultural sector, with a focus on the European Union.

Common agricultural policy: Food, the environment, and the countryside are the three main pillars of the Common Agricultural Policy (CAP). As a partnership between society and agriculture, CAP safeguards farmers' income, protects the environment, and keeps rural areas vibrant.

Cost function: It is a mathematical formula that shows how production costs will change with output.

Digestibility: Feed or nutrients are digested as a percentage of the amount consumed usually expressed as a percentage.

Extrapolation: Is a statistical technique aimed at inferring or forecasting the unknown from the known.

Elasticity: This is a measure of the responsiveness of one variable to changes in another. An example of price elasticity of demand is how sensitive the quantity demanded is to changes in its price relatively small.

Endogenous variables: In a statistical model, endogenous variables are variables whose values are determined by their relationships with other variables. The endogenous variables are dependent variables, which means that they are correlated with other factors, though they can be positively or negatively correlated.

Non-linear: Is a change that is not based on a simple proportional relationship between cause and effect.

Marginal profit: Is the amount of additional profit earned by a firm or individual by producing and selling one additional unit of its product or service.

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Market Equilibrium*:* Is a market state where the supply in the market is equal to the demand in the market.

MITERRA-EUROPE: Is a deterministic and static N cycling model which calculates N emissions on an annual basis, using N emission factors and N leaching fractions. A carbon module is also included, which calculates soil organic carbon changes using the default IPCC methodology.

Mitigation technology: Encompasses technologies and practices that can lead to a reduction in greenhouse gas (GHG) emissions or increase the capacity of carbon sinks to absorb GHGs from the atmosphere.

Iterations: The repeating of an action or process or a procedure in which repetition of a sequence of operations yields results successively closer to a desired result.

Livestock Unit: A standard measurement used in agriculture and livestock management to quantify the feed requirements and relative size of different types of livestock or animals on a farm. It is a way to standardize the assessment of the resource needs and carrying capacity of a particular land area or pasture.

National Task Force (NTF): A network of relevant local Operational Groups, local farmers/farmer organisations, other stakeholders at national/regional level interested in nutrient recovery and recycling and operating in the target countries.

Nutrient recycling: The continued recovery, transfer and use (with possible temporary accumulations) of nutrients between different compartments (soil, plants, animals, humans, water, air) and trophic levels in the biosphere.

Positive mathematical programming: A method developed for calibrating agricultural production models using nonlinear yield or cost functions. At the regional or farm levels, nonlinear parameters are implicit in the observed land allocation decisions.

Voluntary coupled support: Is a production-limiting scheme and is designed to limit the distortion of market competition. The VCS scheme aims to prevent the escalation of these difficulties, which could cause production abandonment and affect other parts of the supply chain or associated markets.

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Executive Summary

In this deliverable, we explored the potential mitigation potential of technology options from WP2 in Nutri2Cycle feasible for modelling in CAPRI and MITTERA-Europe, incrementally increasing their implementation share from the assumed initial level to the maximum level possible. These scenarios involve the exclusive application of one mitigation technology at a time, keeping other technologies at their baseline levels. Each scenario and technology is compared against the 2030 baseline in both CAPRI and MITERRA-Europe, with manure treatment practices modelled exclusively in MITERRA-Europe. The findings presented in this deliverable show the potential impact of Nutri2Cycle technologies on agricultural greenhouse gas (GHG) emissions, mineral fertiliser and manure use, leaching and N-surplus in the European Union by 2030. The findings presented in this deliverable show that among all modelled technologies farm-scale anaerobic digestion of agro-residues/pig manure to increase local nutrient cycling & improve nutrient use efficiency ("Pocket anaerobic digestion") emerges as a solution, offering the most significant benefits at the EU level with regard to agricultural GHG emissions. In terms of the nutrient-related environmental impacts of the modelled technologies Sensor technology to assess crop N status (N-Sensor) has exhibited the most significant impact on mineral fertilizer use, resulting in a reduction across the EU ranging from 1% to 3% compared to the baseline. Precision farming coping with heterogeneous qualities of organic fertilizers in the whole chain (“NIRS”) shows the highest direct effect on manure use ranging via higher manure use efficiency. Compared to other technologies, the N-Sensor shows the highest potential for reducing N-surplus, achieving a 2.6% reduction in the EU at maximum implementation share.

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1 Introduction

Sustainable agricultural intensification is needed to tackle food insecurity in Europe, but it is also associated with various environmental challenges, such as GHG emissions, acidification and eutrophication. Moreover, European agriculture suffers from economic pressure due to its high reliance on the import of primary nutrients and energy. A planetary boundary framework shows that several ecological and physical limits are at risk. These include climate change, land system change, biodiversity loss, and the biochemical flow of nitrogen (N) and phosphorus (P) (Richardson et al., 2023). Europe exceeds its limit for nitrogen and phosphorus losses by a factor of 3.3 and 2, respectively (EEA, 2020). Inadequate manure management and excessive nitrogen and phosphorous fertilizer application lead to eutrophication, contamination of ground and surface water with nitrates, and nutrient enrichment of waterbodies, which leads to algae growth, deoxygenation, and a loss of aquatic biodiversity (IPCC, 2014; Poore and Nemecek 2018; Jwaideh, 2022). European food production depends on imported P fertilizers, but P use is inefficient, and P accumulation in soils and losses to the environment are high. The EU28 relies 92% on P imports to secure its own agricultural production and food security (P-REX Policy Brief, 2015).

The development of innovative technologies and new farming management practices in agriculture can help bridge the current nutrient gap, reducing environmental pressure and increasing the EU's energy independence. As part of Nutri2Cycle, existing CNP flows and innovative farm management systems and technologies are proposed, tested, and implemented. Furthermore, these technologies were evaluated in order to determine how farm-level impacts can be extrapolated to regional and European levels.

This report is one of the major outputs of Nutri2Cycle WP4, and it contains the main results of the research carried out within Task 4.2 (Upscaling and quantifying effects at regional, national, and EU level). The main objective is to extrapolate the impact assessed at the farm level to the regional, national, and EU level on a consistent, high-resolution scale. Moreover, aggregate environmental, economic, and social effects of innovations are assessed, as well as efficiency gains in the nutrient cycles. The results can serve as policy guidance regarding the environmental and social-economic impacts of implementing these selected innovative agricultural technologies and management practices aimed at closing nutrient loops and efficiently mitigating losses in the EU.

This report will build upon the progress made and data collected from the previous work packages (WP) 1, 2, 3 & 6 to fulfil the objectives of Task 4.2. The outcomes of task 4.2 provide support for the policy recommendation of task 4.3. Using the baseline CNP flows and losses derived from the MITERRA-Europe model in WP 1 (as reported in D1.5), the most promising technologies have been identified in the priority list for further advancement in the C, N, and P loop closure in D3.2. After assessing the environmental, social, and microeconomic impacts of introducing these identified technologies and practices at the field and farm level in WP 3, the most promising developments were validated in WP 6 using prototypes and demos (D6.1 and D6.2). Subsequently, using the results and experience gained at a local/regional scale in WP 1,2, 3 & 6, in WP4 we then extrapolated the uptake of innovations modelled in CAPRI to identify their environmental impact at European scale.

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Promising innovations identified in WP2 are implemented in the CAPRI and MITERRA modelling system with regard to impacts on nutrient flows, and factors influencing uptake. The technologies developed in WP2 will be analysed in this deliverable in order to extrapolated their uptake and the environmental effects at European scale.

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2 Methodology

The mitigation technologies are analysed by the CAPRI model and the MITERRA-Europe model, which are briefly explained in this chapter. CAPRI (Common Agricultural Policy Regional Impact) is an economic agricultural sector model covering the whole of EU at regional NUTS2 level and global agricultural markets. The main objective is the ex-ante impact assessment of agricultural, environmental and trade policies on production, income, markets, trade, and the environment, from global to regional scale for the years 2030 and 2050. The MITERRA-Europe model is a detailed deterministic nutrient flow and emission model, which calculates greenhouse gas emissions, nitrogen emissions, N and P flows and soil organic carbon stock changes on, using emission factors and leaching fractions. The main objective is to assess the effects and interactions of policies and measures in agriculture on nutrient flows and GHG emissions on a NUTS2 level in the EU.

Most mitigation technologies have been modelled with the CAPRI model, as that model is able to simulate both the economic effects as well as the emission to the environment. However, not all mitigation technologies could be modelled by CAPRI as more detailed information on nutrient flows are necessary which limits the application of CAPRI to adequately model these innovations. Therefore, the MITERRA-Europe model has been used to assess the impact of selected manure treatment solutions and the application of digestate from sewage sludge at European scale. However, as MITERRA-Europe can only simulate the environmental impacts, the indirect effects due to changes in markets are not taken into account for these technologies.

2.1. CAPRI Model

The scenarios are analysed with the CAPRI model (Britz and Witzke 2014) combining regional supply models and a global market model. The supply module is based on programming models for the approximately 280 NUTS2 regions of the EU (or similar administrative units in auxiliary countries). The production decision of a farmer is modelled based on mathematical programming models depicting the supply at the regional level of approximately 50 primary and processed agricultural products including the current ceilings and financial support implemented by the Common Agricultural Policy (CAP) after 2014. This includes greening measures, premium schemes, entitlements, and voluntary coupled support (VCS). Animal products are highly interlinked via the young animal market, the herd flow model and fodder ratios to depict animal production adjustments in the EU and their interlinkage to global markets. The interaction between animal and crop production is established via the feed module. It defines how many kg of certain feed categories or single feedstuffs are used per animal, depending on its prices. It thus accounts for the nutrient requirements of animals. Total feed use might be produced regionally (grass, fodder root crops, silage maize and other fodder from arable land) or bought from the market at fixed prices. These prices, however, change with each iteration with the market module of CAPRI. The supply model uses positive mathematical programming for calibration. Supply not observed or small in the baseline stay zero or relatively small, even if higher price changes occur. The market model is defined by a system of behavioural equations differentiated by commodity and geographical units. International trade in the CAPRI market model is implemented following the

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Armington assumption (Armington 1969). Market equilibria in CAPRI are reached by iterations between the supply and market modules. These two modules iteratively exchange information on prices, supply and feed demand until convergence is reached.

2.1.1. Environmental indicators in CAPRI

CAPRI endogenously calculates EU agricultural GHG emissions based on the inputs and outputs of production activities in the supply module. The CAPRI model incorporates a detailed nutrient flow model per activity and region (which includes explicit feeding and fertilising activities, i.e., balancing nutrient needs and availability) and calculates yields per agricultural activity. With this information, GHG emissions are calculated following the IPCC guidelines (IPCC 2006). The activity-based emission factors are calculated using the more detailed Tier 2 approach, but where the respective information is missing, a Tier 1 approach is applied (e.g., rice cultivation). The quantification of methane emissions from enteric fermentation and manure management follows a Tier 2 approach for cattle activities and a Tier 1 approach for swine, poultry, sheep and goats. Feed digestibility is calculated endogenously on the basis of the feed ration. Nitrogen fluxes (e.g., N_2O emissions) are calculated according to a mass flow approach developed for the MITERRA-EUROPE model using data from the GAINS database.

