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Assessment of environmental impacts upon application of biobased fertilising products recovered from digestate

A report from the H2020 project SYSTEMIC

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A full list of all end products is available at www.systemicproject.eu. The SYSTEMIC project was coordinated by Oscar Schoumans (oscar.schoumans@wur.nl) and Inge Regelink (inge.regelink@wur.nl) from Wageningen Environmental Research.

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Content

Preface

This study was carried out and published as a part of the European demonstration project SYSTEMIC funded by the H2020 programme (project number 730400). The project SYSTEMIC focuses at five large scale biogas plants where innovative nutrient recovery processing techniques were implemented and monitored in addition to anaerobic digestion. One of the tasks within the SYSTEMIC project is to do an Environmental Impact Assessment (EIA) i.c. to evaluate the impact of utilising the produced biobased fertilisers on agricultural land on the environment (i.e. nutrient leaching, volatilisation, metal accumulation, etc.), compared to the common conventional practice. The results of this EIA are presented in this report.

This report describes the modelling approach, input data, scenarios of biobased fertiliser application, and the results and conclusions in terms of environmental impacts. For all demonstration plants scenarios were worked out in terms of application rates of digestate and/or biobased fertilisers, and the associated applied nutrients and heavy metals to the soil. Thereafter, the model simulations were carried out which were discussed during a SYSTEMIC internal webinar. Finally, the outcome of the environmental impact assessments were reviewed by the demoplants and other partners of the SYSTEMIC project consortium.

We would like to acknowledge the plant owners and staff of Acqua & Sole (IT), Am-Power (BE), Waterleau NewEnergy (BE), BENAS (DE) and Groot Zevert Vergisting (NL) whom delivered information about the product quality of the produced biobased fertilisers and information on the distribution and application of their products in their countries. Furthermore, we would like to acknowledge Dr. Georges Hofman (emeritus professor Ghent University, Belgium), Dr. Karoline D’Haene (ILVO, Belgium) and Dr. Susanne Klages (Thünen-Institute, Germany) regarding collecting information and data of the scenarios of respectively Flanders and Germany.

The authors

List of abbreviations

AD	Anaerobic digestion
AmP	Am-Power
AS	Ammonium sulphate solution (synthetic)
AS_b	Biobased ammonium sulphate solution
A&S	Acqua & Sole
BIO	Microbial biomass
BNS	BENAS
BBFs	Biobased fertilisers
BCF	Bioconcentration factor of heavy metals
Ca~P	Precipitates of calcium phosphate
CAN	Calcium ammonium nitrate fertiliser
CEC	Cation exchange capacity of the soil
CECs	Contaminants of emerging concern
CHP	Combined Heat and Power installation
D	Digestate (only used in tables and figures)
DM	Dry matter
DOC	Dissolved organic carbon
DSFD	Dried solid fraction of digestate (only used in tables and figures)
Ev conc	Evaporator concentrate (only used in tables and figures)
EIA	Environmental impact assessment
EOM	Effective organic matter
FM	Fresh matter
GHG	Greenhouse gases
GZV	Groot Zevert Vergisting
HC	Humification coefficient
HUM	Humified organic matter
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
K40	Potassium fertiliser containing 40% K_2O
K60	Potassium fertiliser containing 60% K_2O
LCA	Life cycle assessment
LF	Liquid fraction
LPSI	Low phosphorus organic soil improver (only used in tables and figures)
MF	Mineral fertiliser
Mg~P	Precipitates of magnesium phosphate (for example struvite)
n.m.	Not measured
$N_{eff.}$	Effective nitrogen
NFRV	Nitrogen fertiliser replacement value
Norg	Organic nitrogen
NRR	Nutrient recovery and reuse
Ntot	Total nitrogen
OM	Organic matter
RO	Reverse osmosis
RO conc	Reverse osmosis concentrate (RO-concentrate) (only used in tables and figures)
SC	Soil conditioner

SF	Solid fraction
SOC	Soil organic carbon
SOM	Soil organic matter
TAN	Total ammoniacal nitrogen
TSP	Triple super phosphate
WNE	Waterleau NewEnergy

List of definitions

Term	Abbreviation	Definition
Digestate	D	Solid material remaining after the anaerobic digestion of a biodegradable feedstock.
LF of digestate	-	Liquid fraction (LF) after separation of digestate by a decanter centrifuge or screw press.
SF of digestate	-	Solid fraction (SF) after separation of digestate by a decanter centrifuge or screw press.
Dried SF of digestate	DSFD	Solid fraction of digestate after a thermal drying process
Evaporator concentrate	Ev conc	Liquid fraction of digestate, after evaporation of water and volatile components including ammonia.
RO concentrate	RO conc	Concentrate remaining after removal of water from a liquid stream (liquid fraction of digestate or evaporator concentrate by reverse osmosis (RO)).
Condensed ammonia water	-	Condensate after evaporation of liquid fraction of digestate with a high content of ammonium, and treated by reverse osmosis to reduce the water content.
Ammonium sulphate solution (biobased)	AS_b	Solution of ammonium sulphate (biobased) obtained after ammonia stripping followed by recovery of gaseous ammonia in sulphuric acid (Acqua & Sole) or with gypsum (FibrePlus at BENAS).
Permeate water	-	Permeate after reverse osmosis which needs further purification by means of ionic exchange (IO) prior to discharge to surface water
Purified water	-	Water recovered from digestate by means of reverse osmosis and ionic exchange, purified to be used as process water or to be discharged to surface water.
Low-P soil improver	LPSI	Solid fraction of digestate after flushing with water and sulphuric acid to remove most of the phosphorus (P).
Precipitated phosphate salts	-	Precipitated phosphate salts, obtained by precipitation of phosphate (PO_4) in solution with calcium or magnesium, which is recovered as calcium phosphate or struvite respectively, as a sludge or in solid form.
Low-N organic fibres	-	Solid fraction obtained by a screw press from digestate after nitrogen (N) stripping-scrubbing in the Fibreplus system and used for production of fibre.
Calcium carbonate sludge	-	Precipitate of calcium and carbonate produced as a side product of the FibrePlus nitrogen stripping unit at BENAS by the reaction of striped air containing ammonia and carbon dioxide with gypsum ($CaSO_4$) leading to the formation of ammonium sulphate and calcium carbonate precipitate.

List of demonstration plants

Demonstration plant	Abbreviation
BENAS	BNS
Am-Power	AmP
Groot Zevert Vergisting	GZV
Acqua & Sole	A&S
Waterleau NewEnergy	WNE

Summary

In this study, the environmental impact of application of biobased fertilisers (produced out of digestate) on agricultural land is assessed and compared with a standard application of digestate and synthetic mineral fertilisers. The studied biobased fertilisers (BBFs) are produced at five large scale biogas plants of the Horizon 2020 SYSTEMIC project, in which innovative nutrient recovery techniques have been implemented and monitored. The demonstration plants are Acqua & Sole (A&S, Italy), Am-Power (AmP, Belgium), Waterleau NewEnergy (WNE, Belgium), BENAS (BNS, Germany) and Groot Zevert Vergisting (GZV, the Netherlands). The five biogas plants treat different types of feedstock (pig slurry, sewage sludge, energy crops, poultry and food waste) and have implemented different types of nutrient recovery approaches, leading to a variety of new biobased products in order to meet the needs of crops in their region and to improve their business case (as described in Chapter 2). For each of the biogas plants, representative soil-crop combinations were defined including nutrient recommendations and legislative aspects regarding the Nitrates Directive. In addition, nutrient management scenarios have been defined for each of the soil-crop combination, which means that a part of the digestate and/or mineral fertiliser has been substituted by the produced biobased fertilisers (under the same conditions).

The application rates of fertiliser products in the reference scenarios (digestate and synthetic mineral fertilisers) and the other scenarios (also applying recovered products / biobased fertilisers) were determined by taking into account (1) the legal application standards for nitrogen (all countries) and phosphorus (the Netherlands and Flanders) and (2) the nutrient requirements regarding nitrogen (N), phosphorus (P), potassium (K) and sulphur (S) of the soil-crop combination and by taking into account the composition of the fertilising products and the legislative Nitrogen Fertiliser Replacement Value (NFRV) of the products. This is described in Chapter 3.

The impact on the environment of changes in nutrient management strategy for representative soil-crop combinations is predicted by means of models. The environmental impact is assessed for gaseous emissions of ammonia (NH_3), nitrous oxides (N_2O) to the air, nitrate (NO_3) leaching to groundwater and phosphorus (P) and heavy metals (chrome, arsenic, lead, cadmium, nickel, zinc and copper) accumulation and losses from the rootzone to groundwaters.

The model approach is based on the MITERRA-Europe model approach, which has been widely used at European scale to assess the gaseous emissions, and which has been expanded to include P dynamics and metal accumulation and losses. The overall modelling approach of each observed substance is described in Chapter 4 of this report. The required model input data were obtained from different sources, including scientific papers, reports, databases, existing models and expert judgement and are described in Chapter 5.

For each scenario, the nutrients and heavy metals applied were calculated and are presented in Chapter 6. The setup of the scenarios shows that biobased fertilisers can replace part or all of the applied digestate and/or mineral fertilisers (reference scenario). All scenarios comply with nitrogen legislation of the EU Nitrates Directive and national P legislation where applicable. All scenarios meet *at least* with the crop requirements of potassium, sulphur and also regarding phosphorus in the case of no P legislation. The recommendation values were defined as minimum values to be applied. No maximum values were set, without legislative standards.

In all scenarios where mineral N fertiliser and/or digestate are (partly or fully) substituted by biobased N fertilisers that are rich in S (like recovered ammonium sulphate solution (AS_b) or products of nutrient recovery and reuse technologies that use sulphuric acid in their process), the S application rate becomes often (much) higher than the crop requirements for S. In countries without P legislation, all types of fertiliser products with a low N-P ratio can cause high P field applications above crop requirements for P when N application standards are met. Both circumstances need to be prevented.

The results of the environmental impact assessment are described in detail in Chapter 7 and discussed in Chapter 8 and can be summarised as:

- Since many environmental parameters are evaluated there is no best combination: sometimes the biobased fertilisers perform better for a specific “element-soil-crop combination” and sometimes the reference scenarios (digestate in combination with synthetic mineral fertilisers) perform better. Often the results are comparable.
- It is expected that the application of produced N-rich biobased fertilisers will not lead to additional NH_3 emissions, if urea or fully NH_4-based mineral fertilisers are used as reference for synthetic mineral fertiliser instead of CAN, which contains 50% N-NO_3 and have very low NH3-emissions. Using biobased fertilisers have quite similar or show lower N_2O emissions.
- Substitution of synthetic mineral fertilisers by biobased nitrogen fertilisers shows often similar or lower nitrate leaching for demonstration plants GZV (RO concentrate), BNS, A&S (both ammonium sulphate) and WNE (evaporator concentrate). Meanwhile for AmP (evaporator concentrate), an increase is predicted due to the possibility to increase the application of the amount of total N, while keeping the amount of effective N (N_{eff}) applied equal. In fact, differences in feedstock of the digester (manure versus non-manure) between Waterleau NewEnergy and Am-Power determine what can be applied within the application rate limits (amount total N) and consequently the main differences on nitrate leaching.
- If there is no limit regarding maximum total phosphorus applications (like in Italy and Germany), high P surpluses can occur up to 5-7 times higher than the amount of harvested P (Italy), which will cause severe P leaching problems in the long term, as calculated within this study. Therefore, additional scenarios were implemented to showcase the impact of P equilibrium fertilisation, which do prevent losses of P.
- The leaching of heavy metals chrome (Cr), arsenic (As), lead (Pb) and cadmium (Cd) does not change much over time. Both slightly positive and negative effects are predicted for zinc (Zn), and almost always limited negative effects for copper (Cu) and nickel (Ni). The scenarios with digestate of sewage sludge shows relative high losses of Ni, Cu and Zn compared to the other scenarios. However, in almost all cases (grassland and arable land on all soil types) substitution of digestate and/or mineral fertilisers by produced biobased fertilisers result in lower leaching of heavy metals.
- Overall, the modelling results show that, on grassland, the soil organic carbon content will increase, which is mainly caused by the large contribution of crop residues on grassland compared to the inputs of organic carbon via fertilisation. On arable land, the results vary. Using low-N digestates (BENAS, Aqua&Sole) or low-P soil improvers (GZV) have some positive effect on SOC content, but the difference is more clearly for low-P soil improvers of GZV.

In general it is concluded that application of produced biobased fertilisers of the demonstration plants can be used as substitute for digestate and/or mineral fertilisers (reference conditions) and give often quite similar results in terms of emissions to the air, nitrate and phosphate losses and heavy metal losses. Sometimes the performance is better and sometimes a negative impact is predicted depending on the soil-crop combination and the composition of the biobased fertilisers (which differ remarkably).

In none of the situations all crop-requirements can be exactly met, not even in the reference scenarios, which can, in some cases, cause over fertilisation in terms of phosphate, sulphate and/or heavy metals. In the case where P equilibrium fertilisation is taken into account, together with the N recommendations, often the additional losses were prevented. If ammonium sulphate is used as biobased fertiliser, it is recommended to take into account crop specific sulphur recommendation, in order to limit sulphate losses.

In a sustainable circular economy, and also a linear economy!, the application of each of the required nutrients should not go beyond the crop demand of that specific nutrient, because in the long term, nutrient losses will increase if no additional measures are taken. Under these conditions there are no severe negative impacts expected of the biobased fertilisers as produced by the demonstration plants.

1 Introduction

The current European policy strongly focuses on the transition from a linear economy towards a circular economy (EC, 2015). The main goal is 'an economic sustainable growth by increasing the value of products, materials and raw materials as long as possible in the economy'. The three main strategies are (a) reduce waste to a minimum, (b) promote re-use and recycling of materials and products and (c) create value: from waste to valuable raw material. The European Commission proposes a large package of measures to set product requirements regarding reparability, sustainability and recyclability mainly to prevent the production of waste. One of these measures is the recycling of waste materials and by-products as fertilising product.

As part of this process, the European Commission is working on the introduction of a new Fertiliser Regulation (Regulation on fertilising products). The regulation focuses on the production of fertilisers from renewable raw materials which are classified into different categories. There is much attention on the organic fertilisers and organo-mineral fertilisers. Another main development at this moment is that the European Commission will set up criteria for nitrogen (N) fertilisers derived from manure which may be applied above the N application standard for manure as substitute for (industrially produced) mineral nitrogen fertilisers. Furthermore, there is a European initiative to increase the soil organic carbon stock in the soil with 4 promille (so called '4 promille initiative'[1]).

Our current European economic growth can be characterized as a linear economy in which natural finite raw materials are often used for the production of food and feed. Agricultural production is highly dependent on the availability of (fresh) water, macronutrients including N, phosphorus (P) and potassium (K) and a healthy soil.

Phosphorus is a life-essential, irreplaceable element and the fossil P reserves are limited. The current worldwide P reserves are estimated at 70,000 Tg P and the world mining production in 2018 was 270 Tg P (USGS, 2019). Essentially, all chemical fertiliser and P in feed additives is mined from phosphate-rich rocks which are located in a few places (mainly Morocco 75%, but also in China and USA). As Europe has no significant phosphate mines, it is highly dependent on the import of phosphate ore (De Ridder *et al.*, 2012). Recycling of P makes the EU less dependent on phosphate rock import from politically unstable regions. Recycling is also important for N, because large quantities of fossil fuel are used for the production of mineral N fertilisers. N fertiliser production is based on the Haber-Bosch process, which requires 22 GJ t^{-1} NH_3 fossil energy (EFMA, 2004).

Organic biomass (like manure, digestate and compost and, in some countries, also sewage sludge) is used as source of organic matter, and to recycle macro (N, P and K), secondary (Ca, Mg and S) and micro (B, Cu, Fe, Mn, Mo, Zn, …) nutrients. Furthermore, there is a trend to create more value out of organic biomass 'waste' streams e.g. by producing biogas as a substitute for natural gas and by recovering nutrients as a substitute for industrially produced mineral fertilisers.

Within the Horizon 2020 project SYSTEMIC (Grant Agreement no. 730400) innovative nutrient recovery techniques are implemented at five large scale biogas plants. The overall objective of the SYSTEMIC project is to reach a break-through in reuse of nutrients recovered from biowaste (manure, sewage sludge as well as food, feed and agricultural waste) in the agricultural production cycle. The focus of the project is on demonstration of circular economy solutions for biowaste management by an effective combination of anaerobic digestion and novel nutrient recovery and reuse (NRR) technologies in five full-scale demonstration plants. The demonstration plants are studied from the technical, environmental, economic and business perspective, as well as from the operational, regulatory and institutional point of view. SYSTEMIC will validate the technical and economic viability of the presented integrated approach at the demonstration cases and focus on practical information transfer and business development to other

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[1] https://www.4p1000.org

(biogas) outreach locations in order to demonstrate business opportunities elsewhere in Europe and to strengthen the position of the European biogas sector by offering them innovative mineral recovery technologies.