Nutrient surpluses and nutrient balances are computed on the NUTS2 level for each group of crops and for each of the three nutrients Nitrate (N), Phosphorus (P_2O_5), and Potassium (K_2O). The NPK needs of plants are covered via different fertilisers available from three different sources: purchased mineral fertiliser, animal manure, and crop residues. Fertilisers in animal manure are produced per animal per head per year depending on the type of animal, the raising period in the number of days, and the kilogram live weight at the start and the end of the raising period. The nitrogen emission factors from animal activities are coupled with crude protein intake. In CAPRI, each crop has a requirement per hectare, calculated based on the yield. Alternative technologies are available for each cropping activity, letting the producer choose between a higher input and higher yield technology and a lower input and lower yield technology (Britz and Witzke 2014). For more detailed information about the computation of nutrient balances and fertilisation in CAPRI, see Jansson et al. (2019).

2.1.2. Modelling approach for costs and uptake of mitigation technologies in CAPRI

In the CAPRI model, a number of already existing or innovative mitigation technologies (ECAMPA technologies) for the European agricultural sector are available (see Table 1). A detailed description of the modelled technological options can be found in Perez Dominguez et al. (2020). The main assumptions related to implementation costs, cost savings, implementation limits, and mitigation potential are mainly taken from the GAINS database. Based on a non-linear mitigation cost function, the implementation share of each mitigation technology is determined endogenously for each region as an economic decision by farmers. The scope and degree of adaptation of a mitigation technology in each region is an endogenous variable. This variable is determined by the cost of the technology (annual investment cost and operational costs), the revenue generated by it (e.g., economic value of the biogas generated from anaerobic digestion), cost savings (e.g., using less mineral fertilizer through precision farming), and other incentives such as subsidies or taxes. Hence, as the agents in the CAPRI regional programming models are assumed to be profit maximisers, farmers will only apply a mitigation option if the marginal profit (according to a gross value-added concept) increases.

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The CAPRI model utilizes a general approach for specifying cost functions, which is also applied to the costs associated with the implementation of mitigation technologies. The non-linear cost function results in non-linear CAPRI supply equations, which consider additional costs that are not included in pure accounting cost statistics. These costs may increase disproportionately as production expands due to factors such as labour and machinery bottlenecks, crop rotation constraints, or risk-aversion behaviour by farmers. To account for these non-linear costs, CAPRI employs a smooth responsiveness approach to reflect the gradual shift towards the production of a more profitable commodity rather than sudden and significant changes that may result in over-specialization. This approach, referred to as calibration costs, is a commonly used and well-established modelling method.

Regarding the production of commodities, how responsive producers are to economic and political incentives is typically expressed in terms of (price–supply) elasticities. This shows how much a commodity's production would increase if that commodity's price went up by 1%. However, elasticities can't be used for technological mitigation measures because the adoption rates of these measures are usually zero in the base year. Instead, the responsiveness of applying a mitigation technology is measured by looking at how much the implementation share of that technology increases when a subsidy is granted. For example, if a subsidy is given for a certain mitigation technology, the implementation share of that technology would increase. This is illustrated by considering the choice of the mitigation share for a single fixed activity where a subsidy is paid for mitigation, and there may also be secondary revenue. The objective is to minimize the net costs of adoption:

Equation 1

$$min_{mshar}\, N\left(mshar_{a,m,e}\right) = C^{m}\left(mshar_{a,m,e}\right) - S_{a,m,e} * mshar_{a,m,e} - R_{a,m,e} * mshar_{a,m,e}$$

where:

mshar	vector of mitigation (implementation) shares a set of production activities (e.g., dairy cows)
m	set of mitigation technologies (including 'no mitigation')
e	emission type (e.g. CH_4 from manure management)
N	net cost function, equal to the cost net of the subsidy
Cm	mitigation cost per activity level for mitigation option m, which depends on mitigation (implementation) share $mshar_{a,m,e}$ for activity *a*, mitigation option *m* and targeting emission type *e*
S	subsidy for implementation of the mitigation option *mshar*
R	secondary revenue from implementation of the mitigation option *mshar*

The specification used splits the CAPRI mitigation cost function, C^{m}, into (1) a part coming from the cost database (i.e., GAINS and other sources) and (2) other costs not accounted for in that database. The latter are costs directly related to the determinants of technology adoption going beyond pure profitability considerations and are generally unknown

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Equation 2

$$C^m(mshar_{a,m,e}) = (\kappa_{a,m,e} + \beta_{a,m,e}) * mshar_{a,m,e} + 0.5 * (\lambda_{a,m,e} + \gamma_{a,m,e})^2$$

where:

$\kappa_{a,m,e}$	cost per activity level for full implementation of a certain mitigation option as given in the cost database; emission type *e* from activity a, if a mitigation technology *m* is used
$\lambda_{a,m,e}$	parameter for non-constant accounting cost per activity level for full implementation of a certain mitigation option, *m* for emission type *e* from activity *a* (typically 0)
$\beta_{a,m,e}, \gamma_{a,m,e}$	(additional) cost parameters not covered by the cost database

The average cost of mitigation for each activity unit using the technology can be represented by C^m. This refers to the cost of the technology per commodity to which the measure is applied. Typically, as the mitigation share increases, we anticipate a rise in average costs. Therefore, we assume that farms first implement measures that are less expensive to adopt. When specifying the parameters, it is necessary to distinguish between two scenarios: one in which the mitigation technology is already in use during the base year and one in which it is not (see further details in Perez Dominguez et al. (2020).

2.3. MITERRA-Europe model

MITERRA-Europe is a deterministic nutrient flow and emission model, which calculates greenhouse gas emissions (CO_2, CH_4 and N_2O), nitrogen emissions (N_2O, NH_3, NO_x and NO_3), N and P flows and soil organic carbon stock changes on annual basis, using emission factors and leaching fractions. The model was developed to assess the effects and interactions of policies and measures in agriculture on N losses on a NUTS2 (Nomenclature of Territorial Units for Statistics) level in the EU-28 (Velthof et al., 2009; de Vries et al., 2011). The MITERRA-Europe was originally based on the models CAPRI (Common Agricultural Policy Regionalised Impact), and GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies), and was supplemented with an N leaching module, a soil carbon module, and a module for greenhouse gas mitigation measures. The MITERRA-Europe model is described in more detail in Velthof et al. (2009) and Lesschen et al. (2011).

Input data consist of activity data (e.g., livestock numbers and crop areas and yield from CAPRI, Eurostat and FAOSTAT), spatial environmental data (e.g., soil and climate data), GHG emission factors (IPCC), and NH_3 emission factors, excretion factors and manure management system data (GAINS). These are described in more detail in the Nutri2Cycle D1.5 (Duan et al., 2021). For soil carbon, the calculation principles (pools and flows of carbon) and parameters of the well-known soil carbon model RothC (Coleman and Jenkinson, 2014) are used.

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The model includes measures to simulate carbon sequestration and mitigation of GHG and NH_3 emissions and NO_3 leaching. The model can also assess all GHG and nitrogen emissions following a LCA approach until the farm-gate (Lesschen et al., 2011). For this Deliverable the MITERRA-Europe model was used to assess the impact of selected manure treatment solutions and the application of digestate at European scale.

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3 Scenario description

In this report, we investigate the (potential) mitigation of environmental emissions from implementation of each technology. The mitigation effect is quantified for a range of implementation shares, ranging from the assumed initial implementation share to the maximum estimated implementation share (further details how this is estimated below) following the modelling approach and the assumptions explained in Chapter 2.1.2.

The scenarios are applied and analysed in the following way:

- One scenario per technological mitigation option, i.e., only one mitigation technology is applied (active) at a time, whereas the uptake of the other technologies is ‘frozen’ to their baseline levels.
- In each scenario, the initial implementation share of the technology under investigation is continuously increased by ten percentage points up to the maximum implementation share possible. The initial implementation share is assumed to be zero for most modelled technologies and the definition of the maximum implementation share is technology specific (see chapter 3.2 for more details).
- In all scenarios, market adjustments are not taken into account, meaning that only the CAPRI supply model is utilized, and as a result, there is no price feedback from global agri-food markets. As a consequence, trade effects are not calculated.
- Despite the absence of market adjustments, the ‘forced’ implementation of mitigation technology results in modifications to the optimal allocation of land use and livestock production. These modifications arise from the profit maximization framework of CAPRI.
- Each scenario and technology is compared to the baseline scenario 2030 in CAPRI and MITERRA-Europe where the implementation share of technologies equals their initial implementations share.
- The manure treatment practices and digestate application are modelled in the MITERRA-Europe model and not in CAPRI, as CAPRI lacks detailed information on nutrient flows for manure treatment.

In this report, we cover all five Nutri2Cycle research lines, with at least one innovative solution for each. In addition, we included already existing technologies in the CAPRI model (”ECAMPA”) to the different research lines (RL), sub research line (SRL) referenced from D2.2 and long list number referenced from D2.1 (see Table 1 for details). The description and implementation of the already existing technologies in CAPRI (”ECAMPA”) are explained in detail in Perez Dominguez et al. (2020). The current report mainly focuses on the implementation of innovative technologies developed in WP2 in Nutri2Cycle. However, also considering the already existing technologies is beneficial, because it enables us to compare their performance to the Nutri2Cycle technologies regarding environmental effects.

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Table 1: Considered technologies for analysis of environmental impacts in the European Union

	SRL	LL	Long list abstract title	Model
RL 1 - Innovative solutions for optimized nutrient & GHG in animal husbandry				
Nutri2Cycle	13	10	Small/Farm-scale anaerobic digestion of agro-residues/pig manure to increase local nutrient cycling & improve nutrient use efficiency	CAPRI
Nutri2Cycle	15	24	Adapted stable construction for separated collection of solid manure and urine in pig housing	CAPRI
RL2- Innovative soil, fertilisation & crop management systems & practices				
Nutri2Cycle	1	16	Using digestate, precision agriculture and no-tillage focusing on OM stocking in an area characterized by the lack of it	MITERRA-Europe
RL 3-Tools, techniques & systems for higher-precision fertilization				
Nutri2Cycle	19	30	Precision farming coping with heterogeneous qualities of organic fertilizers in the whole chain	CAPRI
Nutri2Cycle	23	13	Sensor technology to assess crop N status	CAPRI
ECAMPA			Nitrification inhibitors	CAPRI
ECAMPA			Precision farming	CAPRI
ECAMPA			Optimised fertilizer timing	CAPRI
RL 4-Biobased fertilisers (N, P) and soil enhancers (OC) from agro-residues				
Nutri2Cycle	7	2	Substituting external mineral nutrient input from synthetic fertilisers by recycled organic based fertilizers in arable farming	MITERRA-Europe
Nutri2Cycle	4	55	Pig manure processing and replacing mineral fertilizers	MITERRA-Europe
RL 5 - Novel animal feeds (produced from agro-residues)				
ECAMPA			Feed additives: Nitrate	CAPRI
Nutri2Cycle	12	41	Floating wetland plants grown on liquid agro-residues as a new source of proteins	——[1]

Source: Own depiction

3.1. Description of analysed technologies

RL 1 - Innovative solutions for optimized nutrient & GHG in animal husbandry

Small/Farm-scale anaerobic digestion of agro-residues/pig manure to increase local nutrient cycling & improve nutrient use efficiency (SRL 13, LL 10)

Anaerobic digestion at the farm scale improves nutrient use efficiency. Anaerobic digestion can reduce methane emissions from manure storages, generate renewable energy (biogas) and digestate, reduce odours, and increase the proportion of mineral nitrogen (N) available for plants. The agro-residues, such as livestock manure and crop residues, are fed into farm-scale anaerobic digesters. In the absence of oxygen, the agro-residues ferment in the reactor, resulting in production of biogas and digestate

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[1] This technology originating from research line 5 (RL 5) stands apart from other solutions due to its emphasis on an alternative protein source for livestock feed. Notably, it doesn't fall into the category of on-farm solutions. The CAPRI and MITERRA-Europe models, unfortunately, cannot replicate or model this technology. However, we provide an estimate of the potential impact of this solution when applied at European scale.