By implementing nutrient recovery processing techniques at biogas plants the digestate will change in composition and, depending on the processing techniques, different types of biobased fertilisers will be produced. Consequently, new nutrient management strategies for agricultural land will become available, since different products are recovered from digestate. From an agronomic point of view, the available nutrients can be applied more in line with crop requirements. However, the environmental impact can also change due to the changes in applied products (both quality and quantity). The main aim of this study is to quantify the environmental impact of changes in nutrient management strategies on agricultural land due to nutrient recovery. Within the SYSTEMIC study this was identified as Environmental Impact Assessment (EIA). Although, an EIA should also consider the social consequences and alternative actions (https://iate.europa.eu/) these aspects were not part of the SYSTEMIC project (as defined in task 1.4) and not considered. In another SYSTEMIC study the Life Cycle Assessment (LCA) of the biogas plants has been carried out. The assessment of the overall CO_2 footprint (transport of biomass streams, use of mineral fertilisers, et cetera) will also be part of that LCA study.

This report presents the Environmental Impact Assessment (EIA) of the application of the produced biobased fertilisers at the five demonstration plants on agricultural land. The results are compared to a system without biobased fertilisers (e.g. digestate and/or mineral fertilisers). By means of scenario analysis, the impact of changes in nutrient management strategy on the gaseous emissions of ammonia (NH_3) and nitrous oxides (N_2O) to the air, and N and P leaching from the root zone to waters was assessed. Dynamic model approaches were used to predict changes in environmental aspects over time, taking potential accumulation of N, P and heavy metals in soils into account. Furthermore, the consequences of heavy metals accumulation and losses to water bodies were evaluated with available heavy metal tools.

Such models are not available for contaminants of emerging concern (CECs, like antibiotics, hormones and pharmaceuticals, biocides, zoonosis, contagious animal diseases). Depending on the type of feedstock of the biogas plants a long list of substances/compounds can be potentially measured in digestate, in particular in digestate from sewage sludge. In many countries, digestate of sewage sludge can be applied on agricultural land taking into account the European and national/regional legislation. Due to the implementation of nutrient recovery techniques at biogas plants there is a possibility that some of the substances will also (partly) end up in the biobased fertilisers. It is assumed that these products may also be applied on agricultural land taking into account the current legislation. However, for each of the demonstration plants, using different types of feedstock, a screening has been performed to determine whether residues of herbicides, pesticides and pharmaceuticals are present in digestate and derived BBFs (Sigurnjak et al., 2022).

The nutrient management scenarios resemble the situation of agricultural practical options with and without nutrient recovery at the biogas plants and the application of their products on agricultural land. The environmental impact of nutrients (N and P) and heavy metals was evaluated.

Reader

In the next chapter, the five SYSTEMIC Nutrient Recovery and Reuse (NRR) demonstration plants are shortly described including the produced biobased fertilisers. The scenarios are defined in Chapter 3, and Chapter 4 focuses on the description of the modelling approach and process description. Chapter 5 concerns the data collection. In Chapter 6 the application rates are presented for each scenario and in Chapter 7 the results of the EIA are shown. Finally, in Chapter 8 and 9 the conclusions and recommendations are summarised.

2 Demonstration plants

2.1 General description of implemented techniques

The five large scale demonstration plants are located in Belgium (Am-Power, Pittem and Waterleau NewEnergy, Ieper), Germany (BENAS, Ottersberg), Italy (Acqua & Sole, Vellezzo Bellini) and the Netherlands (Groot Zevert Vergisting, Beltrum). Table 2-1 gives an overview of the feedstock and produced products of the demonstration plants.

Table 2-1 Digester capacity, feedstock and products of the five SYSTEMIC demonstration plants part of this environmental impact assessment (from Brienza, et al., 2022).

Name	**Location**	**Feedstock quantity (2020)**	**Feedstock**	**Biobased fertilisers produced and other end-products**
Groot Zevert Vergisting	Beltrum (NL)	115 kt/y	Pig slurry, residues from agro-food industry, glycerine	• RO concentrate (RENURE product)[1] • MF concentrate[1] • Solid fraction of digestate • Precipitated P salt • Low-P soil improver • Purified water
Am-Power	Pittem (BE)	135 kt/y	Residues from agro-food industry	• Dried solid fraction of digestate • Evaporator concentrate • Permeate water[2]
Acqua & Sole	Vellezzo Bellini (IT)	77 kt/y	Sewage sludge, residues from agro-food industry	• Ammonium sulphate solution • Digestate
BENAS	Ottersberg (DE)	87 kt/y	Energy crops (maize and rye) and poultry litter (until 2020)	• Solid fraction digestate • Liquid fraction of digestate • Ammonium sulphate • Calcium carbonate sludge • Low-N organic fibres
WaterleauNewEnergy	Ypres (BE)	66 kt/y	Pig manure, sludge and biowaste from agro-food industry	• Dried solid fraction of digestate • Evaporator concentrate • Condensed ammonia water • Purified water

[1] RO: reverse osmosis, MF: micro-filtration. MF concentrate was not considered as a product in the EIA

[2] Am-Power was not yet equipped with an RO installation for treatment of the condensate of the evaporator into permeate water.

There are different drivers for the biogas plants to invest in NRR technologies. Depending on the feedstock, high ammonia (NH_3) concentrations can occur in the biogas which inhibit biogas production (toxic concentration for micro-organisms). This can be the situation if e.g. poultry manure or sewage sludge is used. Nitrogen-stripping is an option to reduce and control levels of NH_3 in the digester, avoiding inhibition of biogas production. This type of technique is implemented at the plants Acqua & Sole and BENAS. The produced ammonium sulphate is directly used on agricultural land. At Acqua & Soil farmers in the surrounding of the plant use the digestate as well as the ammonium sulphate. The demonstration BENAS has own land where both the digestate as well as the ammonium sulphate can be directly used.

In the Netherlands, the production of nutrients from manure is much higher than the amount that can be applied on agricultural land due to limits in P and N application standards. The P application standard is often the limiting factor in the maximum amount of manure that can be applied. As a result, the surplus of manure is mainly exported over large distances against high costs. The main focus of GZV is to reduce convert digestate into a SF that can be exported over long distances, an RO concentrate (RENURE product) that can be applied locally, and purified water that can be discharged to surface water. Both P and N are recovered. Phosphate can be recovered as magnesium ammonium phosphate (struvite) or calcium phosphate. Nitrogen is recovered as RO concentrate via reverse osmosis (RO) technique. The focus is put on producing RO concentrates because in the Dutch 6th Action Plan Nitrates Directive there is a pilot 'Biobased fertilisers Achterhoek region' running, which focuses on the practical implementation of the produced RO concentrate.

In Flanders (northern part of Belgium), both Am-Power and Waterleau NewEnergy have to pay for the food (processing industry) waste and other high energy content wastes as feedstock for the biogas production. To date, the dried SF of digestate as well as the evaporator concentrate are exported to France, because the regional market is not developed yet, since both plants are located in a manure nutrient surplus area. This represents a net cost resulting from hygienisation (e.g. by bio-thermal drying installations), storage, transport and spreading. The main driver for Am-Power was to reduce the moisture content of its products and reduce transportation costs. At the demonstration plant Am-Power, an evaporator is used to produce concentrates with a relatively high N and K concentration. Waterleau NewEnergy (WNE) is facing the same problems as Am-Power regarding digestate disposal. Additionally, because WNE is also including animal manure in its feedstocks, the digestate has the status of "animal manure". This cannot be used in large amounts on land in the region, so the surplus N has be processed via biological nitrification-denitrification treatment, exported outside Flanders, or used in industry or gardens. Since the costs for long distance transport (export) of digestate or external biological nitrification-denitrification treatment would be too high, WNE had been focussing on technologies to remove the water from the digestate and concentrate the nutrients on site until 2021. Therefore, they have chosen for N separation technology cascade, because an alternative marketing route was found around 2012-2015: use of condensed ammonia water as alternative to urea for DeNOx (selective non-catalytic reduction) of flue gases in incineration plants. For the concentrated digestate (i.e. evaporator concentrate and SF of digestate), removal of water and mixing to more desired NPK nutrient ratios can also reduce the costs by increasing the small profit margins for export and use of these products in France. Meanwhile, these NRR processes can help them to use the residual heat of the Combined Heat and Power installation (CHP) to a maximum extent, which provides subsidies in the form of 'Heat certificates'.

2.2 Composition of the produced biobased fertilisers

The construction of most of the nutrient recovery techniques at the five large scale demonstration plants was more complex than expected beforehand. Table 2-2 shows the average composition of the dry matter and organic matter content and the content of the macro nutrients based on the information of the demonstration plants. Detailed information of the composition (macro nutrients, secondary nutrients, micro nutrients, heavy metals, pathogens and organic pollutants) is reported in SYSTEMIC deliverable 1.13 *'Document on product characteristics, lab results and field trials (year 4)'*. The composition in terms of heavy metal content is presented in Appendix B. Due to differences in feedstock of the digesters the composition of the digestate varies substantially between the demonstration plants. Furthermore, at

Waterleau NewEnergy condensed ammonia water is also produced, but this product is not applied on agricultural land and not taken into account as a fertiliser product. Also, recovered precipitated phosphate salts produced at Groot Zevert Vergisting are exported and not used in the region. The low N organic fibres produced at BENAS are not used on agricultural land, but to make paper products. Finally, the impact of recovered lime produced at BENAS is not considered in the environmental impact assessment. It could potentially have an indirect effect on N, P and heavy metal emissions, but no quantitative information is available for crop-soil combinations.

Table 2-2 The composition of digestate and produced biobased fertilisers (n.m. = not measured) of the five demonstration plants. All parameters are expressed in fresh matter contents (FM).

Parameters		Groot Zevert Vergisting	Am-Power	Waterleau NewEnergy	Acqua & Sole	BENAS
Digestate		*Digestate*	*Digestate*	*Digestate*	*Digestate*	*Digestate*
Dry matter	(g/kg FM)	81	81	57	106	107
Organic matter	(g/kg FM)	59	50	32	63	73
N-total	(g/kg FM)	7.3	5.2	6.4	8.0	7.2
NH_4-N	(g/kg FM)	5.0	2.2	4.3	3.7	3.8
P-total	(g/kg FM)	1.7	1.3	1.0	3.4	1.4
K-total	(g/kg FM)	4.5	3.4	3.9	0.59	6.1
S-total	(g/kg FM)	0.67	1.0	0.84	1.1	1.1
(Organo-) Mineral nitrogen		*RO-Concentrate*	*Evaporator concentrate*	*Evaporator concentrate*	*Ammonium Sulphate*	*Ammonium sulphate*
Dry matter	(g/kg FM)	37	115	190	360	233
Organic matter	(g/kg FM)	14	63	92	n.m.	n.m.
Total organic carbon	(g/kg FM)	n.m.	26	44	<1	0.35
N-total	(g/kg FM)	8.1	9.0	11	75	46
NH_4-N	(g/kg FM)	8.0	7.0	5.1	71	45
P-total	(g/kg FM)	0.15	1.0	2.1	<0.02	<0.01
K-total	(g/kg FM)	7.9	9.7	22	<0.02	<0.01
S-total	(g/kg FM)	1.5	12	12	85	54
(Organo-) Mineral Phosphate		*Precipitated phosphate salts*				
Dry matter	(g/kg FM)	171				
Organic matter	(g/kg FM)	70				
N-total	(g/kg FM)	8.4				
NH_4-N	(g/kg FM)	5.2				
P-total	(g/kg FM)	9.3				
K-total	(g/kg FM)	2.6				
S-total	(g/kg FM)	15				

Table 2-2 (Continued) The composition of digestate and produced biobased fertilisers (n.m. = not measured). All parameters are expressed in fresh matter contents (FM).

Parameters		Groot Zevert Vergisting	Am-Power	Waterleau NewEnergy	Acqua & Sole	BENAS
Liming products						*CaCO3*
Dry matter	(g/kg FM)					698
Organic matter	(g/kg FM)					23
N-total	(g/kg FM)					13
NH_4-N	(g/kg FM)					10
P-total	(g/kg FM)					0.18
K-total	(g/kg FM)					0.39
S-total	(g/kg FM)					29
Organic products		*Low-P soil improver*	*Dried SF of digestate*	*Dried SF of digestate*		*Low-N organic fibres*
Dry matter	(g/kg FM)	237	823	904		234
Organic matter	(g/kg FM)	212	511	637		203
N-total	(g/kg FM)	5.3	23	30		4.6
NH_4-N	(g/kg FM)	2.0	0.88	2.6		<0.1
P-total	(g/kg FM)	1.1	19	25		2.3
K-total	(g/kg FM)	1.1	13	15		5.7
S-total	(g/kg FM)	5.8	11	11		1.2

2.3 Disposal of digestate and recovered products

2.3.1 Groot Zevert Vergisting (the Netherlands)

Groot Zevert Vergisting is situated in the eastern part of the Netherlands in a region with intensive agriculture where disposal of manure and digestate is costly because the livestock sector produces more manure than can be applied within the crop- and soil specific P application limits (17-52 kg P/ha or 40-120 kg P_2O_5/ha) and the limit for N from animal manure (170 kg N/ha, NVZ). GZV started their biogas activities in 2004 and have since then expanded to become one of the largest AD plants in The Netherlands, treating nowadays about 115 ktonnes of manure (pig slurry) and residues from agro-food industry and producing about 10 Mm^3 biogas on a yearly basis. Until 2018, digestate was exported to Germany over distances of 200 to 300 km. To lower costs for digestate disposal and to reduce their dependency on German buyers, GZV decided to develop a new business case for valorisation of their digestate. They invested in an installation (named 'GENIUS')for the production of a SF of digestate, RO concentrate and purified water in order to reduce the volume of their end products. Though RO concentrate is still considered 'animal manure', they were granted a temporary exemption to use RO concentrate as a replacement for synthetic N fertiliser under the pilot 'biobased fertilisers Achterhoek'. The MF concentrate is a by-product consisting of the sludge produced by the micro-filtration unit. The SF of digestate was still exported to regions in Germany with a demand for P fertilisers. In order to turn SF of digestate into a valuable product, GZV developed a new technological approach (named 'RePeat') together with Wageningen Environmental Research and Nijhuis Industries to separate SF of digestate into a low-P soil improver and a precipitated P salt - calcium phosphate (Ca~P) or magnesium ammonium phosphate (Mg~P, struvite). The low-P soil improver can be used as a source of organic matter on sandy soils in the region of the plant or can be further upgraded towards a peat replacer to be used in potting soil. The performance of the installations and quality of the end products have been monitored as part of the SYSTEMIC project.

2.3.2 Am-Power (Belgium)

Am-Power is located in the western part of Flanders (Belgium), a region characterized by an excess of animal manure and still a high market demand for formulated synthetic fertiliser. In 2011 the first biogas production activities started and they are now the largest biogas installation in Belgium. Though Am-Power's digestate is not designated as manure – they solely process organic residues from domestic sources and food industry - their digestate has a negative economic value due to the surplus of manure in their region. Prior to the start of SYSTEMIC, Am-Power was already equipped with a novel treatment line for the production of dried SF of digestate and RO concentrate from their digestate. Poor economic results, however, forced Am-Power to further enhance their business case. They developed a novel technological approach based on vacuum evaporation in combination with RO, through which they expect to reduce both operational costs (lower use of chemicals compared to baseline) and costs for product disposal. Their aim is to produce fertilising products with a high nutrient value, and hence a low water content, which can be transported over larger distances to regions with a demand for nutrients. To date, they produce dried solid fraction of digestate (high P content) and evaporator concentrate (high N,K,S). In addition, they convert part of their digestate into purified water to be used on-site for cleaning purposes. The cleaning water still needs to be purified further, in order to discharge the permeate to surface water.