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production. The main component of biogas is methane, and a combined heat and power unit can provide the farm with heat and electricity. Digestate is the nutrient-rich fermented biomass resulting from the process that can be used directly as an organic fertilizer for crops. Alternatively, digestate can be separated into more concentrated bio-based fertilizers, which potentially reduces the transportation costs and emissions. Additionally, farm-scale anaerobic digestion has the potential to reduce greenhouse gas emissions from the manure storage significantly.

At the EU level, farm-scale anaerobic digestion was ranked as the third most transferrable technology in D4.1, with a mean short-term transferability rank of 2.4 (out of a maximum of 5) and a mean medium-term transferability rank of 3.4.

Adapted stable construction for separated collection of solid manure and urine in pig housing (SRL 15, LL 24)

The purpose of an adapted stable construction in pig housing is to separate pig slurry into solid manure and pig urine. Stables are constructed with a shallow cellar beneath the slatted floor to separate urine and solid manure. Solid manure is removed from the manure gutter every day using a scraper. As a result of this primary separation of manure in the cellar, ammonia emissions are reduced. Greenhouse gas emissions are also reduced. Moreover, post-processing is easier because P is primarily found in the thick fraction, whereas N is mainly found in the urea fraction. The VeDoWS stable construction system increased organic carbon content from 28.4–36.1 grams/kg to 214-384 grams/kg in the solid fraction. In addition, the solid pig manure fraction's methane potential was measured and found to be 342 m3/ton of DM. This makes the solid pig manure fraction suitable for anaerobic digestion. It is shown that this solution can produce N- and P-rich pig urine for use as fertilizer, and solid pig manure that has a good biogas potential for green energy production.

According to D4.1, at EU level for short-term transferability, the experts ranked the adapted stable construction for manure processing technology 11th out of 14 (mean rank value of 1.3). According to the survey respondents, short-term transferability was ranked at 1.9. Based on a panel of expert opinions, medium-term transferability was ranked at 3.1.

RL 2 - Innovative soil, fertilisation & crop management systems & practices

Using digestate, precision agriculture and no-tillage focusing on OM stocking in an area characterized by the lack of OM in sandy soil (SRL 1, LL 16)

To maximize the efficiency of digestate as a fertilizer and soil enhancer, this solution integrates a high-efficiency nitrogen stripping process with precision farming and minimal tillage tools. The ammonia is stripped from digestate by contacting it with biogas, which acts as a stripping agent. The ammonia-enriched biogas is purified by combining it with sulphuric acid to produce inorganic ammonium sulphate, which can be used as a valuable biobased fertilizer. A decrease in nitrogen levels allows higher digestate doses per hectare without exceeding the nitrogen limit, thereby increasing OM levels. In soil, OM is important for crop growth (physical features), carbon stocking, and nutrient and water retention.

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Through three reactor tanks in sequence, the digestion phase takes place at 55°C for at least 20 days, ensuring that the effluent is hygienic and low in odour. Moreover, nitrogen in the digestate is mainly found in ammonium form, which plants can easily absorb. Precision farming and minimal tillage tools improve the efficiency of this highly valuable effluent. By combining minimal tillage with GPS geolocation, the precision farming system delivers accurate fertilizer doses. In addition to reducing nutrient waste and organic matter loss, these techniques can increase carbon storage, closing the carbon cycle along with biogas production.

In the European evaluation, the use of digestate, precision agriculture and no-tillage to improve soil organic matter received mid-range transferability rankings. As reported in report 4.1, this technology ranks 9th in the short-term in the expert evaluations (Transferability rank 2) and 7th in the survey feedback (1.9) evaluations in the short-term.

RL 3 - Tools, techniques & systems for higher-precision fertilization

Precision farming coping with heterogeneous qualities of organic fertilizers in the whole chain (SRL 19, LL30)

This innovative solution optimises nutrient supply according to plant needs and site-specific conditions while dealing with heterogeneous nutrient contents of liquid manure. The processing of manure can provide homogeneous amounts of manure. The near-infrared (NIR) sensor technology enhances precision in the nutrient application of liquid manure by monitoring the nutrient content of the liquid manure on-the-fly during field application, so the volumetric rate of application can be continuous adjusted to meet the exact crop demand. Using liquid manure according to plant needs can help reduce the risk of N and P overapplication, which can eliminate leaching into groundwater or surface waters. The NIR-sensors work based on the principle that liquid manure reflects and absorbs certain wavelengths of light. There are three common ways to use NIR-sensors to detect nutrients: a) during the filling of manure from storage to the application tank; b) during mixing of manure in the application tank or c) during application via NIR-sensor mounted on distributor. Cattle, pig manure, and liquid digestate can be monitored using precision sensing equipment. It is possible to estimate the dry matter, total nitrogen, ammonium nitrogen (NH_4-N), potassium oxide (K_2O), and phosphorus pentoxide (P_2O_5) concentration with the NIR-sensors. Additionally, tracking manure transportation and documenting application rates improves nutrient management at the farm level and serves to comply better with legal requirements. This innovation allows tracking of manure transport using Geographic Information Systems and Global Positioning Systems (e.g. as required in the Netherlands).

Sensor technology to assess crop N status (SRL 23, LL13)

A tractor-mounted YARA N-sensor utilizes reflectance spectroscopy to monitor nitrogen requirements and uptake of the crop, based on certain indices of spectral reflectance bands. This information can be utilised for determining variable-rate application of nitrogen fertilisers, adjusted to site-specific crop demand, which increases the nitrogen use efficiency of applied fertiliser. At two farms in Hungary, this solution demonstrated that precision fertilisation could significantly reduce nitrogen use

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and potentially provide information about nitrogen use efficiency (WP 3). By utilizing tractor mounted N sensors, mineral fertilizers and pesticides can be distributed based on soil nutrient availability and crop nutritional requirements. The sensor can be used to apply mineral N fertilizer or liquid manure to plants in proportion to their needs, thereby reducing the risk of overapplication and groundwater pollution caused by N and P leaching. A major factor in the adoption of the YARA N-sensor was its economic and environmental benefits. As mentioned in D2.6, the cost for a new YARA sensor is up to 30.000€. It saves 12-21 euros/ha by reducing NH4NO3 fertilizer by 30-50 kg/ha. The fertiliser saving rate is between 20-25%.

One of the most transferable technologies in Europe is the use of sensor technologies in plant cropping systems. In D4.1, this technology ranked 2nd most transferable in the short-term and 3rd most transferable in the medium-term.

RL 4 - Biobased fertilisers (N, P) and soil enhancers (OC) from agro-residues

Substituting external mineral nutrient input from synthetic fertilisers by recycled organic based fertilizers in arable farming (SRL 7, LL 55)

The aim of this research line is to develop bio-based fertilizers (containing mainly N, P) and soil enhancers (containing mainly organic C) from agro-residues. In Europe, animal manure, biowaste, sewage sludge, and food and feed waste are the most abundant waste streams, which are the most valuable resources for producing energy as well as recovering and reusing mineral nutrients such as nitrogen (N), phosphorus (P) and potassium (K).

The most common way to recover energy and nutrients from biowaste is via an anaerobic digestion process that results in the production of biogas and digestate. Consequently, mineral fertilizers can be substituted by the digestate, resulting in less carbon footprint from mineral fertilizer production. However, digestate contains a high amount of water, which causes significant storage and transport costs. This issue can be addressed by evaporating digestate, which would reduce water volume by 60 percent (HRS, 2019). The process involves boiling treated (liquid) streams under negative pressure, which results in highly concentrated substances and condensate that can be recycled or used as discharge water.

This technology is ranked as the 5th most transferrable technology for both expert evaluations and NTF survey feedback for bio-based fertilisers to maximise carbon storage in soil and nitrogen cycling at EU level. In the medium-term the survey results showed that transferability is also high (4th rank). D4.1 showed that Southern Europe could especially benefit from bio-based fertilizer technologies to improve soil carbon storage and nutrient cycling. This technology has the lowest level of transferability in Eastern Europe with a short-term expert rank of 1, a short-term survey rank of 1.7, a medium-term expert rank of 2, and a medium-term survey rank of 2.3, according to D4.1.

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Pig manure processing and replacing mineral fertilizers

This solution contains two different technologies for recovery of bio-based fertiliser.

1. **Low temperature ammonium-stripping using vacuum (SRL 4, LL 2)**

A low-temperature vacuum ammonium-stripping solution is used to recover ammonia from livestock slurry for reuse as a fertiliser. The recovered ammonia can be in the form of ammonium sulphate or nitrate salt solution. The technology involves evaporating ammonia under vacuum. In an enclosed reactor, vacuum reduces the boiling point temperature below normal boiling point, decreasing energy costs since a lower heating requirement is required. A Stainless-steel reactor equipped with serpentines is required to circulate hot water. The thermal bath will maintain the reactor temperature between 40 and 45 degrees Celsius. A mixing system is also necessary to improve ammonia transfer from the liquid phase to the gas phase. A vacuum pump is connected to the reactor in order to provide operating pressure between 20-40 kPa. In the final step, a system of acid traps will absorb the evaporated ammonia. This technology can be applied directly to the liquid fraction to prevent ammonia gas emissions to the atmosphere.

2. **Pig manure evaporation plant (SRL 7, LL 43)**

This innovation aims to separate pig manure into fertilizer products for N, P, and K. This ensures a more efficient use of nutrients, allowing precision fertilization. As a result of these bio-based fertilizers replacing mineral fertilizers, environmental pollution can be reduced. First, pig manure goes through the biogas process, then the digestate is solid-liquid separated, and the solids fraction is dried to 90% dry matter before being processed into organic fertilizer pellets. The evaporation unit concentrates the liquid fraction and in the process ammonium N is recovered via ammonia-stripping technology. The condensated water is clean and can return to surface water. N, P and K in the different product fractions can be used as separate fertilizing products. This innovative technology solution is currently being applied at a pig farm in Oirschot, the Netherlands.

In Europe, pig slurry processing is rated as one of the most transferrable technologies for replacing mineral fertilisers as basal fertilisers. D4.1 indicates that Northern Europe has the highest potential for replacing mineral fertilisers with processed pig slurry, with a short-term expert rank of 4, a short-term survey rank of 2.8, a medium-term expert rank of 5 and a medium-term survey rank of 4.

RL 5 - Novel animal feeds (produced from agro-residues)

Floating wetland plants grown on liquid agro-residues as a new source of proteins (SRL 12, LL 41)

This innovative solution aims to recover nutrients from liquid agro-residues by growing protein-rich floating wetland plants, such as duckweed. It is necessary for plants to take up nutrients like phosphate, ammonium, and nitrate in order to grow. However, these nutrients in liquid agro-residues may result in water pollution if discharged untreated. Wastewater treatment removes or transforms these nutrients into neutral forms. Instead it is possible to apply these nutrients to some floating wetland plants, which can absorb them and convert them into proteins. In Europe, there is a high

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demand for feed proteins due to intensive livestock production, and a substantial proportion of this protein demand is supplied from imported soybean feed. The introduction of floating wetlands as an alternative protein source for animal feed in livestock agriculture may therefore reduce external nutrient import in protein-feeds and partially closes the Nitrogen-Phosphorus cycle. By increasing the recirculation of nutrients, excess N and P produced in waste streams can be treated, recovered and utilised, thereby reducing the environmental impacts.

Based on expert panels and survey responses, floating wetland plants grown on liquid agro-residues as a new source of protein have the lowest transferability rating at the EU level both in the short- and medium-term. According to report 4.1, this technology scored 2.5 on expert evaluations and 2 on survey evaluations for medium-term transferability.

3.2. Implementation of technologies in the CAPRI and MITERRA model

Small/Farm-scale anaerobic digestion of agro-residues/pig manure to increase local nutrient cycling & improve nutrient use efficiency ("pocket anaerobic digestion")

For modelling the technology option pocket anaerobic digestion with CAPRI, we modify the basic assumptions used by Perez Dominguez et al. (2020), assuming that only cattle farms with more than 80 livestock units (LSU) and pig farms with more than 300 LSU can use this technology as an economically viable technological option to mitigate emissions from manure. Therefore the maximum implementation share is restricted by farm size as, the adoption of pocket anaerobic digestion is assumed not profitable for farms with less LSU than the mentioned thresholds for cattle and pigs. Information on LSU has been taken from the EU farm structure survey. During the pre-digester phase, a methane (CH_4) loss of 25% is assumed for liquid systems without natural crust cover, and leaching losses during the digester phase are estimated to be 3%. CH_4 yield, revenues, and CO_2 savings resulting from reduced burning of fossil fuels are calculated based on Mottet et al. (2015). Table 2 summarizes all the assumptions used in the CAPRI model for modelling pocket anaerobic digestion based on data provided from D2.6 and additional interviews with the technology experts from WP2 in Nutri2Cycle.

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Table 2: Assumptions for pocket anaerobic digestion in the CAPRI model

Pre-digester storage CO_2 loss rate	2%
Pre-storage CH_4 loss rate	25%
CH_4 conversion factor of the digester	85%
CH_4 leakage in the digester (% of CH_4 produced)	4%
CH_4 density	0.67 kg/m3
Energy content of CH_4 MJ/kg	55 MJ/kg
Energy conversion factor of CH_4 kWh/GJ	277.8 kWh/GJ
Efficiency of heat generation	45%
Heat used in the anaerobic AD plant (% of the heat produced)	9%
Efficiency of electricity generation	31%
Electricity used in the AD plant (% of the electricity produced)	12%
Lifetime in years	15
Engine hours	7000 (kWh/year)/kW
Emission intensity of heating	0.26 kg CO2/kWh
Emission intensity of electricity	0.33 kg CO2/kWh
Heat price; Electricity price[2]	Nation values based on PRIMES estimates

Source: Own depiction

Based on the assumptions from Table 2, the energy content from CH_4 combusted (E_{CH4}) in kilowatt-hours per animal and year can be calculated (see Equation 3).

Equation 3

$$E_{CH4} = VS * 365 * Bo * (1 - PreDig_{CO2} - MCF_{Tank} * PreDig_{CH4}) * MCF_{Dig} * (1 - CH_{4-leak}) \\ * Dens_{CH4} * ECont_{CH4} * EConv_{CH4}/100$$

VS, Bo and MCF_{Tank} depend on the animal type and the region. $Dens_{CH4}$ is the CH_4 density, $ECont_{CH4}$ is the energy content of CH_4, $EConv_{CH4}$, the energy conversion factor of CH_4, $CH_{4\text{-leak}}$ is the CH_4 leakage in the digester (% of CH_4 produced), $PreDig_{CO2}$, the Pre-digester storage CO_2 loss rate, $PreDig_{CH4}$ is the Pre-digester storage CH_4 loss rate, MCF_{Dig} is the methane conversion factor of the digester, Bo the maximum methane production potential (m^3 CH_4 / kgVS), MCF_{Tank} is the methane conversion factor in the tank (%), VS, the volatile solid produced (kg VS/animal·day).

The net costs of pocket anaerobic digestion are determined by subtracting revenues from gross costs (see Equation 1). The average costs (gross costs) of implementing and running the AD plant are calculated on the basis of the amount of manure (m^3), which is an endogenous variable in CAPRI, and the regional farm size structure. Using Equation 4 from Mottet et al. (2015), we can determine the average costs (C_{AD}) observed for various farm size categories in different regions and types of animals.

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[2] Electricity or biogas prices are not assumed to be subsidised. The modelling approach accounts for the normal heat and electricity prices based on national values as provided by IIASA (more precisely by price estimates done with the PRIMES model for 2030).

Smaller farms are assumed to have higher average costs, so the larger farms are expected to adopt the measure first. As we increase the proportion of manure used for anaerobic digestion, we will be shifting towards smaller farms, resulting in higher costs.

Equation 4

$$C_{AD} = E_{CH4} * \frac{\gamma_{elec}}{eng_h} * \left[\alpha * \ln\left(E_{CH4} * \frac{\gamma_{elec}}{eng_h} * sf\right) + \beta\right] * (r/(1 - \left(\frac{1}{1+r^t}\right)) + C_{Op}$$

γ_{elec}	efficiency of electricity generation (31%)
engh	engine hours (7000 (kWh/year)/kW)
sf	size of farm (animal/farm)
α, β	constants in the equation of capital cost
r	discount rate (2%)
t	lifetime (15 years)
C_{Op}	5 % of capital costs

This equation calculates the observed average costs for a set of points corresponding to the different farm size classes in every region and for animal type. Considering that the average costs are higher for the smaller farms, the first ones applying the measure are supposed to be the biggest farms. As we increase the share of manure used for anaerobic digestion, we will move to smaller farms, and the costs will increase. Based on the resulting C_{AD} cost curves can be calculated providing the total annualized costs of pocket anaerobic digestion per animal for a specific animal type and region. However, as pocket anaerobic digestion can only be applied to liquid manure and only during the time animals spend in the stable, adjustments are made to account for the proportion of manure in liquid form and the proportion of time animals spend in housing.

Sensor technology to assess crop N status (“N-Sensor”)

The basic concept underlying the N-Sensor is that a control system uses data from an electronic map or specific sensors to determine the input requirements of a crop in a particular soil. Then, it transmits this information to a controller that delivers the necessary input to the designated location. The main assumptions regarding costs and mitigation effects are based on Eory et al. (2015) and adjusted for the N-Sensor investigated in Nutri2Cycle in accordance with data provided in D2.6 and corresponding experts from WP2 (see Table 3).

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Table 3: Assumptions for Sensor technology to assess crop N status ("N-Sensor") in the CAPRI model

Investment costs	30,000€
Maintenance costs per year	650 €
Training costs per 5 years	650 €
Amortisation period sensor	15 years
Mineral fertilizer saving (N)	25%
Default N application	140 kg/ha
Minimum farm size to be economically viable	80 ha

Source: Own depiction

Considering an interest rate of 3.5%, we get the following values for early costs per farm for the N-Sensor:

Equation 5

$$C_{N-Sensor} = 30{,}000€ * \frac{1.035^{15} * 0.035}{1.035^{15} - 1} + \ 650€ + 650€ = \ 3905€$$

These costs are further reduced by cost savings depending on the farm size as they are generally related to the number of hectares planted or the amount of fertiliser input. In the CAPRI model, cost savings from fertiliser reduction are endogenously calculated. In order to derive farm size-dependent cost curves, we use the approach of Perez Dominguez et al. (2020).

Following this approach for deriving cost curves based on farm size, data on the distribution of farm sizes in each NUTS2 region from the farm structure survey is used. Non-linear cost curves are approximated by a linear function, giving higher weights to the larger farm size classes, which are based on the share of arable land represented by a size class. Larger farms are assigned greater weights in the analysis, as we assume that farms with less than 80 ha are unlikely to adopt the technologies that are approved by corresponding technology experts from WP2 (see Perez Dominguez et al. (2020) for further details).

The reduction effects concerning mineral fertilizer usage from the N-Sensor, and therefore, the maximum implementation share, are also restricted in CAPRI, in addition to the minimum farm size of 80 hectares. Based on information such as fertiliser sales, animal production, the crude protein content of plants, and yields, CAPRI estimates endogenous 'business-as-usual' over-fertilisation factors (i.e., nitrogen availability divided by nitrogen need) at the regional level. Hence, if we simply use externally provided reduction factors, the resulting nitrogen availability could fall below the actual nitrogen requirement of the plants. To avoid this, a maximum threshold is set for the reduction impact of all measures. This threshold is based on the 'business-as-usual' over-fertilization factor, plus 10 %, to account for uncertainties.

However, less costly measures for reducing fertiliser application may be chosen by applying only the upper limit. This could pose a problem as a low over-fertilisation factor is indicative of an already

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efficient fertilisation strategy. This implies that achieving further reduction is only feasible through the implementation of more advanced, typically more expensive technologies. As a result, the availability of cheaper alternatives becomes increasingly limited in situations characterized by lower over-fertilisation factors.

Precision farming coping with heterogeneous qualities of organic fertilizers in the whole chain ("NIRS")

The near-infrared sensor (NIRS) technology has been developed to measure the N content of slurry on-the-fly during the application, allowing tankers to change the flow rate or travelling speed to adjust the N application rate. With the NIRS technology, slurry N may be applied at the intended N application rate, eliminating excessive N application and overcoming fluctuations caused by slurry heterogeneity.

The assumptions for implementing NIRS in CAPRI are based on findings from D2.6, D3.4[3] and expert opinions from providers of this technology. NIRS can be applied only to available liquid manure in a region, but it is not applicable to manure fallen on pastures during grazing, for which a correction is done in CAPRI, restricting the maximum implementation share. According to findings from D3.4 in WP3 for NIRS, we assume an average efficiency increase of applied manure N by 17.6% per ha, which in other words, reduces the necessary amount of liquid manure applied to the soil and may induce substitution effects with regard to mineral fertiliser. In addition, we assume a reduction of N leaching by 22.6% and a positive yield effect of 1.5% based on D3.4 findings. According to information from technology providers, NIRS is mainly used via contractors with an average cost of 0.45 € per m^3 of manure for the farmers, so no investment costs are considered (see Equation 6).

Equation 6

$$Cost_{NIRS} = Nman_{m3} * 0.45€$$

For calculating the costs of NIRS ($Cost_{NIRS}$), we first derive the country-specific m^3 of manure N applied per ha by dividing the average nitrogen application per ha (kg N/ha) with manure by the animal-specific nitrogen content per m^3 of liquid manure (kg N/m^3). Based on these results, we derive the amount of manure in m^3 equivalent to one kilogram of nitrogen ($Nman_{m3}$) and multiply this by the average cost of 0.45 € per m^3 of manure.

Technology experts provided information on initial implementation shares for the Netherlands (5%), Germany (3%), Denmark (3%), and France (1%). For all other countries in the EU, zero implementation shares are assumed in CAPRI for NIRS.