2.3.3 Waterleau NewEnergy (Belgium)

Waterleau New Energy (WNE) BV operates a mesophilic AD plant in Ypres (80 km west of Ghent), West-Flanders, Belgium. The plant is in operation since 2012 with a total annual substrate treatment capacity of 120,000 t to process manure, sewage sludge and residues from agro-food industry. WNE is located in a nitrates-vulnerable-zone. Since there is a surplus of N from animal manure in the region, WNE implemented a process to recover ammonia from the liquid fraction of digestate as condensed ammonia water to be sold as flue gas DeNOx reductant, thereby reducing their dependency on the local manure market. Until 2020, the remaining evaporator concentrate, which contains a mixture of macro-nutrients, but is low in N, was sold to arable farmers in The Netherlands. Currently, evaporator concentrate is blended with the dried SF of digestate and sold to a composting company that eventually exports the end product to France. WNE aims to improve the market value of the end products to improve their overall business case.

2.3.4 Acqua & Sole (Italy)

Acqua & Sole s.r.l. is an operator of anaerobic digestion activity. The main driver behind this investment was the desire for recycling organic waste flows and particularly urban waste flows to organic fertilisers. Acqua & Sole is located in an area (Lomardy) with some 100,000 ha of arable land, of which 85% is used for rice cultivation. Livestock rearing is not a major activity in the region, only 1.7% of animals reared in Lombardy live in the area, about 33,000 out of a total of 32 million. Animal manure is therefore neither an environmental issue, nor an available fertilising material. The vicinity of Milano (15 km) with close to 3.3 million people, and the food industry are the main sources of feedstock for Acqua & Sole. Services are consequently focusing on the offtake of sewage sludge from communal WWTPs and food waste from urban and commercial suppliers.

Waste streams are converted into sanitised digestate and ammonium sulphate with two applications in mind:

- About 1,000 ha of own farmland;
- About 4,000 ha farmland in the neighbourhood of the plant.

The first benefits of N stripping is control of ammonia levels in the digester, enabling them to run the digester at thermophilic conditions rather than at mesophilic conditions, without inducing inhibition of the biogas production due to toxicity of ammonia. This translates into a higher biogas production as well as sanitation of their digestate. Secondly, lowering the N content of digestate offers economic benefits because more digestate, and also more organic matter, can be applied per hectare of soil within the N application rate limits. There is no P application limit in Italy.

The business model does not aim at revenues from energy conversion, but on closing the nutrient and organic materials loop. Recovery of nutrients and organic matter is a major driver for the AD plant Acqua & Sole, especially since incineration is also an upcoming alternative treatment and disposal route for sewage sludge in Italy. Incineration means a loss of nitrogen and organic matter and, if ashes are not used as a fertiliser, also a loss of phosphorus. Recycling of organic matter is considered of high importance due to the progressing degradation of the peri-urban, industrially managed farmland south of Milano.

2.3.5 BENAS (Germany)

The biogas plant BENAS, located in Ottersberg (near Bremen, Germany), was realized in 2006 and converts energy crops (mostly maize) and poultry litter into biogas and fertilisers. The input of the digester varies between the years as the intake of poultry manure depends on the market prices. High prices for poultry litter led to a decline in the portion of poultry litter in the input of the AD plant in 2020 compared to the years before. In order to reduce NH_3 levels in the digester, BENAS has implemented a N-stripping system (*FiberPlus* system) in 2007/2008. The N-stripping system has been developed by GNS which is a consultancy company and partner within SYSTEMIC.

The innovative N-stripping and scrubbing system relies on binding NH_3 and CO_2 with dihydrate calcium sulphate (gypsum), producing a mixture of AS solution and liming substrate. The liming substrate is predominantly composed by calcium carbonate ($CaCO_3$) with traces of calcium sulphate ($CaSO_4$). This mixture is indicated from now on as calcium carbonate (CC) sludge. AS solution and CC sludge are separated by means of a filter press. The digestate with a reduced NH_4 content is fed back into the digester diluting the feedstocks and preventing ammonia inhibition. Digestate after the post-digester is separated into a solid and liquid fraction and used for fertilisation of cropland owned by BENAS to grown energy crops for the AD plant. An additional product of the FiberPlus installation are the low N-fibres, which are obtained by means of a screw press from the digestate leaving the N stripper, and which therefore has a low NH_4 content. Over the course of the SYSTEMIC project, BENAS and GNS developed a new market for these low-N fibres. They now use the low-N fibres for on-site production of paper- and cardboard.

3 Scenarios for biobased fertiliser application

In this chapter, the scenarios are described to predict the environmental impact of implementing biobased fertilisers in agricultural practice in the region where the demonstration plant is located. Different nutrient management regimes (combination of applied products) are defined for representative soil-crop combinations and/or rotations. For grassland fields it is assumed that they are only mowed during the year (no grazing).

This means that regional soil-crop specific recommendations and national and/or regional legislative aspects are taken into account.

3.1 Definitions of the reference situation and scenarios

Based on the marketing strategy of demonstration plants to utilise the produced biobased fertilisers and the legal framework to apply these fertilisers in the region, several representative scenarios have been defined. First, the most common soil type and crop type, on which the produced fertilisers are or will be applied, were defined. Secondly, options for potential combination of the produced biobased fertilisers (Table 2-2) and synthetically produced mineral fertilisers (shortly, referred to as mineral fertilisers in the text) were proposed. These scenarios were compared to the reference scenario for the same soil type and crop type combination. Only digestate and mineral fertilisers are applied in the reference scenario. In the scenarios, a part of the mineral fertilisers and/or digestate has been substituted by one or more biobased fertiliser(s). Table 3-1 gives an overview of the scenarios.

For Acqua & Sole and BENAS, specific scenarios based on P equilibrium fertilisation (indicated with A&S_P and BNS_P) were added as well. For Acqua & Sole these were added because there are no P legislation limits on the application of fertilisers, resulting in rather high fertiliser applications in the standard scenarios for this plant. For BENAS, rules from the German Düngelmittelverordnung apply: P equilibrium fertilisation is a prerequisite in the case where certain P limits in the soil are exceeded[2]. Because the soil P status is unknown, both P equilibrium fertilisation and no equilibrium fertilisation are taken into account (see also Table 3-3 for application standards).

The following biobased fertilisers were taken into account for the scenario analyses: biobased ammonium sulphate solution, evaporator concentrate, RO concentrate, low-P soil improver and dried solid fraction of digestate. Some of the produced products of the demonstration plants were not applied within the scenario analyses regarding environmental impact assessment. These were precipitated P salts (resource for fertiliser industry), condensed ammonia water (used as DeNOx of flue gases in incineration plants), calcium carbonate sludge (just a liming product not relevant in terms of environmental impact) and low-N organic fibres (resource for paper industry).

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[2] https://www.gesetze-im-internet.de/d_v_2017/D%C3%BCV.pdf, p 4-5

Table 3-1 (Part 1) Definition of the soil types, crop types and scenarios considered for each of the demonstration plants and the reference (REF) scenarios, including Groot Zevert Vergisting (GZV), Am-Power (AmP), Acqua & Sole (A&S), BENAS (BNS) and Waterleau NewEnergy (WNE). Code products: see footnote table.

#	Plant	Crop	Soil	Option	Combination of products	Code products
1	GZV	Grassland	Sand	1	REF: Digestate and mineral fertilisers	D + MF
2	GZV	Grassland	Sand	2	Digestate, RO concentrate and mineral fertilisers	D + RO conc + MF
3	GZV	Grassland	Sand	3	Digestate and RO concentrate	D + RO conc
4	GZV	Grassland	Sand	4	RO concentrate and mineral fertilisers	RO conc + MF
5	GZV	Grassland	Clay	1	REF: Digestate and mineral fertilisers	D + MF
6	GZV	Grassland	Clay	2	Digestate, RO concentrate and mineral fertilisers	D + RO conc + MF
7	GZV	Grassland	Clay	3	Digestate and RO concentrate	D + RO conc
8	GZV	Grassland	Clay	4	RO concentrate and mineral fertilisers	RO conc + MF
9	GZV	Arable	Sand	1	REF: Digestate and mineral fertilisers	D + MF
10	GZV	Arable	Sand	2	Digestate, RO concentrate and mineral fertilisers	D + RO conc + MF
11	GZV	Arable	Sand	3	Digestate and RO concentrate	D + RO conc
12	GZV	Arable	Sand	4	Low-P soil improver, RO concentrate and mineral fertilisers	LPSI + RO conc + MF
13	GZV	Arable	Clay	1	REF: Digestate and mineral fertilisers	D + MF
14	GZV	Arable	Clay	2	Digestate, RO concentrate and mineral fertilisers	D + RO conc + MF
15	GZV	Arable	Clay	3	Digestate and RO concentrate	D + RO conc
16	GZV	Arable	Clay	4	Low-P soil improver, RO concentrate and mineral fertilisers	LPSI + RO conc + MF
17	AmP	Grassland	Sand	1	REF: Digestate and mineral fertilisers	D + MF
18	AmP	Grassland	Sand	2	Digestate, Evaporator concentrate and mineral fertilisers	D + Ev conc + MF
19	AmP	Grassland	Sand	3	Evaporator concentrate and mineral fertilisers	Ev conc + MF
20	AmP	Grassland	Clay	1	REF: Digestate and mineral fertilisers	D + MF
21	AmP	Grassland	Clay	2	Digestate, Evaporator concentrate and mineral fertilisers	D + Ev conc + MF
22	AmP	Grassland	Clay	3	Evaporator concentrate and mineral fertilisers	Ev conc + MF
23	AmP	Potatoes	Sand	1	REF: Digestate and mineral fertilisers	D + MF
24	AmP	Potatoes	Sand	2	Digestate, Evaporator concentrate and mineral fertilisers	D + Ev conc + MF
25	AmP	Potatoes	Sand	3	Dried SF of digestate, Evaporator concentrate and mineral fertilisers	DSFD + Ev conc + MF
26	AmP	Potatoes	Clay	1	REF: Digestate and mineral fertilisers	D + MF
27	AmP	Potatoes	Clay	2	Digestate, Evaporator concentrate and mineral fertilisers	D + Ev conc + MF
28	AmP	Potatoes	Clay	3	Dried SF of digestate, Evaporator concentrate and mineral fertilisers	DSFD + Ev conc + MF

AS_b:	Biobased ammonium sulphate solution
D:	Digestate
DSFD:	Dried solid fraction of digestate
Ev conc:	Evaporator concentrate
LPSI:	Low-P soil improver
MF:	Mineral fertilisers
RO conc:	Reversed Osmosis (RO) concentrate

Table 3-1 (Continued). Definition of the soil types, crop types and scenarios considered for each of the demonstration plants and the reference (REF) scenarios, including Groot Zevert Vergisting (GZV), Am-Power (AmP), Acqua & Sole (A&S), BENAS (BNS) and Waterleau NewEnergy (WNE). Code products: see footnote table.

#	Plant	Crop	Soil	Option	Combination of products	Code products
29	Acq	Corn	Loam	1	REF: Digestate and mineral fertilisers	D + MF
30	Acq	Corn	Loam	2	Digestate, ammonium sulphate solution and mineral fertilisers	D + ASb + MF
31	Acq	Rice	Loam	1	REF: Digestate and mineral fertilisers	D + MF
32	Acq	Rice	Loam	2	Digestate, ammonium sulphate solution and mineral fertilisers	D + ASb + MF
33	Acq_P	Corn	Loam	1	REF: Digestate and mineral fertilisers *in case of P equilibrium fertilisation*	D + MF
34	Acq_P	Corn	Loam	2	Digestate, ammonium sulphate solution and mineral fertilisers *in case of P equilibrium fertilisation*	D + ASb + MF
35	Acq_P	Rice	Loam	1	REF: Digestate and mineral fertilisers *in case of P equilibrium fertilisation*	D + MF
36	Acq_P	Rice	Loam	2	Digestate, ammonium sulphate solution and mineral fertilisers *in case of P equilibrium fertilisation*	D + ASb + MF
37	BeN	grassland	Sand	1	REF: Digestate and mineral fertilisers	D + MF
38	BeN	grassland	Sand	2	Digestate, ammonium sulphate solution and mineral fertilisers	D + ASb + MF
39	BeN	winter wheat	Sand	1	REF: Digestate and mineral fertilisers	D + MF
40	BeN	winter wheat	Sand	2	Digestate, ammonium sulphate solution and mineral fertilisers	D + Asb + MF
41	BeN_P	grassland	Sand	1	REF: Digestate and mineral fertilisers *in case of P equilibrium fertilisation*	D + MF
42	BeN_P	grassland	Sand	2	Digestate, ammonium sulphate solution and mineral fertilisers *in case of P equilibrium fertilisation*	D + ASb + MF
43	BeN_P	winter wheat	Sand	1	REF: Digestate and mineral fertilisers *in case of P equilibrium fertilisation*	D + MF
44	BeN_P	winter wheat	Sand	2	Digestate, ammonium sulphate solution and mineral fertilisers *in case of P equilibrium fertilisation*	D + ASb + MF
45	WNE	Grassland	Sand	1	REF: Digestate and mineral fertilisers	Dig + MF
46	WNE	Grassland	Sand	2	Digestate, Evaporator concentrate and mineral fertilisers	Dig + Ev conc + MF
47	WNE	Grassland	Sand	3	Evaporator concentrate and mineral fertilisers	Ev conc + MF
48	WNE	Grassland	Clay	1	REF: Digestate and mineral fertilisers	Dig + MF
49	WNE	Grassland	Clay	2	Digestate, Evaporator concentrate and mineral fertilisers	Dig + Ev conc + MF
50	WNE	Grassland	Clay	3	Evaporator concentrate and mineral fertilisers	Ev conc + MF
51	WNE	Potato	Sand	1	REF: Digestate and mineral fertilisers	Dig + MF
52	WNE	Potato	Sand	2	Digestate, Evaporator concentrate and mineral fertilisers	Dig + Ev conc + MF
53	WNE	Potato	Sand	3	Dried SF digestate, evaporator concentrate and mineral fertilisers	DSFD + Ev conc + MF
54	WNE	Potato	Clay	1	REF: Digestate and mineral fertilisers	Dig + MF
55	WNE	Potato	Clay	2	Digestate, Evaporator concentrate and mineral fertilisers	Dig + Ev conc + MF
56	WNE	Potato	Clay	3	Dried SF digestate, evaporator concentrate and mineral fertilisers	DSFD + Ev conc + MF

AS_b:	Biobased ammonium sulphate solution
D:	Digestate
DSFD:	Dried solid fraction of digestate
Ev conc:	Evaporator concentrate
LPSI:	Low-P soil improver
MF:	Mineral fertilisers
RO conc:	Reversed Osmosis (RO) concentrate

In the Netherlands and Flanders (for Am-Power and Waterleau NewEnergy) both clay soils and sandy soils were taken into account, and the scenarios in Italy and Germany accounted for loam and sandy soils, respectively. In all countries, except Italy, the biobased fertilisers are applied on both grassland and arable land. For Italy, only arable land was considered because that is the agricultural practice in the region where Acqua & Sole applies its digestate. In the Netherlands, the following crop rotation on arable sandy soils were used for calculation: consumption potato (25%) winter wheat (25%), silage maize (25%) and sugar beet (25%). On arable clay soils onions (12.5%) were also taken into account, along with potato (25%), winter wheat (25%), silage maize (12.5%) and sugar beet (25%). For Flanders, grassland and potatoes were selected as the most important crops. In Italy the most relevant crop-soil combination is corn or rice on a loam soil. In Germany the products were applied on sandy (moderately fine texture/loamy) soils in cultivation of cereals, such as winter wheat.

3.2 Application standards for nitrogen and phosphorus

The amount of biobased products that can be applied depends on the N and P application standards, which are country-dependent and defined for crop types, the amount of nutrients in the products and the fertiliser replacement values for NPK. For manure and manure-based digestate the Nitrates Directive also has to be taken into account, which states that, within nitrate vulnerable zones, a maximum of 170 kg N ha^{-1} y^{-1} may be applied as (digested) manure per year based on the total-N content of the manure. However, some countries (the Netherlands and Flanders) have derogation, so farmers may apply a higher specified amount of nitrogen in the form of manure and manure based digestate under specific conditions. For example, dairy farms with more than 80% grassland may apply a maximum of 230 kg N ha^{-1} y^{-1} as (digested) manure on sandy and loess soils in the following provinces: Overijssel, Gelderland, Utrecht, Noord Brabant or Limburg. For all other provinces in the Netherlands, the derogation allows 250 kg N/ha. However, farms that make use of this derogation may not use mineral P fertilisers.