Adapted stable construction for separated collection of solid manure and urine in pig housing ("Adapted stable construction")

In pig farming, an adapted stable construction is designed to separate pig slurry into solid manure and pig urine effectively. The stables are built with a shallow cellar beneath the slatted floor, which

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[3] We use the results from D3.4 where imperfect information about the exact nutrient content of applied slurry by farmers is assumed. In case of perfect knowledge of farmers about the nutrient contents results from D3.4 show no significant benefit in terms of improving crop yields or reducing N emissions as compared to conventional methods.

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facilitates the separation of urine and solid manure. A scraper is used to remove solid manure from the manure gutter on a daily basis. This primary separation of manure in the cellar helps in reducing ammonia emissions.

The implementation of adapted stable construction is based on an already existing quite similar technology in CAPRI called low-emission housing, which covers a number of options that prevent ammonia emissions from animal housing. This technology basically reduces the surface area and exposure time of manure in the animal house and includes flushing systems or other means of immediate transport of manure into storage (Klimont and Winiwarter 2011; Perez Dominguez et al. 2020). We adjusted the low-emission housing options for cattle and pigs in CAPRI to ensure that adapted stable construction is only valid for pigs which restricts the maximum implementation share. With regard to NH_3 emissions by adapted stable construction, we follow assumptions[4] from Amann et al. (2012), as no specific results for NH_3 removal potentials could be provided in WP2. The assumed NH_3 removal efficiencies for housing-related emissions are 40%. NH_3 reductions with regard to manure management (60%) and storage (80%) are taken from MITERRA-Europe.

The main assumptions related to the costs of adapted stable construction are based on the GAINS model (Klimont and Winiwarter 2011). In general, three cost categories can be differentiated:

- Investment costs
- Fixed operating costs (costs of maintenance, insurance and administrative overhead)
- Variable operating costs (e.g., energy, water, labour costs, feed and fertilizer price, costs of waste disposal, etc.).

The total costs of adapted stable construction ($C_{i,r}^{Total}$) are calculated as the sum of investment costs ($I_{i,r}$), fixed operating costs (OP^{fix}) and variable operating costs (Op^{var}) based on the provided costs in D2.6 from WP2 (see Equation 7).

Equation 7

$$C_{i,r}^{Total} = I_{i,r} + OP_{i,r}^{fix} + OP_{i,r}^{var}$$

$$I_{i,r} = ci_i^f + \frac{ci_i^v}{ss_{i,r}}$$

$$OP_{i,r}^{fix} = I_{i,r} * fk_i$$

$$OP_{i,r}^{var} = q_i * c_{i,r}$$

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[4] The assumptions for reduction potentials in NH_3 emissions are equivalent to the low emission housing option in CAPRI.

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where:

I	investment costs
i,r	animal type (here pigs), country
ci^f, ci^v	investment function coefficients
ss	average farms size (average number of pig places on a farm)
OP^{fix}	fixed operating costs
fk	percentage of investment costs
Op^{var}	variable operating costs
q	parameter type (additional energy, labour, waste disposal, etc.)
c	unit price of given q

The calculation of investment costs ($I_{i,r}$) for adapted stable construction takes into account the size of an installation, typically expressed as the average number of animal places on a farm for pigs. The investment costs per animal place contain a constant (ci^f,ci^v)and a size-dependent part, the latter typically characterized by the average farm size ($ss_{i,r}$) expressed as the average number of pig places on a farm. Fixed operating costs (OP^{fix}) cover the costs of repairs, maintenance and administrative overhead per animal place and are not related to the actual use of the installation. As a rough estimate for annual fixed expenditures, a standard percentage fk_i of the total investments is used (Klimont and Winiwarter 2011). The variable operating costs (Op^{var}) consist of additional demand for energy, labour, waste disposal times the respective unit price.

Using digestate, precision agriculture and no-tillage focusing on OM stocking in an area characterized by the lack of OM in sandy soil ("Digested sludge application")

This Nutri2Cycle solution from Italy is quite specific and a combination of different new practices. For the modelling at the EU scale, we had to simplify this solution and focus on the digestate application aspect, as precision agriculture is already addressed in some of the other solutions. This solution has been modelled by MITERRA-Europe.

The MITERRA-Europe model already includes organic inputs from sewage sludge, based on information from Eurostat (Sewage sludge production and disposal from urban wastewater [TEN00030]). This data set contains information on sewage sludge production at the member state level and information about its disposal, for which the following categories are distinguished: use in agriculture, compost, landfill, incineration or other. The current implementation share is based on the amount of sludge currently being applied in agriculture. For the simulation of full implementation, we assumed that all sewage sludge currently going to landfill, incineration and 50% of the other category would also go to agriculture. In some countries, the application of sewage sludge in agriculture is not

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allowed, e.g., Netherlands, Slovenia and Slovakia, but for the scenario, we assumed that also in these countries, sludge can be used in agriculture. The digested sludge was allocated to arable land and a nitrogen fertilizer replacement factor of 50% was used based on Petersen (2003). The potential GHG savings from the digestion of the sludge have not been included in the calculations, as these are not part of the agriculture sector.

Substituting external mineral nutrient input from synthetic fertilisers by recycled organic based fertilizers in arable farming (“N stripping pig manure”)

This solution is modelled by MITERRA-Europe. First, the manure surplus at NUTS2 was calculated based on the amount of manure produced and the amount that can be applied based on the maximum manure application rate defined in the Nitrates Directive. Currently, some countries still have derogation to apply more than 170 kg N/ha. However, the European Commission is no longer extending this derogation to several countries. Therefore, we assumed that by 2030 the maximum manure N application rate will be 170 kg N/ha.

For this solution, we assumed that only pig slurry will be treated, as most cattle farmers normally have sufficient land for applying their manure. For poultry manure, other manure treatment techniques are often used, such as incineration or drying and exporting. The current use of manure treatment techniques is based on Hou et al. (2017), who provided estimates at the national level for ten techniques based on a survey from Foged et al. (2011). For poultry manure incineration, nitrification-denitrification and manure drying, we assumed that this amount of manure is removed from agriculture (at least within the country). No data is available to estimate the current share of implementation, but as this is so far only applied at pilot scale, we assumed a 10% implementation rate. For the full implementation we assumed that all surplus pig manure would be treated this way.

For modelling this solution, we used the information from Nutri2Cycle solutions LL1 and LL2, as described in D3.4 and D2.6, which were tested in Belgium. The first step in treating of the surplus pig manure is the separation of manure into a liquid and a solid fraction. It is not indicated which technique is used for liquid solid separation. Based on Nutri2Cycle D1.4 (Lesschen et al., 2022) there is a large variety in separation efficiencies depending on the technique used. We used the average separation efficiency of the centrifugation and sedimentation techniques, as these have the highest separation between N and P. In the solid fraction 58% of the dry matter remains, 30% of the N and 61% of the P (Hjorth et al., 2011). The solid fraction is assumed to be applied in the region, while the liquid fraction is further processed. We used the emission factors from Hou et al. (2017) for the N emissions from manure treatment.

Current practice in Belgium is to treat this liquid fraction by nitrification-denitrification (NDN), where all N is lost. With this solution, the NH_3 in the liquid fraction is stripped and scrubbed with sulphuric acid. A stripping efficiency of 30% is assumed, based on information in Nutri2Cycle D1.4 (e.g., Ledda et al., 2013). This is at the higher end of the values found in the literature, but improvements are expected, as new treatment plants in the Netherlands have demonstrated. The ensuing ammonium sulphate is considered as a mineral fertiliser substitute and will substitute the mineral N fertilizer in

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the region. The stripping residue is still treated in an NDN system from which the effluent is clean enough to be discharged.

Pig manure processing and replacing mineral fertilizers ("Mineral concentrate pig manure")

This solution is modelled by MITERRA-Europe as well and is similar to the previous solution, only for the treatment of the liquid fraction another technique is used. This solution is based on information from Nutri2Cycle solution LL55, as described in D3.4 and D2.6. The first step is the separation of the surplus pig manure into a liquid and solid fraction. Based on the data for LL55, we used the following separation efficiencies: 67% of the dry matter remains in the solid fraction, 20% of the N and 67% of the P. In the next step, reverse osmosis is used to further process the liquid fraction into a mineral concentrate high in N and K, purified water and a residual fraction. The reverse osmosis results in a concentrate with 42% of the N. The NK concentrate complies with the RENURE criteria and is used to substitute mineral N fertilizer in the region. The purified water can be discharged, and the residual fraction is assumed to be exported to regions without a manure surplus. No data is available to estimate the current share of implementation, but as this technology is so far only applied at pilot scale, we assumed a 10% implementation rate. For the full implementation we assumed that all surplus pig manure would be treated this way.

Floating wetland plants grown on liquid agro-residues as a new source of proteins

This technology from research line 5 is different from the other solutions, as it is focussed on an alternative source of proteins for feed, but it is not an on-farm solution. The CAPRI and MITERRA-Europe models are not able to simulate this technology. However, we tried to provide an estimate of the potential impact of this solution when applied at European scale. The main challenge is to get data of the area where this technology can be applied. Based on a report by EUMOFA on freshwater aquaculture in Europe we found information on the area of ponds in the EU member states (Table 4). This area was corrected for the share of Natura 2000, as there no intensive livestock production would occur. This results in a potential area of almost 300 kha. However, it is unlikely that all ponds can be used, as fish production will be the main objective. Therefore, we assumed that 50% of the area could be used, i.e. 147 kha.

Based on information from the LemnaPro project, the LCA from Nutri2Cycle on this technology in D3.4 (Beyers et al., 2023) and results from Dutch studies, as described in Lesschen and Sanders (2023), we assumed a duckweed production of 10 ton dry matter per ha per year. The protein content of duckweed is about 30%, which results in a N uptake of 480 kg/ha. This could replace about 900 kton of soybean, which is about 5% of the current import of soybeans into the EU. As this technology does not reduce emission from agricultural land or livestock production and is not focused on replacement of mineral fertilizer, the indicators as included in the Results section are not affected.

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Table 4: Area of ponds and share of Natura 2000 area for EU member states

	Area of ponds (ha)	Share Natura 2000
Austria	2700	?
Bulgaria	7987	<10
Czech Republic	41000	<10
Germany	23231	<10
France	60000	>30
Italy	30000	10-30
Hungary	24161	<10
Croatia	14361	?
Lithuania	9904	?
Poland	64000	<10
Romania	80091	<10
Sweden		<10
Total	357435	

Source: EUMOFA (2021)[5]

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[5] https://www.eumofa.eu/documents/20178/442176/Freshwater+aquaculture+in+the+EU.pdf

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4 Results

In this section, the Nutri2Cycle technologies, modelled with CAPRI and MITERRA, shown in Table 1, are investigated regarding mitigating GHG emissions, mineral fertilizer use, manure use, N-Surplus, and leaching effects.

For all results, two effects are differentiated: (i) the mitigation directly achieved by the specific technological mitigation option (termed "Tech only") and (ii) the overall effects on agricultural emissions and other considered environmental indicators in each scenario as a result of the CAPRI profit maximisation framework following the forced adoption of the mitigation technology leading to changes in optimal land use and livestock production allocation, termed "Total" in the following. For the technologies modelled in MITERRA-Europe only the specific technological mitigation option (termed "Tech only") can be computed as agricultural activity levels are constant because the model does not simulate any economic effects as opposed to the CAPRI model.