Taking into account *the maximum amount of N that can be applied as manure (Nitrates Directive with or without derogation)* and the total N-content of the manure (or manure based digestate), the total amount of (digested) manure can be calculated. This is different for *the total amount of all nutrients (including mineral fertilisers)* that may be applied on agricultural land, because only the effective part (read Nitrogen Fertiliser Replacement Value; NFRV) of the nutrients in the applied products has to be taken into account. For phosphate and potassium, the fertilisers replacement values are set at 100%. For N the situation is different. The amount of effective N (comparable with mineral fertiliser N) depends on many factors, like application technique, moment of application, pH, decomposition rate and C/N ratio of the organic materials in the digestate/manure, and length of N-uptake by the crops. Table 3-2 shows the country-specific defined NFRV values according to legislation. These values mentioned are used in this study. The NFRV of all mineral products is set to 100% in all countries (mineral fertilisers, ammonium sulphate solution and RO concentrates), although the RO concentrate can contain some organic material (Table 2.2). For evaporator concentrates, the NFRV is set to 60%. The digestate NFRV is often 50 – 60%, only in the Netherlands a value of 80% is used on sandy soils. For the dried SF of digestate a value of 30% was used. The Low-P soil improver is a completely new product which is currently tested in a pilot, and for this pilot a NFRV value was set at 10% by the Ministry of Agriculture.

Table 3-2 Legislative Nitrogen Fertiliser Replacement Values (NFRV) of digestate, biobased fertilisers and mineral fertilisers as defined by the Netherlands, Flanders (Belgium), Italy and Germany.

Plant	Product	Soil type	NFRV (%)
Groot Zevert Vergisting	Digestate from pig manure	Sand	80$^{1)}$
	Digestate from pig manure	Clay	60$^{1)}$
	RO concentrate	All	100
	Low-P soil improver	All	10
Am-Power and Waterleau NewEnergy	Digestate	All	60$^{2)}$
	Dried solid fraction of digestate	All	30$^{2)}$
	Evaporator concentrate	All	60$^{2)}$
Acqua & Sole	Digestate	All	50$^{3)}$
	Ammonium sulphate solution	All	100
BENAS	Digestate	All	60$^{4)}$
	Ammonium sulphate solution	All	100
All plants	Mineral fertilisers	All	100

$^{1)}$ Based on *Mestbeleid 2019-2021, Tabel 3*

$^{2)}$ Based on *Brochure normen en richtwaarden (n.d.)*

$^{3)}$ Based on *Programma d'Azione regionale per la protezione delle acque dall'inquinamento provocato dai nitrati provenienti da fonti agricole nelle zone vulnerabili ai sensi della Direttiva nitrati 91/676/CEE – 2020-2023*

$^{4)}$ Based on the German Fertilisation ordinance of 2017

In the countries of the demonstration plants, N and/or P application standards are enforced. In the Netherlands, these standards are reported in *Mestbeleid 2019-2021 Tabel 1* and *Tabel 2*[3] and *Uitvoeringsregeling Meststoffenwet*[4]. Colleagues from ILVO and UGent (Flanders), Acqua & Sole (Italy) and Thuringen (Germany) provided information about the application standards in their countries. As Italy and Germany do not have P application standards, the soil-crop recommended amount of P is set as a *minimum amount of P application to ensure optimal yield*. For Germany, the standard for effective N for grassland has in this study been set to 350 kg N/ha, which is the highest N requirement listed for permanent grassland, for a yield of 12 tonne/ha (S. Klages, personal communication, 14/04/20). For the application standard for effective N for winter wheat, *Steckbrief Winter Weizen* published by *Landwirtschaftskammer Niedersachsen* (2017) was consulted.

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[3] https://www.rvo.nl/sites/default/files/2020/02/Tabel-2-Stikstof-landbouwgrond-2019-2021.pdf

[4] https://wetten.overheid.nl/BWBR0018989/2021-02-18

Table 3-3 Application standards for nitrogen (N) and phosphorus (P) defined for combinations of soil type and crop type in the countries of the demonstration plants. GZV = Groot Zevert Vergisting, AmP = Am-Power, A&S = Acqua & Sole, BNS = BENAS and WNE = Waterleau NewEnergy.

Plant	**Soil type**	**Crop type**	**Total application standards**		**Application standard for manure or manure based digestate**
			Nitrogen effective	Phosphorus	Nitrogen
			kg N ha^{-1}	kg P ha^{-1}	kg N ha^{-1}
GZV	sand	Grassland	320	39	230
		Arable crop rotation[1]	157	26	170
	clay	Grassland	385	39	250
		Arable crop rotation[2]	184	26	170
AmP	sand	Grassland	375[3]	42	- [4]
		Potato	190[3]	33	- [4]
	clay	Grassland	385[3]	42	- [4]
		Potato	210[3]	33	- [4]
WNE	sand	Grassland	375[3]	42	*250*
		Potato	190[3]	33	*170*
	clay	Grassland	385[3]	42	250
		Potato	210[3]	33	170
A&S	loam	Corn	270	≥ 37[5]	- [4]
		Rice	270	≥ 24[5]	- [4]
BNS	sand	Grassland	350[6]	≥ 32[5]	170[7]
		Winter wheat	260[8]	≥ 24[5]	170[7]

[1] Average of potato (25%) winter wheat (25%), silage maize (25%) and sugar beet (25%)

[2] Average of potato (25%) winter wheat (25%), silage maize (12.5%), sugar beet (25%) and onion (12.5%)

[3] Presented limits of effective N are based on the of effective N limits for area type ('gebiedstype') 0, representing best water quality, according to the Flemish MAP6

[4] The digestates produced by Am-Power and Acqua & Sole are not based on manure. There are, therefore, no restrictions on digestate application related to manure application standards.

[5] Italy and Germany do not have phosphorus application standards. Therefore, application of products are not limited by P application rates. The reported values in this Table are equal to the phosphorus yield, resembling equilibrium fertilisation. These values are the minimum of P application.

[6] Germany does not have application standards for effective nitrogen for grassland. According to S. Klages (personal communication, 14/04/20), the highest nitrogen needs are listed for permanent grass land with 350 kg N/ha, for a yield of 12 tonne/ha.

[7] including N from animal and plant sources (biogas digestate from plant origin) (New German Fertiliser Ordinance, 2017)

[8] Based on *Steckbrief Winter Weizen* (2017)

3.3 Potassium and sulphur recommendations

Besides the N and P application standards (Table 3-3), crop requirements for potassium (K) and sulphur (S) were taken into account (Table 3-4), in order to assess the need of an additional amount of mineral fertilisers as respectively K60 fertiliser and/or AS. On grassland often K40 is used, which also contains Na and Cl as salt. However, because these components are not modelled, K60 was used in this study as mineral K fertiliser for grassland as well.

3.3.1 GZV

For demonstration plant GZV, K fertilisation on grassland was calculated according to *Bemestingsadvies Commissie Bemesting Grasland en Voedergewassen* (2019) for the first cut[5]. The dry matter yield of the first cut was set to 3.5 tonne/ha, the K-$CaCl_2$ concentration was set to 100 mg/kg for both sandy and clay soil, and the CEC was 70 mmol/kg and 250 mmol/kg for sandy and clay soil, respectively. It was furthermore assumed that the fertilisation for the first cut occurred before the 15th of March. Because of rainfall, leaching losses occur. For an average year, this means that a loss of 20% should be accounted for fertilisation before the 15th of March. The application rate of K is therefore increased with 20%. For following four cuts, standard values are given for K fertilisation in *Bemestingsadvies Commissie Bemesting Grasland en Voedergewassen* (2019). Dry matter yields of these cuts were assumed to be 2.5, 2, 1.5 and 1.5 tonne/ha.

For S fertilisation of grassland on sandy soils, *Bemestingsadvies Commissie Bemesting Grasland en Voedergewassen* (2019) advises 15 kg S/ha for the first cut and again for the second cut when the sulphur supplying capacity is 6-11 kg S/ha (category 'low', occurring on sandy soils that are prone to leaching), amounting to a total of 30 kg S/ha. For later cuts, it is recommended not to fertilise S anymore. For clay soils, no S fertilisation is recommended.

For arable land, *Adviesbasis voor de bemesting van akkerbouw- en vollegrondsgroentengewassen* (2013) gives information on K and S fertilisation per crop type and soil type. Because a rotation has been assumed, the values for each crop were combined and averaged.

3.3.2 Am-Power and Waterleau NewEnergy

For demonstration plants Am-Power and Waterleau NewEnergy, data for grassland are reported in *Praktijkgids Bemesting Grasland en Voedergewassen*[6] (2016). For arable land, data were provided in consultation by colleagues from ILVO and UGent.

3.3.3 Acqua & Sole and BENAS

For Acqua & Sole and BENAS, no recommendations for K and S fertilisation rates were found; therefore, Dutch values were used instead, based on *Bemestingsadvies Commissie Bemesting Grasland en Voedergewassen* (2019) and *Adviesbasis voor de bemesting van akkerbouw- en vollegrondsgroentengewassen* (2013).

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[5] K-application (kg K_2O/ha)= exp(-6.973 + 1.30572*ln(dry matter yield) – 0.08551*K-$CaCl_2$ + 0.5264*ln(K-$CaCl_2$) - 0.001607*CEC +0.1275*ln(CEC) + 0.010836*K-$CaCl_2$*ln(CEC))

[6] https://www.rundveeloket.be/sites/default/files/inline-files/Praktijkgids%20bemesting%20-%20Grasland%20en%20voedergewassen.pdf

Table 3-4 Crop requirements for potassium (K) and sulphur (S) per SYSTEMIC demonstration plant

Plant	Soil type	Crop type	Recommendation	
			K requirements kg K ha^{-1} y^{-1}	S requirements kg S ha^{-1} y^{-1}
Groot Zevert Vergisting	Sand	Grassland	101	30
	Clay	Grassland	134	0
	Sand	Arable crop rotation¹⁾	121	8
	Clay	Arable crop rotation²⁾	108	1
Am-Power and Waterleau NewEnergy	Sand	Grassland	332³⁾	28³⁾
	Clay	Grassland	290³⁾	28³⁾
	Sand	Potato	250⁴⁾	20⁴⁾
	Clay	Potato	250⁴⁾	20⁴⁾
Acqua & Sole	Loam	Corn	92⁵⁾	10⁵⁾
	Loam	Rice	92⁵⁾	10⁵⁾
BENAS	Sand	Grassland	101⁵⁾	30⁵⁾
	Sand	Winter wheat	92⁵⁾	10⁵⁾

1) Potato (25%), winter wheat (25%), silage maize (25%) and sugar beet (25%)

2) Potato (25%), winter wheat (25%), silage maize (12.5%), sugar beet (25%) and onion (12.5%)

3) According to Praktijkgids Bemesting Grasland en Voedergewassen (version 28.01.2016)

4) According to G. Hofman and K. D'Haene based on equilibrium fertilisation and crop requirements (pers. comm.)

5) For Italy and Germany, no K and S recommendations were available. Therefore, Dutch values were used.

4 Modelling approaches

4.1 Description of the applied models and tools

For this Environmental Impact Assessment of the use of BBFs from digestate, the conceptual model approach of the MITERRA-Europe model (Velthof *et al.*, 2009a; Lesschen *et al.*, 2011a; Velthof *et al.*, 2014) was used. Within the H2020 Nutri2Cycle project, a farm/field level version of this model is being developed and extended with existing model approach of heavy metal accumulation and losses and an existing modelling approach for phosphate accumulation and losses of phosphate, the so-called MITERRA-FARM model. However, the integrated version was not available yet to be applied within SYSTEMIC, therefore, the individual modelling approach and tools were used in this environmental scenario analysis. A model period of 100 years was taken into account, since the impact often takes place after many years.

The environmental impacts in and from agriculture that are taken into account are:

- Soil carbon balances, and changes in C stock
- nitrogen balances, emissions to air (NH_3, N_2O) and soil/water (nitrate leaching)
- phosphorus balances, soil accumulation and leaching
- heavy metal accumulation and leaching.

The model approaches and data requirements are described in resp. this chapter 4 and 5.

4.2 Processes

4.2.1 Direct nitrogen emission to the air

The direct N emissions to air comprise emissions of ammonia (NH_3) and nitrous oxide (N_2O and NO_x) and nitrogen (N_2). These emissions are modelled using emission factors for each of the different sources of N emissions in agriculture, as illustrated in Figure 4-1. The emissions for storage are not part of this environmental impact study, the focus is on the emission from the soil. For grassland, no grazing is assumed, only mowing is taken into account. The main sources of nitrogen to the soil are inputs of digestate, biobased fertilisers, mineral fertilisers, deposition and N fixation. In the MITERRA model approach, surface runoff is calculated as a fraction of the N input at the soil surface. The surface runoff fraction that depends on slope, land use, precipitation, soil type and depth to rock. The environmental impact assessment is applied for defined representative soil-crop combinations on a field. The hydrologic situation can vary highly from field to field. In this study it is assumed that the soil-crop combinations are located on flat fields (with limited or no slope) and, consequently, that surface runoff can be negated and only nitrate leaching from the root zone will take place.

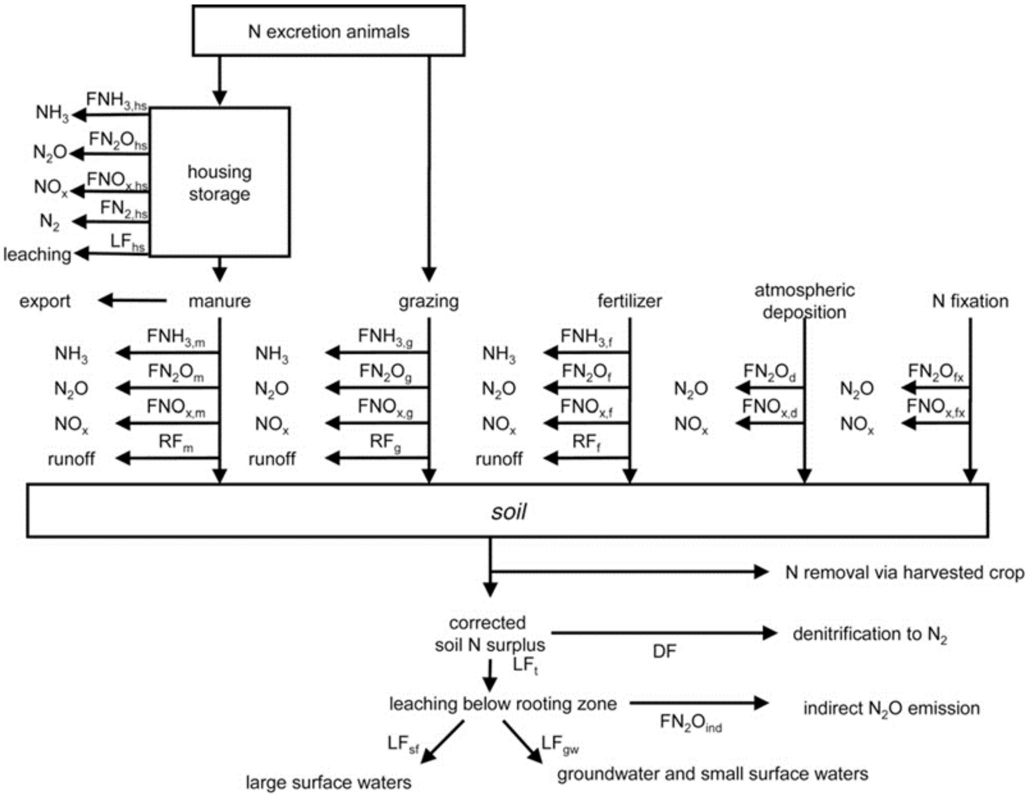

Figure 4-1 Schematic presentation of nitrogen (N) flows in the MITERRA model. Letter F indicates emission factor for gaseous emission, LF leaching fraction, DF denitrification fraction, and RF runoff fraction (Velthof et al., 2009a).

NH_3 emissions

Ammonia (NH_3) emissions can have negative impacts on air quality, ecosystem productivity, and human health. In addition, it results in indirect N_2O emissions due to atmospheric deposition of volatilised N. For the NH_3 emissions the Tier2 approach of the EMEP-EEA 2009 emission inventory guidebook (European Monitoring and Evaluation Programme – European Environment Agency[7]) was used. For NH_3 emissions from soils due to N fertiliser volatilization an emission factor was used, which depends on the type of N fertiliser, temperature and the pH of the soil (pH < or > 7.0).

N_2O and NO_x emissions

For nitrous oxide (N_2O) emissions the Tier 1/2 emission factors from the IPCC 2006 guidelines were used. N_2O emissions from agriculture comprise manure management (3B) and soil emissions (3D). N_2O emissions from agricultural soils mainly consist of direct soil emissions from the application of N fertiliser and animal manure, crop residues and the cultivation of organic soils. The N_2O emissions were calculated with emission factors taken from the IPCC (2006).