The detailed results for the already existing technologies in CAPRI ("ECAMPA") from Table 1 are provided in the Annex. These results are not the main focus of this report but may provide some insights into how other technologies perform in the scenarios.

4.1. Impact of technologies on agricultural GHG emissions

Table 5 shows agricultural total GHG emissions, CH_4, N_2O emissions as well as NH_3 emissions of Nutri2Cycle technologies compared to the reference in 2030. Based on the aggregated reduction in greenhouse gas emissions in agriculture (GWP) solely achieved by using a technological mitigation option ("Tech only"), farm-scale anaerobic digestion of agro-residues/pig manure can yield the greatest benefits at the EU level to improve local nutrient cycling and the efficiency of nutrient use ("Pocket anaerobic digestion").

The maximum application of pocket anaerobic digestion leads to the mitigation of 18.8 million tonnes (Mt) of CO_2 equivalents (CO_2 eq.), which reduces the agricultural GHG emissions in the EU-27 by 4.8%. The highest reductions occur in livestock-intensive countries like Germany (6.9 Mt CO_2 eq.), Spain (3.3 Mt CO_2 eq.), Italy (2.2 Mt CO_2 eq.), France (1.7 Mt CO_2 eq.), and Denmark (1.7 Mt CO_2 eq.). For the maximum application scenario, the reductions in GHG emissions by pocket anaerobic digestion are mainly due to changes in CH_4 emissions (-6.2%) and N_2O emissions (-1.9%) related to manure management.

The maximum application of precision farming coping with heterogeneous qualities of organic fertilizers in the whole chain ("NIRS") reduces GHG emissions by 3.2 Mt CO_2 equivalents (0.8%), which is mainly due to the mitigation of N_2O emissions (-1.6%) and NH_3 emissions (-4%). The N-Sensor at maximum implementation share could reduce agricultural GHG emissions by 1.9 Mt CO_2 equivalents, implying a reduction of 0.4% of total EU agriculture emissions compared to the reference.

The adapted stable construction has the lowest mitigation potential from the considered technologies in Nutri2cycle, reducing EU agriculture emissions by around 0.7 Mt CO_2 equivalents, which can be mainly attributed to targeted NH_3 and CH_4 emission reductions. Among the technologies considered

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in Nutri2cycle, the adapted stable construction has the lowest mitigation potential, reducing EU agriculture emissions by 0.7 Mt CO_2 equivalents primarily due to NH_3 and CH_4 emission reductions.

The application of digested sludge at maximum implementation share could reduce agricultural GHG emissions by 1.5 Mt CO_2 equivalents, implying a reduction of 0.34% of total EU agriculture emissions compared to the reference. However, the soil N2O emissions show an increase as the total N application increases. However, this is compensated by a reduction in GHG emissions related to the production of mineral N fertilizer and additional soil organic carbon sequestration. This last aspect is also one of the main reasons why this solution is used, as the application of digested sludge should target the low SOC content of these soils. We did not consider the potential GHG savings due to the anaerobic digestion of the sewage sludge, as that is not part of the agriculture sector, but this would increase the GHG mitigation potential of this solution.

Accounting also for the land use allocation and livestock production adjustments, the net effect on aggregated agricultural GHG emissions for each technological mitigation option is a reduction in total emissions. For all technologies, the changes in agricultural production reduce the direct effects of the technologies (so compared to “Tech only”). The reduced mitigation in overall agricultural emissions (“Total”) for technologies e.g., pocket anaerobic digestion, comes mainly from an increase in utilised agricultural area (mostly related to increased cereal production), a decrease in set aside and fallow land as well as higher mineral fertiliser use with resulting higher emissions related to fertiliser production and application. These effects compensate for the mitigation realised by slightly reduced animal production in the EU via the implementation of pocket anaerobic digestion. The exogenously ‘forced’ adoption of mitigation options in the scenarios in most cases reduces farmers’ profitability as otherwise they would be adopted voluntarily, and this income loss is minimised by shifting away from the affected activities. The largest EU overall effects on agricultural GHG emissions (“Total”) are achieved by pocket anaerobic digestion (-13.5 Mt CO_2 eq.), N-Sensor (-1.7 Mt CO_2 eq.) and NIRS (-1.5 Mt CO_2 eq.), which implies a reduction of 3.45%, 0.44%, and 0.33%, respectively, of total EU agriculture emissions compared to the reference. The lowest total emission savings result from the increased implementation of adapted stable construction, reducing the agricultural GHG emissions by 0.16 Mt CO_2 eq. (-0.02%) in the EU-27 at maximum implementation share.

The lowest total emission savings result from the increased implementation of adapted stable construction, reducing the agricultural GHG emissions by 0.17 Mt CO_2 eq. (-0.02%) in the EU-27 at maximum implementation share and the two manure treatment mitigation options. N stripping of pig manure has a potential GHG reduction of 0.15 Mt (0.03%) and pig manure processing to mineral concentrates has a potential of 0.23 Mt (0.05%). For manure treatment, the lower GHG emission is due to lower animal manure application and the replacement of mineral N fertilizer by ammonium sulphate or mineral concentrate, which reduces the emissions related to mineral fertilizer production. Also, the high N_2O emissions related to the current nitrification-denitrification process are reduced.

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Table 5: Absolute and relative changes in emissions for the entire EU-27 ranging from an increase of the initial implementation (first number) to the maximum implementation share (second number) of Nutri2Cycle technologies compared to the reference

		Pocket anaerobic digestion	**Adapted stable construction**	**Digested sludge application**	**NIRS**	**N-Sensor**	**N stripping pig manure**	**Mineral concentrate pig manure**
RL1		1	1	2	3	3	4	4
Model		CAPRI	CAPRI	MITERRA-Europe	CAPRI	CAPRI	MITERRA-Europe	MITERRA-Europe
GHG emissions (1000 t CO_2 eq.)								
Tech only	Abs. Δ	-2414.4 to -18825	-55.2 to -167.8	-744 to -1466	-748.9 to -3236.5	-778.1 to -1938.4	-14.7 to -147	-22.7 to -227
	%-Δ	-0.6 to - 4.8	-0.01 to -0.04	-0.17 to -0.34	-0.2 to -0.8	-0.2 to -0.4	-0.003 to -0.03	-0.005 to -0.05
Total	Abs. Δ	-1358.4 to -13505.3	-74.9 to -91.8		-297.2 to -1526.9	-540.2 to -1732.9		
	%-Δ	-0.3 to -3.4	-0.01 to -0.02		-0.08 to -0.4	-0.1 to -0.4		
CH_4 emissions (1000 t)								
Tech only	Abs. Δ	-64.6 to -508.2	-4.2 to -13.9					
	%-Δ	-0.7 to -6.2	-0.05 to -0.2					
Total	Abs. Δ	-39.3 to -315.9	-6.7 to -22.2		-0.7 to 1.9	2.2 to 2.1		
	%-Δ	-0.4 to -3.8	-0.08 to -0.3		-0.01 to 0.02	0.03 to 0.04		
N_2O emissions (1000 t)								
Tech only	Abs. Δ	-2.7 to -20.5	0.2 to 0.6	1.6 to 3.3	-2.5 to -10.9	-2.6 to -6.5	-0.001 to -0.13	-0.02 to -0.19
	%-Δ	-0.4 to -3.0	0.02 to 0.09	0.43 to 0.91	-0.4 to -1.6	-0.4 to -0.9	-0.003 to -0.03	-0.005 to -0.05
Total	Abs. Δ	-0.4 to -17.7	0.2 to 1.6		-1.2 to -6.9	-2.7 to -7.9		
	%-Δ	-0.7 to -2.5	0.04 to 0.2		-0.2 to -1.0	-0.4 to -1.1		
NH_3 emissions (1000 t)								
Tech only	Abs. Δ	4.4 to 32.5	-16.5 to -53.9	-2.3 to -4.7	-21.0 to -90.6	-7.5 to -18.9	-1.3 to -12.7	-1.3 to -13.4
	%-Δ	0.2 to 1.5	-0.7 to 2.4	-0.09 to -0.18	-0.9 to -4.0	-0.3 to -0.8	-0.04 to -0.47	-0.05to -0.49
Total	Abs. Δ	7.6 to 31.7	-14.5 to -37.5		-0.3 to -21.9	-4.7 to -15.7		
	%-Δ	0.3 to 1.4	-0.6 to 1.7		-0.02 to -0.9	-0.2 to -0.7		

Source: Own depiction bases on CAPRI and MITERRA-Europe results

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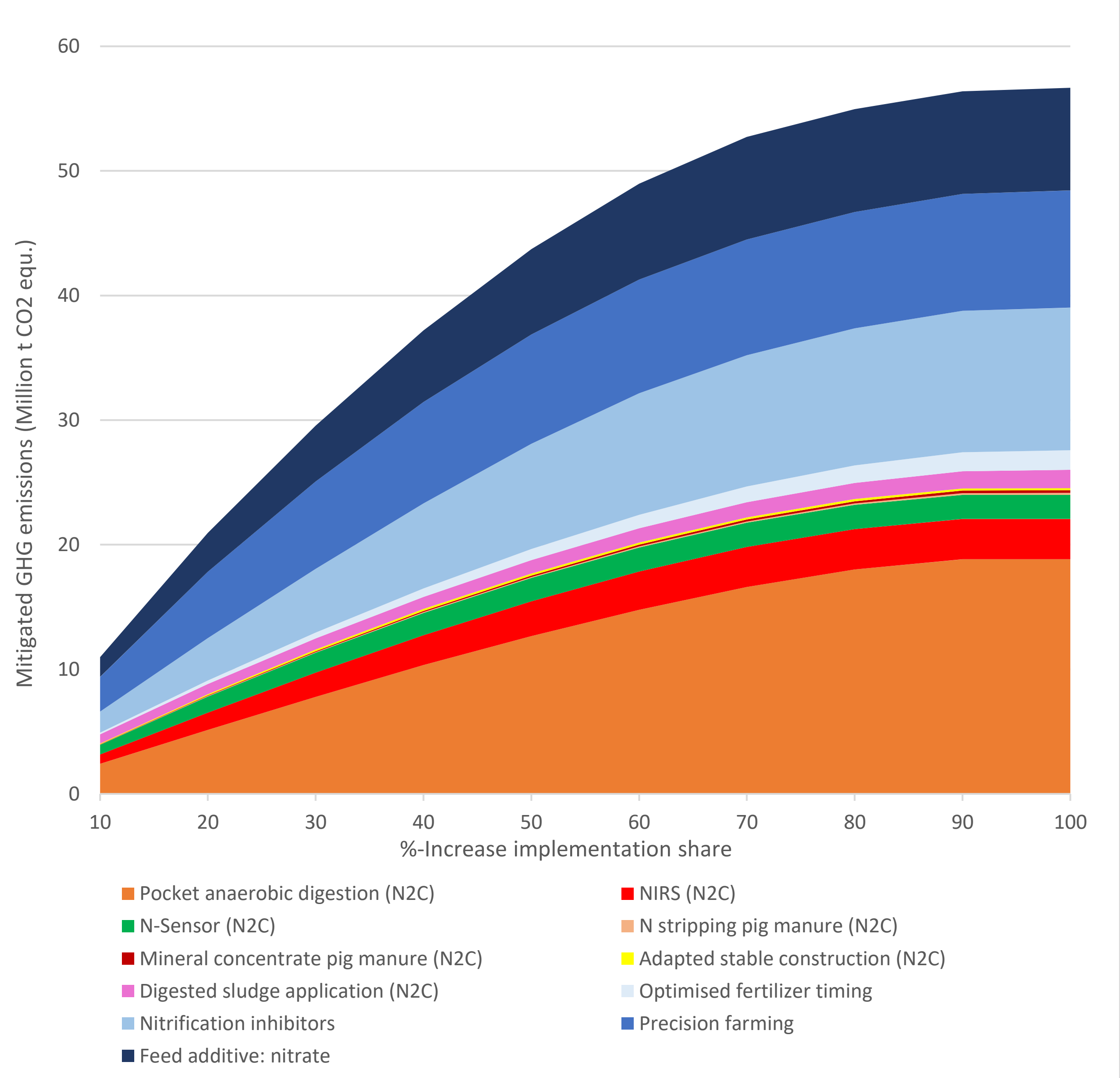
To further explore the mitigation potential of technologies developed in Nutri2Cycle with regard to other technologies, we also investigate the already existing technologies in CAPRI ("ECAMPA"), which could be attributed to the different research lines in Nutri2Cycle (see Table 1). With regard to GHG emission reduction, this comparison is appropriate as the ECAMPA technologies have been selected based on their emission mitigation potential primarily. Figure 1 shows the changes in mitigated GHG emissions for the different increases in initial implementation shares up to their maximum implementation share.

Figure 1: Mitigated GHG emissions (million tonnes CO_2 eq.) for all technology specific scenarios compared to the reference.



Source: Own calculations with CAPRI and MITERRA-Europe

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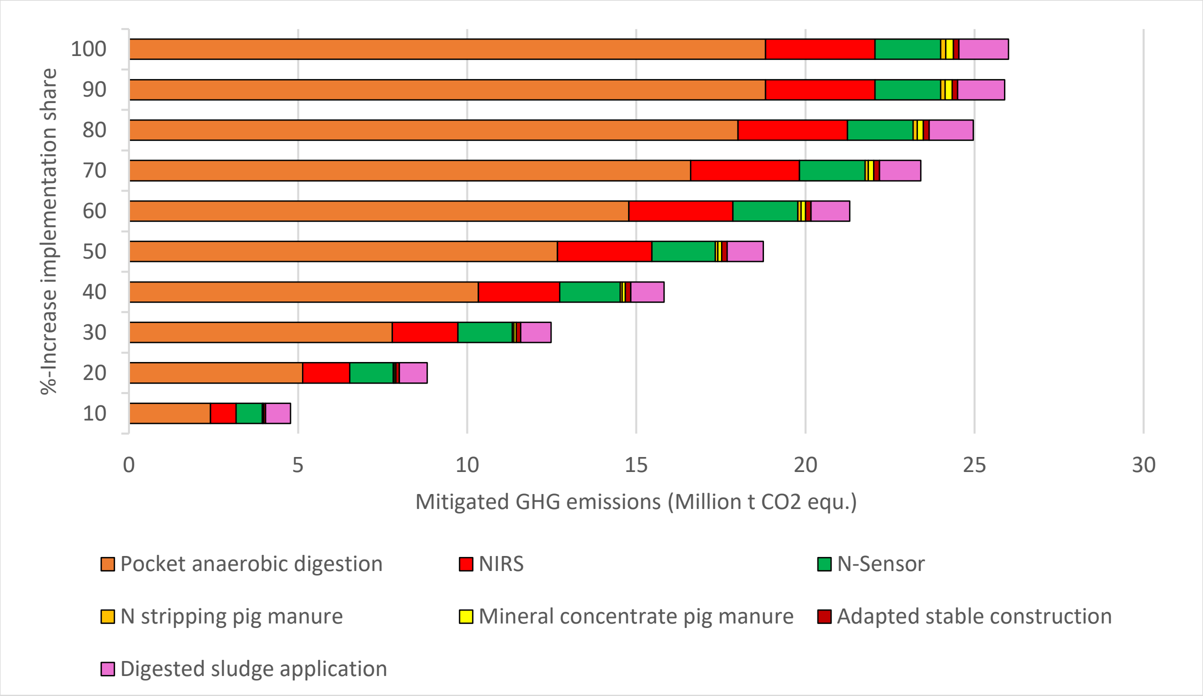
The curvature of the technology-specific mitigation potential across the implementation shares is not completely linear for many technologies. The main reason is that for certain regions, the maximum implementation share is reached earlier, which is then fixed, and the procedure is continued until all regions in Europe reach their maximum implementation share. This modelling approach results in lower mitigation increases with higher shifts in the initial implementation shares as most regions have already achieved their maximum uptake of technologies. The results show that the highest mitigation potential is reached for farm-scale anaerobic digestion of agro-residues/pig manure to increase local nutrient cycling and improve nutrient use efficiency ("Pocket anaerobic digestion") developed in Nutri2Cycle reducing GHG emission in Europe between 2.4 and 18.8 million tonnes CO_2 equivalents. Next to pocket anaerobic digestion, the modelled ECAMPA technologies of nitrification inhibitors and precision farming show comparatively high mitigation potential, reducing GHG emissions between 1.6 and 11.4 million tonnes of CO_2 equivalents and 2.8 and 9.4 million tonnes of CO_2 equivalents, respectively. The mitigation potential of other technologies developed in Nutri2Cycle (N2C) is comparably lower, which is not surprising as the main focus of the technologies is closing nutrient cycles in Europe rather than reducing GHG emissions (see Figure 2 for a more detailed view of Nutri2cycle innovations).

Figure 2: Mitigated GHG emissions (million tonnes CO2 eq.) for Nutri2cycle technologies scenarios compared to the reference



Source: Own calculations with CAPRI and MITERRA-Europe

4.2. Impact of technologies on fertiliser use, nitrogen surplus and leaching

The effect on mineral fertiliser use, manure use, nitrogen surplus, and leaching of the innovative solutions investigated are shown in Table 6. According to the previous chapter, the technologies can only produce direct effects on environmental indicators that are specifically targeted. Therefore, only N-Sensor and NIRS have a direct influence ("Tech only") on mineral fertiliser use and manure use, respectively, whereas all technologies have a direct effect on leaching.

The highest reduction in mineral fertiliser use at the EU level is achieved by the sensor technology to assess crop N status ("N-Sensor"), which is not surprising as it is the only technology directly targeting the mineral fertiliser application. The decline in total mineral fertiliser use ("Total") for the N-Sensor ranges between 0.1 Mt and 0.3 Mt, implying a reduction between 1 and 3%, respectively. The reduction in mineral fertiliser use consists of the direct effect of the N-Sensor ("tech only") and the decrease in UAA (utilised agricultural area), which slightly offsets the direct effect of the technology. In most cases, farmers' profitability is reduced as a consequence of the exogenously forced adoption of mitigation options. This income loss is minimised by shifting away from affected activities. Hence, for the N-Sensor, farmers shift from crop to animal production increasing the availability and thus the use of manure as fertiliser. The increasing implementation of the N-Sensor in the EU also positively affects other environmental indicators such as nitrogen surplus and leaching. At maximum implementation share, the N-Sensor could reduce leaching by 3.5% and the N-Surplus by 2.6% compared to the reference in 2030. In comparison to other technologies, the reduction potential of N-Sensor with regard to N-surplus is the highest.

Precision farming coping with heterogeneous qualities of organic fertilizers in the whole chain ("NIRS") also shows a reduction in mineral fertiliser use across all implementation scenarios ranging between 0.04 and 0.24 million tonnes (Mt). The lower use of mineral fertiliser can be explained by a substitution effect with manure which is assumed to have a higher efficiency with NIRS (see chapter 3.2) and the decrease in UAA due to enforced technology implementation. The direct effect of NIRS on manure use ("Tech only") is relatively high, ranging from 0.1 to 0.4 Mt which is equivalent to an EU-wide reduction of 1.9% and 7.4%, respectively. Including the production effects ("Total") particularly due to reduced UAA and higher animal production in Europe these mitigation effects is again reduced which aligns with previous findings.

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Table 6: Absolute and relative changes in mineral fertilizer use, manure use, N-surplus and leaching for the EU-27 ranging from an increase of the initial implementation to the maximum implementation share compared to the reference in 2030

		Pocket anaerobic digestion	**Adapted stable construction**	**Digested sludge application**	**NIRS**	**N-Sensor**	**N stripping pig manure**	**Mineral concentrate pig manure**
RL1		1	1	2	3	3	4	4
Model		CAPRI	CAPRI	MITERRA-Europe	CAPRI	CAPRI	MITERRA-Europe	MITERRA-Europe
Mineral Fertilizer Use (1000 t N)								
Tech only	Abs. Δ			-48 to -100		-136.3 to -338.7	-3.2 to -32	-5.1 to -51
	%-Δ			-0.46 to -0.97		-1.4 to -3.4	-0.03 to -0.3	-0.05 to -0.5
Total	Abs. Δ	56.1 to 81.6	-6.1 to -3.4		-39.7 to -242.0	-102.1 to -299.6		
	%-Δ	0.5 to 0.8	-0.06 to -0.03		-0.4 to -2.4	-1.0 to -3.0		
Manure Use (1000 t N)								
Tech only	Abs. Δ				-106.6 to -442.7		-0.4 to -4.4	-0.7 to -7.2
	%-Δ				-1.9 to -7.4		-0.01 to -0.09	-0.02 to -0.2
Total	Abs. Δ	2.7 to -8.4	-3.6 to -10.0		-0.8 to 0.2	3.6 to 3.7		
	%-Δ	0.03 to -0.1	-0.05 to -0.1		-0.01 to 0.01	0.04 to 0.05		
Leaching (1000 t N)								
Tech only	Abs. Δ	0.7 to 3.1	7.4 to 20.4	27 to 57	-14.9 to -58.9	-16.9 to -42.0	-0.14 to -1.4	-0.2 to -2.2
	%-Δ	0.1 to 0.2	0.6 to 1.6	1.2 to 2.6	-1.3 to -5.0	-1.3 to -3.3	-0.01 to -0.05	-0.01 to -0.1
Total	Abs. Δ	1.1 to 0.1	6.6 to 14.0		-18.2 to -67.2	-18.8 to -45.1		
	%-Δ	0.1 to 0.01	0.5 to 1.1		-1.4 to -5.2	-1.5 to -3.5		
N-surplus (1000 t N)								
Total	Abs. Δ	22.3 to 14.0	-6.9 to -26.1	109 to 221	-55.1 to -241.8	-106.7 to -300.6	-0.44 to -4.4	-0.7 to -7.3
	%-Δ	0.2 to 0.1	-0.1 to -0.22	1.5 to 3.0	-0.5 to -2.1	-0.9 to -2.6	-0.01 to -0.09	-0.01 to -0.1

Source: Own calculations with CAPRI and MITERRA-Europe

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The reduction in N mineral fertilizer use for the manure treatment options is relatively low, with a reduction of 0.28% (N-stripping) or 0.45% (mineral concentrates). As we assumed that only the surplus of pig manure within the NUTS2 region will be treated, the total amount is relatively low, as only the Netherlands, Belgium and one region in Germany have a pig manure surplus. For other countries, we expect that local surplus manure will be reallocated within the region and no manure treatment will occur. However, at the farm level the decision of treatment or not depends on whether more farms have a manure surplus. In that case, the farmer has to decide whether he can contract other farmers within the region to use his manure or if it will be more cost-effective to invest in manure processing.