NO_x emissions were calculated in the model as a constant fraction of the 0.3% total N input (Velthof et al., 2009a), and as no additional data is currently available for different types of products, NO_x emissions are not presented as environmental impact parameter in this scenario study. However, the NO_x emissions are taken into account in calculation of the N-surplus in each scenario.

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[7] https://www.eea.europa.eu/publications/emep-eea-guidebook-2019

4.2.2 Nitrogen losses to groundwater and surface water

Nitrogen leaching was calculated by multiplying the soil N surplus (total N input minus N uptake) by a region-specific leaching fraction, which is based on soil texture, land use, precipitation surplus, soil organic carbon content, temperature and rooting depth Velthof et al. (2009a). It was assumed that the average organic N content in agricultural soils is in "equilibrium", hence, there is no net mineralisation or immobilisation of N (in fact averaged over a large time scale). So, nitrate leaching also represents an equilibrium situation determined by defined N-inputs constant over time. The model cannot directly assess the fate in groundwater and surface water, as this would require many local information on the topography and hydrological parameters.

The soil nitrogen surplus as defined by Velthof et al. (2009a):
$N_{surplus,\ soil} = N_{digestate} + N_{manure} + N_{grazing} + N_{BBF} + N_{mineral\ fertiliser} + N_{fixation} + N_{deposition} - N_{crop}$
All values expressed in kg N ha^{-1} yr^{-1}.

In our study, digestate from the demonstration plants was applied instead of manure. Furthermore, grassland fields were mowed and no grazing takes place. The other N-parameters were taken into account.

In order to calculate the amount of nitrogen that maximum can leach out, the $N_{surplus,\ soil}$ has to be corrected for the amount of NH_3-emissions and N of surface runoff emissions (which is zero in our study). So, the N-surplus of the rootzone becomes:

$N_{surplus,\ rz} = N_{surplus,\ soil} - N\text{-}NH_{3\text{-}emission}$

The fraction of N that will leach from the rootzone to groundwater depends on de following factors: land use (f_{lu}), precipitation (f_p), rooting depth (f_r), temperature (f_t), and organic C content of the soil (f_c). The leaching faction is calculated as:

$LF = LF_{soil\ type,\ max} * f_{lu} * MIN(f_p, f_r, f_t, f_c)$
where $LF_{soil\ type,\ max}$ is the maximum leaching fraction that is set per soil type, assuming that soil type is the major factor controlling the ratio between leaching and denitrification. The values of the fractions used in the study reported here, are defined in section 5.6.

4.2.3 Phosphorus losses

The phosphorus model used to calculate P losses is based on the Phosphate Saturation Degree approach, which has been developed in the Netherlands (Schoumans *et al.*, 1986; Van der Zee *et al.*, 1987; Schoumans *et al.*, 1989; Breeuwsma *et al.*, 1990; Van der Zee *et al.*, 1990a; Van der Zee *et al.*, 1990b). The rate dependent process description (Schoumans & Groenendijk, 2000) has been implemented in the Dutch model ANIMO (Groenendijk & Kroes, 2000; Groenendijk *et al.*, 2005a) which is used in the Netherlands to evaluate the impact of the Fertiliser Act on the nutrient losses to surface water (Groenendijk *et al.*, 2005b; Willems *et al.*, 2007; Willems *et al.*, 2013). The model has been developed for acid sandy soils, but has also been parametrised for other soil types (Schoumans, 2015; Schoumans & Chardon, 2015). A simplified approach has been derived, the so called PLEASE model (Schoumans *et al.*, 2010), which has recently been used to map P losses from fields in Denmark (Rolighed *et al.*, 2019). This approach has been included in this environmental impact approach.

The main focus is on inorganic P modelling, because inorganic P is the main form of P in many fertilising products, including manure. Also, in the soil observed in this study, inorganic P is the main component. In countries with application limits for P (the Netherlands and Flanders), the fertiliser replacement value of all phosphorus products applied on agriculture land is assumed to be 100%. The practical implementation is that it is assumed that during growing seasons all applied P is available or will become available as mineral P. In fact, it is assumed that applied P will not accumulate in the organic matter pool in the soil (can be neglected). Therefore, in this study the P surplus or P deficit in the scenarios will have only an effect on the amount of mineral P accumulated in the soils, which is mainly the driver of P losses from the rootzone due to the high P buffer capacity of the soil. The impact of the scenarios on the P losses after 100 years of P-surplus / P-deficit (as defined in the scenarios) is compared with the P losses in the initial (current) situation.

The phosphate sorption in soils is described by a fast reversible adsorption reaction (couple of days) and a time-dependent reaction (up to a couple of years) which is assumed to be "irreversible bound P", in fact very low release of P at low P concentrations in soil solution. The adsorption reaction is a reversible reaction at the surface of reactive components in the soil, like edges of clay minerals, aluminium and iron(hydr)oxides (free, bound to clay plates or associated with organic matter) and calcium carbonates. The time dependent reaction is a diffusion-precipitation reaction of phosphate into aluminium and iron (hydr)oxides. If more phosphate is diffused into the aggregates, the slower the process will go.

The fast adsorption reaction is described by the Langmuir rate equation as follows, with the change in adsorbed amount being equal to adsorption minus desorption:

$$\frac{dQ}{dt} = k_a\, c\, (Q_m - Q) - k_d\, Q$$

c = Concentration of P in solution (mmol P L^{-1})
k_a = Adsorption constant (L $mmol^{-1}$ h^{-1})
k_d = Desorption constant (h^{-1})
Q = Amount of reversibly adsorbed P in the soil (mmol P kg^{-1})
Q_m = Maximum amount of P which can be adsorbed (mmol P kg^{-1})
t = Time (h)

At equilibrium, the fast adsorption – desorption reaction is described by the Langmuir equilibrium equation, which is used to describe the describe the relation between the amount P adsorbed in soils and the ortho-P concentration in soil solution:

$$Q = \frac{K\, c\, Q_m}{1 + K\, c}$$

With
K = k_a / k_d = Langmuir equilibrium constant (L $mmol^{-1}$)

The time dependent diffusion precipitation is described by the Freundlich sorption isotherm:

$$\frac{\partial S}{\partial t} = \sum_{i=1}^{3} a_i\, (K_F\, C^N - S_i)$$

S = amount of P sorbed by the slow reaction (diffusion/precipitation) (mmol kg^{-1} P)
K_F = Freundlich sorption coefficient $(m^3\, mol^{-1})^{1/N}$ mmol kg^{-1}
N = Freundlich exponent (-)
a_i = diffusion or precipitation rate constant (h^{-1})
C = ortho P concentration (mol m^{-3})

From the time-dependent diffusion precipitation equation the maximum amount of P diffused into soil particles ("irreversibly bound P") can be calculated:

$$S_m = \sum_{i=1}^{3} K_F\, C^N$$

Both S_m and Q_m are related to the amount of oxalate extractable Al and Fe in the soil, resp $\alpha * (Al+Fe)_{ox}$ and $\beta * (Al+Fe)_{ox}$.

If the P surplus balance of the soil (P application minus P uptake) is negative, the amount of adsorbed P will decrease. If, after many years, the P concentration in soil solution in the rootzone becomes below 0.05 mg P L^{-1}, the P uptake will decrease leading to a zero balance. At such low P concentrations probably also a part of the "irreversible allocated P" will release, but this has been not taken into account. In case of a positive P surplus, both Q and S will increase, leaching to higher P losses. In the long term the P losses will becomes equal to the P surplus. It is assumed that, in the years between, the P surplus distributes according to the ratio of Q and S in the rootzone, so both will increase. For non-calcareous sandy soils all parameters have been determined by (Schoumans & Groenendijk, 2000) and for other soil types only the Langmuir parameters have been determined (Schoumans, 2015) since those parameters dominantly determine the P losses by leaching. These soil chemical parameters were used to determine the amount of P accumulated or released in soils.

In this scenario study it has been assumed that the initial soil phosphorus fertility status of the soils was classified as 'sufficient', which equals to a P-$CaCl_2$ value of about 2.5 mg P per kg soil. In line with the approach as developed for the soil fertility value of Pw (Schoumans et al., 1997),a relation can also be derived between P-$CaCl_2$ and the initial amount of reversibly adsorbed P (Q_o) in the soil, as shown by Römkens *et al.* (in prep.). Table 4-1 shows the derived parameters, found by Römkens et al. (in prep.), which are used in this study to estimate the initial amount of reversibly bound P (adsorbed P; Qo) based on the P-$CaCl_2$ concentration. Furthermore, the same dataset Römkens et al. (in prep.) was used to determine average ratio between P-$CaCl_2$ (mg P /kg) and total inorganic P (mg P/kg; P_{ox}) showed in sandy, loamy and clay soils and values were found of resp. 0.0049, 0.0050 and 0.0019. These factors were used to set the initial amount of irreversibly bound P in soils ($S_o = P_{ox} - Q_o$).

$$P_{CaCl_2} = \frac{310}{K_L} * \frac{Q_0}{(Q_m - Q_0)} * \left(1 - \mathrm{e}^{-0.2 * K_L \, \mathrm{k_d} \, (Q_m - Q_0)}\right)$$

Table 4-1 Parameters used to estimate the initial amount of P adsorbed in the soil

Parameter	Unit	Value
Beta	(-)	0.074
KL	(L $mmol^{-1}$)	84.6
k_a	(L $mmol^{-1}$ h^{-1})	5.1606
k_d	(h^{-1})	0.061

4.2.4 Heavy metal balances

Changes of the heavy metal content in the topsoil of the experimental fields included in this study are obtained using a dynamic mass balance approach (Römkens *et al.*, 2018). In this approach, developed to calculate spatially explicit mass balances within the EU, heavy metal balances are calculated and converted to changes in the heavy metal content of the (top)soil. In addition, the impact of changes in the soil metal content on uptake by crops and leaching from the soil are quantified. Metal fluxes as calculated by the model are based on inputs from inorganic and organic fertilisers as well as atmospheric deposition.

Outputs from the soil considered include leaching from the topsoil and crop uptake. For both uptake and leaching the concentration in soil in a given year in combination with soil properties are used to calculate the corresponding concentration in crops and soil solution for that year. Here it is assumed that all metals are taken up from the topsoil considered (0 – 25 cm). Crop production data (yields) and the net water loss from the topsoil are used to calculate the corresponding metal flux via crop uptake and leaching respectively. The net difference between inputs and outputs calculated on a yearly basis was used to calculate changes in the soil metal content with time in steps of one year.

Accumulation, or depletion, of heavy metals (Pb, Cd, Zn, Cu, Ni, Cr and As) is calculated based on the sum of inputs and outputs. The general mass balance equation applied is:

$Me_{balance} = Me_{inputs} - Me_{outputs}$

$Me_{inputs} = Me_{digestate} + Me_{inorganic\ fertiliser} + Me_{atm.dep.} + Me_{bbf}$

$Me_{outputs} = Me_{leaching} + Me_{crop\ uptake}$

With Me = metal

Fertiliser inputs

Metal inputs by digestate, mineral fertilisers and BBF are calculated by multiplication of heavy metal content of each of the products (Appendix B) and the amount of the corresponding product applied.

$Me_{load} = \Sigma\ Me_i \times \text{load product } i$

With

Me_i = metal content in product i (mg Me kg^{-1} on fresh matter)

load product i (kg ha^{-1})

Atmospheric deposition

For Cd, Cu, Ni, Pb and Zn spatially explicit data are available derived from them the EMEP heavy metal (HM) model (Ilyin *et al.*, 2009). Here data are available at a 50 km x 50 km grid level. These are converted to corresponding NUTS3 units or upscaled to country levels. For Cr and As data were not available and fixed data are used based on data from the Netherlands (TNO, 2019). The deposition of metals are expressed in g_{Me} ha^{-1} y^{-1}.

Crop uptake

Metal removal rates from soil by individual crops is calculated by multiplication of crop yield data with calculated heavy metal concentrations in the crop (Me_{crop} given as concentration in mg kg^{-1} dry matter). Crop yield data are given as fresh matter and are converted from fresh matter to dry matter using generic data for the crop dry matter content.

$Me_{uptake} = Yield * DM_{crop} * Me_{crop}$

The metal concentration in the crop is calculated using crop specific soil-crop relationships. Such empirical relationships calculate the dry matter concentration in the crop correcting for soil properties that affect the transfer from soil to crop. Here soil pH (pH KCl), organic matter and/or clay is used. This approach is applied for Cd, Zn and Cu for which reasonably reliable models can be derived (Römkens *et al.*, 2007). The regression for Cd, Zn and Cu is for all crops of the following form:

$Me_{crop} = 10 \wedge (g_0 + g_1 * \text{pH-KCL} + g_2 * LOG(\%OM) + g_3 * LOG(\%clay) + g_4 * LOG(Me_{soil,\ tot}))$

With

$Me_{soil,\ tot}$ = total amount in soil (mg kg^{-1} ds, measured as Aqua Regia).

The model parameters are listed in Appendix C.

For other metals (Pb, Cr, Ni and As) relationships between soil and crop do not exist either due to a lack of data (Ni and Cr), the absence of a relationships between concentrations in soil and crop (As) or these relationships are not reliable enough (for Pb).

Hence for As, Cr and Ni fixed levels of metals in crops are used based on data in literature ((Chu *et al.*, 2009; Van der Bolt, 2021, In Press.), *values are listed in Appendix C*).

For Pb an alternative simplified model approach was used based on the Bioconcentration factor (BCF)(Otte, 2011). The Bioconcentration factor is defined as the ratio between the metal concentration in the crop (mg kg^{-1} dry matter) divided by the total soil metal content mg kg^{-1} dry solids):

$BCF = (Me_{crop})/(Me_{soil,\ tot})$

Due to the limited variation in the crop metal content for Pb, the BCF varies strongly with the total soil Pb content. This would lead to erroneous estimates of BCF and to correct for this, the uptake model for Pb was corrected for the total soil Pb content:

$^{10}\log(BCF_{Pb}) \quad = \delta0 + \delta1 * {}^{10}\log(Pb_{soil,\ tot})$

Coefficients for this relationship were derived for a number of crops (Otte, 2011) and listed in Appendix C. The final concentration of lead in the selected crops therefore can be calculated as:

$Pb_{content,\ crops} = (10 \wedge (\delta0 + \delta1 * {}^{10}\log(Pb_{soil,\ tot}))) * Pb_{soil,\ tot}$

Leaching of metals

Leaching losses for metals (g ha^{-1} yr^{-1}) are calculated using the average precipitation surplus (mm yr^{-1}, equivalent to l m^{-2} yr^{-1})) multiplied by the soil solution concentration (Me_{SS} in µg l^{-1}) calculated for the topsoil using generic transfer functions (Römkens *et al.*, 2004). The transfer functions consider differences in soil type via correction of organic matter content (OM), clay, and pH_{CaCls2}:

$Me_{SS} = 10 \wedge (b_o + b_1 * \log(HM_{soilreact}) + b_2 * \log(\%OM) + b_3 * \log(\%clay) + b_4 * (pH_{CaCl2}))$

Note: $HM_{soilreact}$ as calculated from the total metal content needs to be converted to mol.kg^{-1} instead of mg.kg^{-1}. This yields the outcome of Me_{SS} in mmol L^{-1} so this needs to be reconverted to µg L^{-1}.

Table 4-2 Coefficients of the relation between reactive heavy metal content and heavy metal concentration in soil solution. Source: Adapted from (Van der Bolt, 2021, In Press.)

	Cd	Cr	Cu	Ni	Pb	Zn	As
b_0	5.05	-5.74	1.10	3.40	0.51	4.69	-5.77
b_1	1.26	0.199	0.87	0.93	0.70	1.08	0.421
b_2	-0.69	0	-0.28	-0.53	-0.54	-0.35	0.642
b_3	-0.48	0.158	-0.27	-0.20	-0.30	-0.48	-0.400
b_4	-0.40	-0.201	-0.18	-0.45	-0.26	-0.54	0

The calculation of the soil solution concentration is based on the reactive metal concentration in soil (Me_{re}). Usually data on the metal concentration in soil are given as total metal content (Aqua Regia or equivalent). Part of this total metal concentration however is considered inert meaning that it will not participate in the sorption equilibrium. Hence the total metal concentration is converted to a corresponding reactive metal concentration (Mere), using the averaged organic matter content, clay content and total metal content (MeT; mg kg-1 dry solids) as described and parametrised (Table 4-3) by (Römkens et al., 2004):

$Me_{re} = 10 \wedge (a_0 + a_1 * LOG(HM_{soil,\ tot}) + a_2 * LOG(\%OM) + a_3 * LOG(\%clay))$
with $HM_{soil,\ tot}$ (mg.kg^{-1} ds)

Table 4-3 Coefficients of the relation between total and reactive heavy metal content in the soil. Source: (Römkens et al., 2004).

	Cd	Cr	Cu	Ni	Pb	Zn	As
a_0	-0.0890	-1.2879	-0.3310	-1.2060	-0.2630	-0.7030	-0.9536
a_1	1.0750	1.1310	1.1520	1.0546	1.0890	1.2350	1.0220
a_2	0.0220	0.1465	0.0230	0.7513	0.0310	0.1830	0.7470
a_3	-0.0620	-0.2580	-0.1710	-0.2848	-0.1120	-0.2980	-0.5300

Finally, the leaching flux of metals is calculated as the net downward water flux (F) times the concentrations (Me_{SS}):
$Me_{leaching} = 0.1 \times Me_{SS} \times F_{net\ water\ flux}$

With

Me_{SS} = the concentration of a metal in the soil solution

Me_{re} =reactive soil metal concentration

Me_T = total soil metal content

Conversion factor 0.1 to convert the flux from µg m^2 yr^{-1} to g ha^{-1} yr^{-1}.

4.2.5 Soil organic carbon

To assess CO_2 emissions from changes in soil organic carbon (SOC) a SOC balance approach was developed in the EU FP7 SmartSoil project, where inputs of carbon (manure, crop residues, and other organic inputs) and the losses of carbon from decomposition were quantified. The RothC model (version 26.3) (Coleman & Jenkinson, 1996) was used to calculate the SOC balance. RothC is a widely used model of the turnover of organic carbon in non-waterlogged soils that allows for the effects of soil type, temperature, moisture content and plant cover on the turnover process. Soil organic carbon is split into four active compartments and a small amount of inert organic matter in RothC. The four active compartments are Decomposable Plant Material (DPM), Resistant Plant Material (RPM), Microbial Biomass (BIO) and Humified Organic Matter (HUM). Each compartment decomposes by a first-order process with its own characteristic rate (Table 4-4). RothC requires the following input data:

(1) monthly rainfall,
(2) monthly open pan evaporation,
(3) average monthly air temperature,
(4) clay content of the soil,
(5) an estimate of the decomposability of the incoming plant material – the DPM/RPM ratio,
(6) soil cover,
(7) monthly input of plant residues,
(8) monthly input of organic inputs (generally manure), and
(9) soil depth.

Initial carbon content can be provided as an input or calculated according to long-term equilibrium (steady state). The first approach has been used in this assessment. The initial carbon content and clay content should be provided for the specific location. For each product, standard decomposition rates of RothC have been used. The carbon inputs are distributed over the DPM, RPM and HUM pools according to Table 4-5.

Table 4-4 Decomposition rates (k) of RothC pools, including Decomposable Plant Material (DPM), Resistant Plant Material (RPM), Microbial Biomass (BIO) and Humified Organic Matter (HUM).

Pool	Decompostion rates (k) (y^{-1})
DPM	10
RPM	0.3
BIO	0.66
HUM	0.02

Table 4-5 Distribution factors for organic inputs and plant residues inputs over RothC pools including Decomposable Plant Material (DPM), Resistant Plant Material (RPM) and Humified Organic Matter (HUM).

Product	DPM	RPM	HUM
Organic inputs	0.49	0.49	0.02
Plant residues	0.59	0.41	-

5 Input data

In this chapter the data is presented that is used for each of the locations in relation to the scenario analysis.

5.1 Locations and region of application

Table 5-1 shows spatial information of the 5 demonstration plants and the selected region for application of the scenarios. For all demo plants it is assumed that the end products are applied in the same (nearby) region and data is collected at NUTS3 level from European database, or if not available at NUTS2 level. Local data was available for some parameters (mainly Acqua & sole, BENAS and Groot Zevert Vergisting). For both Flemish demo plants, Am-Power and Waterleau NewEnergy, a large part of the products are exported outside Belgium, but in these cases data are used from the region where they are located, because they still aim for local application of their product, and for the intercomparison of the scenarios on field plots it does not matter where the exact location is.

Table 5-1 Locations of the five demonstration plants including country, nearby village/city, X and Y coordinates (google) and the NUTS 2 code and NUTS 3 code of the selected region of application in the scenarios.

Demonstration Plant	Country	City	X	Y	Application Region	NUTS2	NUTS3
GZV	NL	Betrum	52.090808	6.571145	Gelderland, Achterhoek	NL22	NL225
AMP	BE	Pittem	51.007343	3.227216	West Flanders, Arrondissement of Tielt	BE25	BE257
A&S	IT	Vellezzo Bellini	45.288062	9.112009	Lombardy, Pavia (Po valley)	ITC4	ITC48
BNS	DE	Ottersberg	53.122359	9.149159	Lower Saxony, Verden	DE93	DE93B
WNE	BE	Ieper	50.886542	2.880221	West Flanders, Ypres	BE25	BE253

5.2 Precipitation and nitrogen deposition

Besides N-deposition, N-fixation can also occur which increases the N-input. Values are taken over from (Velthof et al., 2009): arable land an average biological N2 fixation of 2 kg N ha^{-1} y-1 and in grasslands 5 kg N ha^{-1} y-1 (not clover rich situations). Table 5-2 presents the annual precipitation in the regions in which the demonstration plant is situated. The precipitation from low to high is ordered Waterleau NewEnergy, Groot Zevert Vergisting, BENAS, Am-Power and Acqua &Sole, with about 20% difference between highest and lowest precipitation. In the scenarios, net precipitation is needed for agricultural land. Differences in net precipitation surpluses of different crop types can vary over time and between regions. However, no local / regional information of the observed crop types was known in the specific regions, therefore differences between in crop types were not taken into account and were based on the average data used in the MITERRA-Europe model (operating at NUTS2 level) and INTEGRATOR (operating at NUTS3 level; (de Vries *et al.*, 2011b; de Vries *et al.*, 2021)) for the regions mentioned in Table 5-1.

Besides N-deposition, N-fixation can also occur, which increases the N-input. Values are taken over from Velthof et al. (2009a): arable land an average biological N_2 fixation of 2 kg N ha^{-1} y^{-1} and in grasslands 5 kg N ha^{-1} y^{-1} (grassland without clover).

Table 5-2 Indication of the annual average precipitation and nitrogen (N) deposition for the region of each demonstration plant (www.weather-and-climate.com) and average net precipitation (mm/year) based on model applications at NUTS2 and NUTS3 level.

	Regional precipitation (mm/y)	Precipitation surplus (mm/y)	N deposition (kg N ha^{-1} y^{-1})
GZV	752	327	24
AMP	831	323	31
A&S	930	376	29
BNS	788	300	29
WNE	750	305	31

5.3 General soil characteristics and initial composition

Soil characteristics are required in order to calculate the accumulation of P, C and heavy metals and the emissions (including N). Table 5-3 provides an overview of the representative soil characteristics for the most common soil types in the regions where the BBFs are assumed to be applied. For the plants in the Netherlands and Flanders two soil types (sand and clay) are used in the scenario analyses, and in the other regions one representative soil type is used.

General soil parameters texture, organic matter and pH were based on the LUCAS 2015 topsoil database published by the European Commission Joint Research Centre (Jones *et al.*, 2020). More information about the soil sampling data and methods can be found in (Orgiazzi *et al.*, 2018) and (D'Andrimont *et al.*, 2020). Per demo plant/application location the closest representative soil was selected from the raw LUCAS dataset. If no sufficient information was available for a specific soil characteristic or soil type within the NUTS3 region, a larger region was taken (NUTS2 region, or NUTS1 region or at the national level). The most important selection criteria was a fit to the soil type categories of sand, loam or clay, separate from checks and filters for other general soil parameters like pH, organic carbon content, land use. For the texture the percentage of sand, silt and clay are in total 100%. The organic matter content is based on measurements of organic C content measurements mentioned in the LUCAS data base and the pH (pH-$CaCl_2$) was set at 6. Bulk densities are estimated based on the organic matter content of the soil (Remmelink *et al.*, 2019).

The total metal content of the soils is presented in the table on dry matter basis for iron (Fe) and aluminium (Al), copper (Cu), zinc (Zn), cadmium (Cd), cobalt (Co), nickel (Ni), lead (Pb), chrome (Cr), mercury (Hg). They are derived from average values of the EU GEMAS European Geochemical Database (Reimann *et al.*, 2014a; Reimann *et al.*, 2014b) for agricultural land, including arable land and grass land. The measurement technique was a wet chemical extraction (aqua regia). Based on the raw sample data per country, median values for per demo plant location were calculated based on a selection of representatives soil samples categorised per soil type. Soil type categories used were: sandy soil is >70% sand, clay soil is >40% clay, and loam soil is <30% clay and >30% silt.

The aluminium and iron (hydr)oxides (Alox and Feox), required to calculate P accumulation and losses, are based on data for Dutch soils (Landelijke Steekproef Kartering, LSK, (Römkens et al., in prep.)) and it is assumed that Alox and Feox for the model soils can be estimated from soils from this database under the conditions that they have a similar texture (sand/clay/loam).

Table 5-3 Main soil characteristics for the selected soil types which are used in the scenario analyses for the 5 SYSTEMIC demonstration plants (see text). Sources: LUCAS 2015 topsoil database (texture, organic matter and pH), the EU GEMAS European Geochemical Database (heavy metal content), a Dutch database (Römkens et al., in prep.) regarding soil P characteristics.

		Country	NL	NL	BE	BE	IT	DE
		Soil type	Sand	Clay	Sand	Clay	Loam	Sand
Characteristics	Parameter	Unit						
Texture	**Sand**	%	76	9.0	88	14	47	85
	Silt	%	20	53	9.0	47	41	14
	Clay	%	4.0	38	3.0	39	12	2.0
Organic matter	**OM**	%	3.5	7.8	2.5	3.4	2.1	4.4
Bulk density	**P**	kg/m3	1450	1180	1520	1450	1520	1390
pH	**pH-$CaCl_2$**1)		5.7	5.1	5.7	7.3	6.2	4.2
Metal content (total)	**Cu**	mg/kg DW	14	15	9.6	12	22	6.2
	Zn	mg/kg DW	29	88	34	53	71	22
	Cd	mg/kg DW	0.28	0.42	0.48	0.37	0.26	0.18
	Co	mg/kg DW	0.86	9.0	0.88	7.4	14	1.4
	Ni	mg/kg DW	1.9	20	2.2	15	26	2.8
	Pb	mg/kg DW	20	35	23	22	34	15
	Cr	mg/kg DW	7.0	26	10	23	43	9.3
	Hg	mg/kg DW	0.05	0.07	0.39	0.05	0.04	0.03
	As	mg/kg DW	2.8	12	4.3	8.8	23	2.6
	Mn	mg/kg DW	128	624	188	541	772	224
Phosphorus characteristic	**P-$CaCl_2$ (P status)**	mg P/kg	2.5	2.5	2.5	2.5	2.5	2.5
	Alox	mmol/kg	37	61	37	61	32	37
	Feox	mmol/kg	20	192	20	192	51	20
	Pox	mmol/kg	16	43	16	43	16	16
	Qo	mmol/kg	1.8	7.6	1.8	7.6	2.5	1.8
	Ptot	mmol/kg	19	50	19	50	19	19

1)The pH-$CaCl_2$ values for the selected soils are reported here. However, a pH of 4.2 for example is not representative for German sandy soils. For calculations (especially concerning P and heavy metal leaching), a pH of 6 is used for all soils.

5.4 Ammonia (NH_3) emission factors

The emission factors (EFs) for ammonia (NH_3) of the produced biobased fertiliser by the demonstration plants and synthetic mineral products are presented in Table 5-4. At this moment, knowledge and data is still limited for many of the produced new biobased products. In general, the NH_3 EFs were based on the emission factors used in the National Emission Model for Ammonia (NEMA model) used in the Netherlands for official environmental impact assessments, which are based on literature and experiments. For most products the EFs were sourced from the report linked to the 2021 version of this model (van Bruggen *et al.*, 2021). The EF for biobased produced ammonium sulphate solution was assumed to be similar to a rising liquid from air scrubbers, based on similar properties relevant for NH_3 emissions, like viscosity, acidity and amount applied. The EFs are sourced from an earlier report linked to the publication of the 2015 version of the model (van Bruggen *et al.*, 2017) and a recent quick scan of NH_3 and greenhouse gas emissions for the application of mineral fertiliser replacement products (Velthof et al. 2021). Biobased ammonium sulphate solution is a liquid product, different from the synthetic mineral ammonium sulphate that is sold and applied in granular form. For RO concentrate the EF was set at 50% of the EF of manure application applied with shallow injection based on the conclusions of the national committee of fertilisers act experts (Commissie van Deskundigen Meststoffenwet,(Meststoffenwet, 2013). The same reduction percentage was used for evaporator concentrate of Am-Power because of the low pH of this product (pH 6.2) compared to digestates (pH 8.1-8.6) and evaporate concentrate of Waterleau NewEnergy (pH 7.7). For all products it is assumed that they are applied according to best management practices. Solid products are applied on land by spreading and liquid products are incorporated directly into the soil. In the scenarios, the solid biobased products low-P soil improver, dry solids and dried SF of digestate are not applied on grassland but only at arable land (directly incorporated in the soil).

Table 5-4 Ammonia (NH_3) emission factors in % of total nitrogen (TN) or % of total ammonia nitrogen (TAN) for the different biobased fertiliser products from the 5 demo plants and mineral fertiliser products. Sources: Velthof *et al.* (2021), NEMA 2021 (van Bruggen et al., 2021), NEMA 2015 (van Bruggen et al., 2017) and (Meststoffenwet, 2013) and Velthof *et al.* (2009b).

Demonstration Plant	Products	NH_3 % of TAN Grassland	NH_3 % of TAN Arable	NH_3 % of TN	Reference	Application technology (BMP)
Groot Zevert Vergisting	Digestate	17.0	2.0	-	NEMA 2021 Table 10.2 Velthof et al. (2021)	Similar to slurry manure, with shallow injection / slit coulter application for grassland and (deep) injection for arable land.
	RO-concentrate	9.0	2.0	-	NEMA 2021 Table 10.2	Reduction of 50% compared to manure application with shallow injection, based on statement of CDM 2013.
	Low P organic soil improver	n.a.	22.0	-	NEMA 2021 Table 10.2	Similar to solid manure; surface spreading followed by direct ploughing afterwards. Within the scenarios, SFs are not applied to grassland.
Am-Power	Digestate	17.0	2.0	-	NEMA 2021 Table 10.2 Velthof et al. (2021)	Similar to slurry manure, with shallow injection / slit coulter application for grassland and (deep) injection for arable land.
	Evaporator concentrate	9.0	2.0	-	NEMA 2021 Table 10.2 Velthof et al. (2021)	Similar to slurry manure, with shallow injection / slit coulter application for grassland and (deep) injection for arable land. Reduced value because of the relatively low pH (6.2) compared to the other biobased N-fertilisers (pH 8.0).
	Dried SF of digestate	-	22.0	-	NEMA 2021 Table 10.2	Similar to solid manure with surface spreading application for grassland, but on arable land ploughing afterwards directly.
Acqua & Sole	Digestate	17.0	2.0	-	NEMA 2021 Table 10.2 Velthof et al. (2021)	Similar to slurry manure, with shallow injection / slit coulter application for grassland and (deep) injection for arable land.
	Ammonium Sulphate	-	-	1.8	NEMA 2015 Table 3.1	Similar properties to rinsing liquid air scrubber. Biobased product, not synthetic product. Based on personal communication Dr. Gerard Verlthof.
BENAS	Digestate	17.0	2.0	-	NEMA 2021 Table 10.2 Velthof et al. (2021)	Similar to slurry manure, with shallow injection / slit coulter application for grassland and (deep) injection for arable land.
	Ammonium Sulphate	-	-	1.8	NEMA 2015 Table 3.1	Similar properties to rinsing liquid air scrubber. Biobased product, not synthetic product. Based on personal communication Dr. Gerard Verlthof.
Waterleau NewEnergy	Digestate	17.0	2.0	-	NEMA 2021 Table 10.2 Velthof et al. (2021)	Similar to slurry manure, with shallow injection / slit coulter application for grassland and (deep) injection for arable land.
	Evaporator concentrate	17.0	2	-	NEMA 2021 Table 10.2 Velthof et al. (2021)	Similar to slurry manure, with shallow injection / slit coulter application for grassland and (deep) injection for arable land.
	Dried SF of digestate	-	22.0	-	NEMA 2021 Table 10.2	Similar to solid manure with surface spreading application (grassland) but on arable land ploughing afterwards directly

Mineral fertilisers	Calcium Ammonium Nitrate	-	-	2.5	NEMA 2021 Table 10.1	Granules / pills, standard application techniques (spreading) as used for granular mineral fertilisers
	Triple Super Phosphate	-	-	-	-	Granules / pills. No nitrogen in the product.
	Kali granulate 60% (K60)	-	-	-	-	Granules / pills. No nitrogen in the product.
	Synthetic Ammonium Sulphate (granular)	-	-	11.3	NEMA 2021 Table 10.1	Granules / pills. Standard application technique as used for granular mineral fertiliser.
	Urea			14	Velthof et al. (2009b) Table B16.3	Granules / pills. Standard application technique as used for granular mineral fertiliser. Average of 4 values: 13% (pH<7.3) and 20% (pH>7.3) for grassland and 12% (pH<7.3) and 18% (pH>7.3) for arable land in the Netherlands.