For the solution application of digested sludge, the mineral N fertilizer use is reduced by almost 1%. However, as the nitrogen fertilizer replacement factor is only 50%, which means that not all nitrogen is directly available for plant uptake, the total N input is increased, which results in a higher N surplus and higher N leaching. Improving the N availability of the digested sludge, or reducing the total N inputs is required to prevent an increase in N emissions and N leaching.

NIRS shows the highest potential at maximum implementation share to reduce leaching across all technologies for both the direct effect of the technology (-5%) and the total effect (-5.2%) in Europe. The N-Surplus is also reduced by NIRS ranging between -0.5% and -2.1% compared to the baseline.

Adapted stable construction for separated solid manure and urine collection in pig housing (“Adapted stable construction”) results in comparably low effects for the considered environmental indicators. The use of mineral fertiliser shows no significant changes across the different implementation shares. The total effect on manure is comparably high caused by the decrease in pig production across Europe triggered by the enforced implementation of this technology. Also, the implementation of pocket anaerobic digestion across Europe shows only minor effects on the considered environmental indicators, particularly for manure use, leaching and N-Surplus. The use of mineral fertiliser slightly increases over the scenarios ranging between 0.5% and 0.8%, mainly caused by an increase in UAA and the mentioned shift away from affected activities to minimise income losses as a consequence of the exogenously forced adoption of the technology.

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5 Conclusion

In this deliverable, we explored the potential mitigation potential of technology options from WP2 in Nutri2cycle feasible for modelling in CAPRI and MITTERA-Europe, incrementally increasing their implementation share from the assumed initial level to the maximum level possible. Each scenario and technology is compared against the 2030 baseline in both CAPRI and MITERRA-Europe, with manure treatment practices modelled exclusively in MITERRA-Europe. The findings presented in this deliverable show that among all modelled technologies farm-scale anaerobic digestion of agro-residues/pig manure to increase local nutrient cycling & improve nutrient use efficiency ("Pocket anaerobic digestion") emerges as a solution, offering the most significant benefits at the EU level with regard to agricultural GHG emissions. Its maximum application can mitigate up to 18.8 million tonnes of CO_2 equivalents (CO2 eq.), resulting in a 4.8% reduction in EU-27 agricultural GHG emissions. Notably, this reduction is most pronounced in livestock-intensive countries, including Germany, Spain, Italy, France, and Denmark. The extensive adoption of precision farming coping with heterogeneous qualities of organic fertilizers in the whole chain ("NIRS") showed lower emission mitigation potential, resulting in a reduction of 3.2 million tonnes of CO_2 equivalents (0.8%). This reduction is primarily attributable to the effective mitigation of N_2O emissions by 1.6% and NH_3 emissions by 4%. Likewise, the N-Sensor technology, when implemented to its maximum capacity, exhibits the potential to curtail agricultural GHG emissions by 1.9 million tonnes of CO_2 equivalents, corresponding to a 0.4% decrease in total EU agriculture emissions relative to the reference scenario. For the application of digested sludge, the GHG emissions are reduced by 1.5 Mt of CO2-eq, a 0.34% decrease in total emissions. However, this is mainly due to the sequestration of carbon in soil organic matter while N_2O emissions increase. In contrast to the previously mentioned technologies, the increased implementation of adapted stable construction demonstrates relatively modest overall emission savings, resulting in a reduction of agricultural GHG emissions by 0.17 million tonnes of CO_2 equivalents (-0.02%) within the EU-27 at maximum implementation share. The two manure treatment strategies, N stripping of pig manure and pig manure processing to mineral concentrates, also yield comparatively lower GHG reductions. N stripping offers a potential GHG reduction of 0.15 million tonnes (0.03%), while pig manure processing to mineral concentrates shows the potential to reduce emissions by 0.23 million tonnes (0.05%). These relatively lower GHG emissions reductions in manure treatment scenarios can be attributed to reduced animal manure application, the substitution of mineral N fertilizer with ammonium sulphate or mineral concentrate, leading to decreased emissions associated with mineral fertilizer production, and a notable reduction in high N_2O emissions linked to the current nitrification-denitrification process.

In terms of the nutrient-related environmental impacts of the modelled technologies, we analyse their influence on mineral fertilizer utilization, manure application, nitrogen surplus, and leaching. The N-Sensor technology has exhibited the most significant impact on **mineral fertilizer use**, resulting in a reduction across the EU ranging from 0.1 to 0.3 million tonnes (Mt), equivalent to a 1% to 3% decrease. This result is not surprising as this technology directly enhances mineral fertilizer use efficiency, distinguishing it from most other modelled technologies. The application of digested sludge emerged as the second-best-performing technology of reducing mineral fertilizer use, achieving a maximum implementation share of 0.1 Mt, corresponding to a 1% decline.

Precision farming coping with heterogeneous qualities of organic fertilizers in the whole chain (“NIRS”) shows the highest direct effect on **manure use** ranging from -0.1 to -0.4 Mt, equivalent to a 1.9% to 7.4% decrease resulting from the higher manure use efficiency via this technology. Technologies associated with pig manure processing, such as “N stripping pig manure” and “Mineral concentrate pig manure”, contribute to a reduction in manure use in agriculture. However, it's important to note that this reduction is constrained by our assumption that only surplus pig manure within the NUTS2 region will be subjected to these treatments. Compared to other technologies, the N-Sensor shows the highest potential for reducing **N-surplus**, achieving a 2.6% reduction in the EU at maximum implementation share, followed by NIRS with a potential reduction of 2.1% compared to the reference in 2030.

Overall, these findings highlight the potential of innovative agricultural technologies to contribute significantly to sustainability goals in the EU. However, they also emphasize the complexity of achieving these goals, requiring careful consideration of various factors, including regional variations and the interconnectedness of agricultural practices and environmental outcomes. This comprehensive assessment underscores the importance of adopting a multifaceted approach to address the intricate challenges of agriculture and environmental conservation in the EU.

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Annex

Table A1: Absolute and relative changes in emissions for the EU-27 ranging from an increase of the initial implementation to the maximum implementation share of ECAMPA technologies compared to the reference

		No tillage	**Optimised fertilizer timing**	**Nitrification inhibitors**	**Precision farming**	**Feed additive: nitrate**
		GHG emission (1000 t CO_2 equivalent)				
Tech only	Abs. Δ	570.2 to -5580.5	-132.4 to -1578.1	-1696.9 to -11433.1	-2784.0 to -9409.7	-1578.8 to -8241.0
	%-Δ	-0.2 to - 1.4	-0.03 to -0.40	-0.4 to -2.9	-0.7 to -2.4	-0.4 to -2.1
Total	Abs. Δ	66.6 to -3585.4	-340.8 to -3305.1	-1409.6 to -11900.4	-2847.0 to -11037.7	-1652.5 to -10005.8
	%-Δ	-0.02 to -0.9	-0.09 to -0.8	-0.4 to -3.0	-0.7 to -2.8	-0.4 to -2.6
		NH_3 emission (1000 t)				
Tech only	Abs. Δ		66.4 to 453.0	43.8 to 298.3	-24.6 to -86.3	
	%-Δ		3.0 to 20.4	2.0 to 13.5	-1.1 to -3.9	
Total	Abs. Δ	-2.0 to -56.8	53.7 to 434.2	40.9 to 293.1	-22.8 to -92.6	2.1 to 2.5
	%-Δ	-0.1 to -2.6	2.4 to 19.6	1.8 to 13.2	-1.0 to -4.2	0.1 to 0.1
		CH_4 emission (1000 t)				
Tech only	Abs. Δ					-63.2 to -329.6
	%-Δ					-0.8 to -4.1
Total	Abs. Δ	-5.1 to -126.4	3.7 to 5.5	4.4 to -4.9	-4.4 to -9.5	-69.8 to -381.0
	%-Δ	-0.06 to -1.6	0.05 to 0.07	0.05 to -0.06	-0.05 to -0.1	-0.9 to -4.7
		N_2O emission (1000 t)				
Tech only	Abs. Δ	1.9 to 18.7	-0.4 to -5.3	-5.7 to -38.3	-9.3 to -31.6	
	%-Δ	0.3 to 2.7	-0.1 to -0.8	-0.8 to -5.5	-1.4 to -4.6	
Total	Abs. Δ	0.3 to -7.1	-1.3 to -10.6	-5.3 to -41.9	-12.2 to -47.9	0.5 to -1.2
	%-Δ	0.04 to -1.0	-0.2 to -1.5	-0.8 to -6.1	-1.8 to -6.9	-0.08 to -0.2

Source: Own computations with CAPRI

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Table A2: Absolute and relative changes for selected environmental indicators for the EU-27 ranging from an increase of the initial implementation to the maximum implementation share of ECAMPA technologies compared to the reference

		No tillage	Optimised fertilizer timing	Nitrification inhibitors	Precision farming	Feed additive: nitrate
Mineral Fertilizer Use Nitrate (1000 t)						
Tech only	Abs. Δ		-1.1 to -9.6	-43.4 to -254.9	-512.6 to -1671.7	
	%-Δ		-0.01 to -0.1	-0.4 to -2.6	-5.1 to -16.9	
Total	Abs. Δ	-42.9 to -712.1	24.2 to 151.1	-25.8 to -336.8	-449.6 to -1757.8	30.0 to 39.5
	%-Δ	-0.4 to -7.2	0.2 to 1.5	-0.3 to -3.4	-4.5 to -17.7	0.3 to 0.4
Manure Use Nitrate (1000 t)						
Tech only	Abs. Δ			-43.4 to -254.9		
	%-Δ			-0.4 to -2,6		
Total	Abs. Δ	-1.1 to -108.7	3.6 to 4.7	5.1 to -0.8	-3.4 to -9.0	2.56 to -5.23
	%-Δ	-0.01 to -1.4	0.04 to 0.1	0.06 to -0.01	-0.04 to -0.1	0.03 to -0.06
Leaching (1000 t)						
Tech only	Abs. Δ	33.2 to 236.6	-39.2 to -187.3	-43.9 to -253.0	-61.2 to -201.9	
	%-Δ	2.6 to 17.0	-3.0 to -14.7	-3.4 to 20.0	-4.8 to -16.1	
Total	Abs. Δ	20.9 to 340.5	31.4 to -208.2	-41.9 to -281.4	-69.4 to -239.3	-3.7 to -8.1
	%-Δ	1.6 to 26.4	-2.4 to -16.1	-3.2 to -21.8	-5.4 to -18.5	-0.3 to -0.6
N surplus (1000 t)						
Total	Abs. Δ	-0.02 to -204.8	24.8 to 148.0	-20.0 to -282.2	-464.8 to -1696.0	8.0 to -34.9
	%-Δ	0.00 to -1.8	0.2 to 1.3	-0.2 to -2.5	-4.0 to -14.8	0.1 to -0.3

Source: Own computations with CAPRI

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