5.5 Nitrous oxide (N_2O) emission factors

The direct nitrous oxides (N_2O) emission factors for the different biobased fertiliser products of the demonstration plants and synthetic mineral products are presented in Table 5-5. The EFs are based on De Vries *et al.* (2011a) and Lesschen *et al.* (2011b). For the N_2O EFs, a distinction is made between soil types (sand, clay and loam) and between land uses (grassland and arable land). Many of the produced products are new innovative products, for which no emission factors are directly available from the literature at this moment, so additional assumptions were made for these products (Table 5-5). Best management practises in application of the products were assumed for both solid and liquid fertilisers. Since N_2O emission factors in De Vries et al. (2011a) were only provided for sandy soils, the EFs for clay soils were calculated by multiplying the EFs for sandy soil with a factor 1.5, based on the data presented by Lesschen et al. (2011b). On loamy soils the EF values are assumed to be in-between that of sand and clay soils, so those values have been averaged to find the EF values on loamy soils.

Table 5-5 Nitrous oxides (N_2O) emission factors in % of total nitrogen (N) for the different biobased fertiliser products from the five demonstration plants and mineral fertiliser products, making a distinction between soil types sand, clay and loam soils and between land uses grassland and arable land. Sources: De Vries et al. (2011a) and Lesschen et al. (2011b).

Plant	Product	Sand		Clay		Loam		Reference	
		Grass	Arable	Grass	Arable	Grass	Arable		Assumptions
Groot Zevert Vergisting	Digestate	0.30	1.30	0.45	1.95	0.38	1.63	De Vries et al. (2011a)	-
	RO concentrate	0.50	0.87	0.75	1.31	0.63	1.09	De Vries et al. (2011a)	-
	Low P organic soil improver	0.17	0.25	0.26	0.38	0.21	0.31	Lesschen et al. (2011b)	Similar to solid manure.
Am-Power	Digestate	0.30	1.30	0.45	1.95	0.38	1.63	De Vries et al. (2011a)	-
	Evaporator concentrate	0.50	0.40	0.75	0.60	0.63	0.50	Lesschen et al. (2011b)	Similar to ammonium based fertiliser.
	Dry solid fraction of digestate	0.17	0.25	0.26	0.38	0.21	0.31	Lesschen et al. (2011b)	Similar to solid manure.
Acqua & Sole	Digestate	0.30	1.30	0.45	1.95	0.38	1.63	De Vries et al. (2011a)	-
	Ammonium Sulphate	0.50	0.40	0.75	0.60	0.63	0.50	Lesschen et al. (2011b)	Similar to ammonium based fertiliser.
BENAS	Digestate	0.30	1.30	0.45	1.95	0.38	1.63	De Vries et al. (2011a)	-
	Ammonium Sulphate	0.50	0.40	0.75	0.60	0.63	0.50	De Vries et al. (2011a)	Similar to ammonium based fertiliser.
Waterleau NewEnergy	Digestate	0.30	1.30	0.45	1.95	0.38	1.63	De Vries et al. (2011a)	-
	Condensed ammonia water	0.50	0.40	0.75	0.60	0.63	0.50	Lesschen et al. (2011b)	Similar to ammonium based fertiliser.
	Evaporator concentrate	0.50	0.40	0.75	0.60	0.63	0.50	Lesschen et al. (2011b)	Similar to ammonium based fertiliser.
	Dried solid fraction of digestate	0.17	0.25	0.26	0.38	0.21	0.31	Lesschen et al. (2011b)	Similar to solid manure.
Mineral fertilisers	Calcium Ammonium Nitrate	1.00	0.50	1.50	0.75	1.25	0.63	Lesschen et al. (2011b)	Similar to nitrate based fertiliser.
	Triple Super Phosphate	0.00	0.00	0.00	0.00	0.00	0.00	-	No N in the product.
	Kali granulate 60% (K60)	0.00	0.00	0.00	0.00	0.00	0.00	-	No N in the product.
	Synthetic Ammonium Sulphate (granular)	0.50	0.40	0.75	0.60	0.63	0.50	Lesschen et al. (2011b)	Similar to ammonium based fertiliser.
	Urea	0.50	0.40	0.75	0.60	0.63	0.50	Lesschen et al. (2011b)	Similar to ammonium based fertiliser.

5.6 Nitrogen losses from the root zone

In this study, these nutrient leaching fractions are used to estimate the fate of fertilisers applied in the different scenario's regarding the losses to groundwater and are described in section 3.2.2. The required parameters were taken over by the values of (Velthof et al., 2009a) as shown in Table 5-6.

Table 5-6 Leaching fractions of the nitrogen (N) surplus for different soil types (Velthof et al., 2009a).

Characteristic	Parameter				
Maximum leaching fraction	Soil type	Sandy soils	Loamy soils	Clay soils	Peat soils
	$LF_{\text{soil type, max}}$	1.00	0.75	0.50	0.25
Reduction factor for land use	Land use	Grassland	Arable		
	f_{lu}	0.36	1.00		
Reduction factor for soil organic content	Total C content	<1%	1–2%	2–5%	>5%
	f_c	1.00	0.9	0.75	0.50
Reduction factor for precipitation surplus	Precipitation surplus	>300 mm	100–300 mm	50–199 mm	<50 mm
	f_p Sand and loam	1.00	0.75	0.5	0.25
	f_p Clay and peat	0.50	1.00	0.75	0.25
Reduction factor for temperature	Temperature	<5°C	5–15°C	>15°C	
	f_t	1.00	0.75	0.5	
Reduction factor for rooting depth	rooting depth	<40 cm	>40 cm		
	f_r	1.00	0.75		

5.7 Phosphorus soil status

Phosphorus leaching out of the top layer of the soil (10-30 cm below surface) to deeper layers and groundwater is highly dependent on the P accumulation in the soil and the maximum P sorption capacity. Often more than 80% of the amount of accumulated P in soils is mineral P because of the high P sorption capacity of soils. The sorption and desorption characteristics are based on experiments of a large dataset described by Römkens et al. (in prep.).

As initial soil P status (from a soil fertility point of view), a value of sufficient is used (P-$CaCl_2$ of 2.5 mg P/ kg). Based on this initial soil P status value and the oxalate extractable AL and Fe (Al_{ox} and Fe_{ox}), which determines the maximum phosphate adsorption and total sorption capacity, the amount of adsorbed P (reversible bound ortho-P; called Q) is calculated by using the sorption and desorption characteristics. By taking into account the total amount of inorganic sorbed P in the soils (P_{ox}), the amount of highly sorbed P (poorly soluble; S) can also be calculated by subtraction the reversibly adsorbed P (Q) from the total amount of inorganic P in soils (P_{ox}) (Table 5-7).

Table 5-7 Initial soil P fertility status and related soil chemical parameters for the soil types used in this study (see section 4.2.3).

Country	Soil type	P-$CaCl_2$	Al_{ox}	Fe_{ox}	P_{ox}	Q	S
		mg P/kg	------------------		mmol/kg	---------------------	
NL	Sand	2.5	37	20	16.4	1.8	14.7
NL	Clay	2.5	61	192	43.4	7.6	35.8
BE	Sand	2.5	37	20	16.4	1.8	14.7
BE	Clay	2.5	61	192	43.4	7.6	35.8
IT	Loam	2.5	32	51	16.1	2.5	13.6
DE	Sand	2.5	37	20	16.4	1.8	14.7

5.8 Heavy metals loads

Metal inputs by digestate, mineral fertilisers and BBF are calculated by multiplication of heavy metal content of each of the products (Appendix B and C) and the amount of the corresponding product applied in the defined scenarios.

Regarding atmospheric deposition spatially data are available for Cd, Cu, Pb and Zn which are derived from them the EMEP heavy metal (HM) model (Ilyin et al., 2009). Here data are available at a 50 km x 50 km grid level and are converted to corresponding NUTS3 units. For Cr, Ni and As no such data is available and data are used based from the Netherlands (TNO, 2019). Since the load of atmospheric deposition is low compared to applied amount of digestate, biobased fertilisers and mineral fertiliser the impact is minor. The deposition of metals are expressed in g_{Me} ha^{-1} y^{-1}. Table 5-8 summarise the atmospheric deposition data of the heavy metals.

Table 5-8 Atmospheric deposition of heavy metals. Source: Cd, Cu, Pb and Zn (Ilyin et al., 2009) and Cr, Ni and As and GZV (TNO, 2019)

Plant	NUTS3	Cd	Cr	Cu	Pb	Ni	Zn	As
GZV	NL225	0.5	1.1	15.9	11.2	3.5	69.4	1.0
AMP	BE257	0.5	1.1	5.9	15.8	3.5	37.7	1.0
A&S	ITC48	0.3	1.1	4.2	14.2	3.5	24.0	1.0
BNS	DE93B	0.5	1.1	9.2	16.8	3.5	63.4	1.0
WNE	BE253	0.4	1.1	5.0	13.3	3.5	33.9	1.0

5.9 Nitrogen and phosphorus uptake

The amounts of nitrogen and phosphorus of the plants are based on country specific information of the harvested amounts of nitrogen and phosphorus (pers. comm. experts as mentioned in the preface of this report). For phosphorus a soil fertility P status of sufficient is used, which means that the amount of phosphorus is not a limiting factor for P-uptake. This is important since the accumulated P in the soil highly, determines a good crop yield and P-uptake.

Table 5-9 Nutrient uptake of nitrogen (N), phosphorus (P) and potassium (K) as used in the scenarios for the demonstration plants for different crop and soil types. Source: personal communication with national experts.

					Yield			
Country	**Demoplant**	**Crop**	**Percentage**	**Soil**	**DM**	**P**	**N**	**K**
					ton DM/y	**kg P/y**	**kg N/y**	**kg K/y**
NL	GZV	Grassland	100%	Sand	11	47	355	385
NL	GZV	Grassland	100%	Clay	11	47	355	385
NL	GZV	Arable	weighted	Sand	47	27	167	147
NL	GZV	Arable	weighted	Clay	48	26	159	135
BE	AmPower	Grassland	100%	Sand	13	50	390	470
BE	AmPower	Grassland	100%	Clay	13	50	390	470
BE	AmPower	Potatoes	100%	Sand	12	25	205	265
BE	AmPower	Potatoes	100%	Clay	12	25	205	265
IT	Acqua&Sole	Corn	100%	Loam	13	37	280	45
IT	Acqua&Sole	Rice	100%	Loam	7	24	160	31
DE	BENAS	Grassland	100%	Sand	9	32	291	315
DE	BENAS	Winter wheat	100%	Sand	7	24	169	30
BE	Waterleau	Grassland	100%	Sand	13	50	390	470
BE	Waterleau	Grassland	100%	Clay	13	50	390	470
BE	Waterleau	Arable	100%	Sand	12	25	205	265
BE	Waterleau	Arable	100%	Clay	12	25	205	265

[1)] *Crop rotation as mentioned in section 3.1*

5.10 Carbon inputs via fertilising products

The data on total precipitation, soil characteristics, crop type and dry matter yield as reported in paragraph 5.2, 5.3 and 5.8 were used. The data on temperature, rainfall and open pan evaporation were derived from the MITERRA-Europe model data at NUTS2 level. For soil depth, a depth of 25 cm was assumed for both grassland and arable land. Additionally, for each scenario it was calculated how much organic matter was applied per fertiliser used (Table 5-10). Organic matter applied via digestate and biobased fertilisers was in the RothC model viewed as manure application, except for Low-P soil improver, which was viewed as compost, and distributed as such over the DPM, RPM and HUM pools.

Table 5-10 (Part 1) Organic matter application (kg OM ha^{-1}) via organic fertilising products per scenario as mentioned in Table 3-1.

Scen.	Plant	Corn	crop type	Digestate	RO or Ev. conc	Soil improver
1	GZV	Sand	Grassland	1345		
2	GZV	Sand	Grassland	1155	342	
3	GZV	Sand	Grassland	1155	342	
4	GZV	Sand	Grassland		531	
5	GZV	Clay	Grassland	1345		
6	GZV	Clay	Grassland	1062	508	
7	GZV	Clay	Grassland	1062	508	
8	GZV	Clay	Grassland		639	
9	GZV	Sand	Arable	897		
10	GZV	Sand	Arable	827	125	
11	GZV	Sand	Arable	827	125	
12	GZV	Sand	Arable		252	2121
13	GZV	Clay	Arable	897		
14	GZV	Clay	Arable	780	209	
15	GZV	Clay	Arable	780	209	
16	GZV	Clay	Arable		297	2121
17	AmP	Sand	Grassland	1615		
18	AmP	Sand	Grassland		2785	
19	AmP	Sand	Grassland		2785	
20	AmP	Clay	Grassland	1615		
21	AmP	Clay	Grassland		2785	
22	AmP	Clay	Grassland		2785	
23	AmP	Sand	Potatoes	1269		
24	AmP	Sand	Potatoes		2188	
25	AmP	Sand	Potatoes			888
26	AmP	Clay	Potatoes	1269		
27	AmP	Clay	Potatoes		2188	
28	AmP	Clay	Potatoes			888
29	A&S	Loam	Corn	2835		
30	A&S	Loam	Corn	2835		
31	A&S	Loam	Rice	2835		
32	A&S	Loam	Rice	2835		

Table 5-10 (Continued) Organic matter application (kg OM ha^{-1}) via organic fertilising products per scenario as mentioned in Table 3-1.

Scen.	Plant	Corn	crop type	Digestate	RO or Ev. conc	Soil improver
33	A&S_P	Loam	Corn	686		
34	A&S_P	Loam	Corn	686		
35	A&S_P	Loam	Rice	445		
36	A&S_P	Loam	Rice	445		
37	BNS	Sand	Grassland	1724		
38	BNS	Sand	Grassland	1724		
39	BNS	Sand	Winter wheat	1724		
40	BNS	Sand	Winter wheat	1724		
41	BNS_P	Sand	Grassland	1669		
42	BNS_P	Sand	Grassland	1669		
43	BNS_P	Sand	Winter wheat	1251		
44	BNS_P	Sand	Winter wheat	1251		
45	WNE	Sand	Grassland	1250		
46	WNE	Sand	Grassland	526	1121	
47	WNE	Sand	Grassland		1840	
48	WNE	Clay	Grassland	1250		
49	WNE	Clay	Grassland	730	841	
50	WNE	Clay	Grassland		1840	
51	WNE	Sand	Potatoes	850		
52	WNE	Sand	Potatoes	466	808	
53	WNE	Sand	Potatoes			841
54	WNE	Clay	Potatoes	850		
55	WNE	Clay	Potatoes	466	808	
56	WNE	Clay	Potatoes			841

6 Applied amounts, nutrients and heavy metals

The application rates of products can be calculated for each scenario, described in Table 3-1, based on the nutrient composition of the digestates and the produced biobased fertilisers (Signurjak et al. 2022), the composition of the mineral fertilisers (appendix D), the NFRV (Table 3-2, the restriction in application standards (Table 3-3) and the recommendations for K and S (Table 3-4).

Table 3-1 gives not only the scenarios, but also mentions the products in the order that they are applied. For example the scenario D+RO conc+MF on grassland on sandy soils means that at first digestate is applied up to the maximum application standard for N or P (most limiting standard for soils with a sufficient P status; see footnotes Table 3-3), thereafter RO concentrate is applied, and finally if needed mineral fertiliser (N, P and/or K) is applied. For each scenario, the application of N and P has to meet exactly with the legislative application standards (Table 3-3). Regarding K and S at least the recommended amount (Table 3-4) has to be applied in the scenario. No maximum limits have been set for K and S.

In some scenarios, mineral fertilisers for N, P, K and/or S are applied. Calcium Ammonium Nitrate (CAN) is used as granular fertiliser for nitrogen, containing 27% nitrogen (13.5% as $N\text{-}NH_4$ and 13.5% as $N\text{-}NO_3$). Phosphorus is used in the form of Triple Super Phosphate (TSP). Potassium is added as K60 (60% K_2O = 498 K g/kg) and S is added as ammonium sulphate ($(NH_4)_2SO_4$ containing 60% SO_3 which equals to 24% S and 21% N). Most of the mineral fertilisers are nitrogen based, which means that the amount of N added as ammonium sulphate has to be subtracted from the N-sources to meet with the N application standards in the country.

The applied amounts of nutrients are calculated by multiplying the amount of fertiliser (mass), as mentioned in Table 6-1, and the nutrient and heavy metal contents of the fertilisers.

In Table 2-2 the nutrient composition of the products is shown. In Appendix B the heavy metal contents of the products are provided. The following heavy metals are taken into account: As, Cd, Co, Cr (but not Cr VI), Cu, Hg, Ni, Pb and Zn. The heavy metal contents are sometimes reported as 'lower than' a certain value or the detection limit. To enable calculation, these values were set equal to the detection limits for the given element and measurement. Therefore, the reported application of heavy metals might in some cases be a little higher (worse case) than would be applied in practice. On the other hand, mercury and arsenic were not measured by Am-Power (noted as 'n.m.' in Appendix B), which could mean that taking the detection limit value is an underestimation. The metal As was also not measured in ammonium sulphate (BENAS) and condensed ammonia water (Waterleau NewEnergy), but in those cases it is not expected. The n.m. values were set to zero to enable calculation, but in this case it will lead to an under estimation.

It has to be mentioned that in the following sections sometimes low application rates of synthetic mineral fertilisers and / or BBFs were calculated to meet with the legal restrictions or crop requirements, which will not be applied in practice. However, in this environmental impact assessment these low amounts are taken into account in the calculations in order to get an equal comparison between the scenarios.

6.1 Groot Zevert Vergisting (The Netherlands)

6.1.1 Application rates

Table 6-1 shows the amounts of the products applied per scenario for Groot Zevert Vergisting. Scenarios that include both digestate and RO concentrate can fill up N and P to the application limits without requiring mineral fertilisers (see scenario 2 & 3, 6 & 7, 10 & 11 and 14 & 15, as they result in the same ratio of products). This means that each two scenario's will give similar results.

Small amounts of mineral P fertiliser are needed on grassland in cases were no digestate or soil conditioner is used (scenario 4 and 8). Applications of CAN and K60 are required in all reference situations and AS fertiliser is needed only for grassland on sandy soils in the reference situation.

After P recovery from the SF of digestate, the soil conditioner has a low P content and rather low N content. In scenarios 12 and 16, the application of soil conditioner is set to a maximum of 10 tonnes per ha on arable land to increase the organic matter content of the soil. This equals to about 2100 kg organic matter per ha. In combination with RO concentrate, negligible amounts of mineral P fertilisers are needed to meet with the crop requirements.

Table 6-1 Total amounts of applied products on grassland and arable land (expressed in tonne FM ha^{-1} y^{-1}) for the defined scenarios of Groot Zevert Vergisting (NL).

Scen.	Crop	Soil	Code products	Biobased fertilisers			Mineral fertilisers			
				D	LPSI	RO conc	CAN	TSP	K60	AS
1	Grassland	Sand	D + MF	22.9			0.64			0.06
2	Grassland	Sand	D + RO conc + MF	19.7		25.3		0.01		
3	Grassland	Sand	D + RO conc	19.7		25.3				
4	Grassland	Sand	RO conc + MF			39.3		0.17		
5	Grassland	Clay	D + MF	22.9			1.06		0.06	
6	Grassland	Clay	D + RO conc + MF	18.1		37.6		0.01		
7	Grassland	Clay	D + RO conc	18.1		37.6				
8	Grassland	Clay	RO conc + MF			47.3		0.16		
9	Arable land	Sand	D + MF	15.3			0.25		0.11	
10	Arable land	Sand	D + RO conc + MF	14.1		9.2		0.00		
11	Arable land	Sand	D + RO conc	14.1		9.2				
12	Arable land	Sand	LPSI + RO conc + MF		10.0	18.6		0.06		
13	Arable land	Clay	D + MF	15.3			0.43		0.08	
14	Arable land	Clay	D + RO conc + MF	13.3		15.5		0.01		
15	Arable land	Clay	D + RO conc	13.3		15.5				
16	Arable land	Clay	LPSI + RO conc + MF		10.0	22.0		0.06		

AS	Ammonium sulphate (synthetic)
CAN	Calcium ammonium nitrate fertiliser
D	Digestate
K60	Potassium fertiliser with 60% K_2O
LPSI	Low-P soil improver
MF	Mineral fertilisers
RO conc	RO concentrate
TSP	Triple Super Phosphate fertiliser

6.1.2 Nutrients

Table 6-2, Figure 6-1 and Figure 6-2 show the amounts of nutrients applied per scenario for Groot Zevert Vergisting. Compared to the reference scenarios, the scenarios that include biobased fertilisers result in the application of higher amounts of K and S, especially on grassland (scenario 1-8, Figure 6-1). On arable land (scenario 9-16, Figure 6-2), the effect on K and S application is relatively small, except for scenario 12 and 16, in which soil conditioner is applied (after P recovery with an acid-base treatment). This causes an increase of S application up to approximately 90 kg/ha.

Table 6-2 Total amounts of applied nutrients as total nitrogen (TN), effective nitrogen (N eff.), total phosphorus (TP), total potassium (TK), total sulphur (TS) and as organic matter (OM) (expressed in kg ha^{-1} y^{-1}) for the defined scenarios of Groot Zevert Vergisting (NL).

Scenario	TN	N eff.	TP	TK	TS	OM
1	353	320	39	102	30	1345
2	349	320	39	288	50	1497
3	349	320	38	288	50	1497
4	320	320	39	312	61	531
5	452	385	39	134	15	1345
6	438	385	39	379	68	1570
7	438	385	37	379	67	1570
8	385	385	39	375	73	639
9	179	157	26	121	10	897
10	177	157	26	136	23	952
11	177	157	26	136	23	952
12	204	157	26	159	87	2373
13	228	184	26	108	10	897
14	223	184	26	182	32	990
15	223	184	25	182	32	990
16	231	184	26	185	92	2418

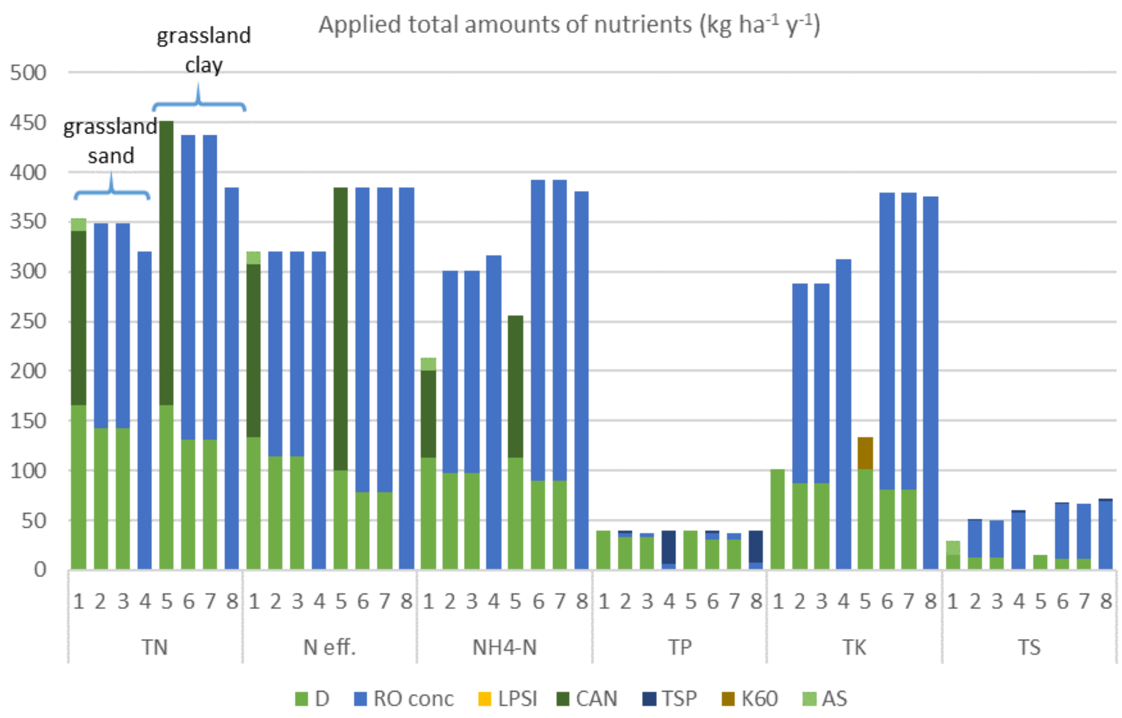

Figure 6-1 Total amounts of applied nutrients (expressed in kg ha^{-1} y^{-1}) on grassland for the scenarios of Groot Zevert Vergisting, for sand soils (scenarios 1-4) and clay soils (scenarios 5-8).

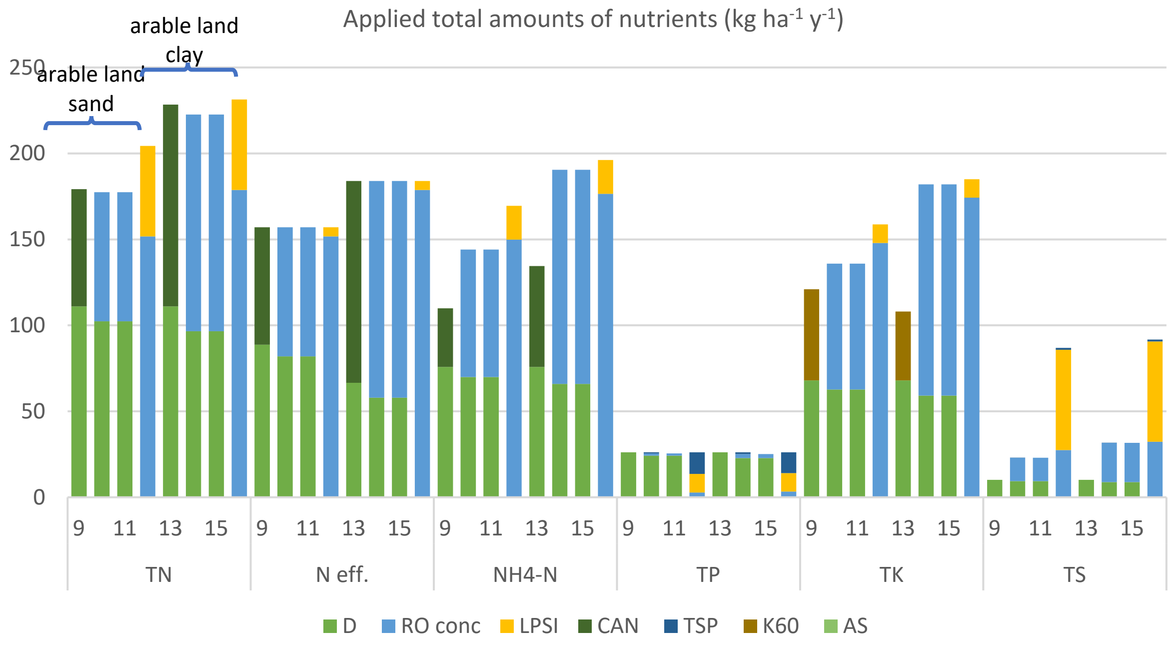

Figure 6-2 Total amounts of applied nutrients (expressed in kg ha^{-1} y^{-1}) on arable land with crop rotation for the defined scenarios of Groot Zevert Vergisting (NL), for sand soils (scenarios 9-12) and clay soils (scenarios 13-16).

6.1.3 Heavy metals

Table 6-3 shows the load of heavy metals per scenario. The RO concentrate contains small amounts of heavy metals. When this partially replaces digestate, the heavy metal load is slightly lower for some elements (Cr, Cu, Mn, Pb, Zn) and slightly higher for others (As, Cd, Co, Ni). In scenarios 4 and 8, where no digestate or soil conditioner are applied, only RO concentrate and mineral fertilisers can contribute to the application of heavy metals. This results in a strong decrease for Cu, Mn and Zn and an increase for Cd. For the mineral fertilisers (CAN, TSP, AS, K60) the heavy metal contents have been taken into account as well.

Furthermore, Cu and Zn application is high compared to Am-Power and BENAS, due to higher Cu and Zn contents of the digestate and soil conditioner as a result of the used feedstock (pig slurry), whereas the digestate of Am-Power and BENAS are mostly produced from food waste, and corn silage and chicken manure, respectively. The Cu and Zn contents of the digestate of GZV (15.4 and 54.0 mg/kg FM) are lower than those of the digestate produced by Acqua & Sole (37.0 and 113.0 mg/kg FM, with sewage sludge as feedstock). The application rate of digestate and soil conditioner are lower as well for GZV, together resulting in a lower heavy metal load, being around 300 g Cu/ha and 1000 g Zn/ha for GZV compared to around 1600 g Cu/ha and 5100 g Zn/ha for Acqua & Sole (see section 6.4.3).

Table 6-3 Total amounts of applied heavy metals as arsenic (As), cadmium (Cd), cobalt (Co), chrome (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn) (expressed in g ha^{-1} y^{-1}) for the defined scenarios of Groot Zevert Vergisting (NL).

Scenario	As	Cd	Co	Cr	Cu	Hg	Ni	Pb	Zn
1	2.1	0.72	2.7	29	354	0.10	28	23	1262
2	2.5	1.1	3.1	31	329	0.12	37	12	1191
3	2.5	0.94	3.1	29	328	0.12	37	12	1187
4	2.6	4.0	1.2	41	45	0.07	25	7.8	266
5	2.2	0.74	2.7	29	355	0.10	28	32	1279
6	2.9	1.3	3.3	32	317	0.14	42	14	1169
7	2.8	1.1	3.3	29	316	0.14	41	14	1164
8	2.9	3.9	1.4	41	52	0.09	29	9.2	303
9	1.4	0.47	1.8	19	236	0.06	19	11	834
10	1.5	0.62	1.9	20	227	0.07	22	7.3	808
11	1.5	0.55	1.9	19	226	0.07	22	7.3	806
12	3.5	2.5	3.0	33	159	0.15	28	15	687
13	1.4	0.48	1.8	19	236	0.07	19	15	842
14	1.7	0.73	2.0	20	220	0.08	24	8.1	796
15	1.6	0.62	2.0	19	220	0.08	24	8.1	794
16	3.6	2.5	3.1	33	162	0.16	30	16	703

6.2 Am-Power (Flanders, Belgium)

6.2.1 Amounts

Table 6-4 shows the amounts of products which can be applied per scenario. In each scenario, K60 is supplemented to reach the K requirements listed in Table 3-4. In all reference scenarios (Digestate + Mineral fertilisers; scenario 17, 20, 23, 26) CAN also has to be applied. The addition of CAN can be reduced by applying evaporator concentrate. Additional S supply is not required for any of the scenarios.

The grass scenarios for sand and clay are quite similar, because the maximum P application factor is the limiting factor that determines the amounts of digestate or evaporated concentrate to be applied. Small differences in the CAN are caused by the difference in N application standard between the two soil types. By introducing evaporator concentrate on grassland, there is no need to apply digestate. These scenario's give similar amounts of products to be applied (e.g. scenario 18&19 and 21&22). On arable land (potatoes) organic-rich dried solid fraction of digestate is applied (scenario 25 and 28). However, relatively small amounts can be applied due to restrictive P legislation and the high P-content in the product. None of the scenarios require TSP. In the scenarios with dried solid fraction of digestate, both CAN and K60 have to be applied to meet with the crop requirements. In the scenarios for potatoes, the crop requirements and/or legal restrictions can be met with applying just evaporator concentrate (24 and 27; negligible quantities of CAN are required).

Table 6-4 Total amounts of applied products on grassland and arable land (expressed in tonne ha^{-1} y^{-1}) to meet with the application standards and crop requirements for the defined scenarios of Am-Power (Flanders, Belgium).

Scen.	Crop	Soil	Code products	Biobased			Mineral fertilisers			
				D	DSFD	Ev conc	CAN	TSP	K60	AS
17	Grassland	Sand	D + MF	32.3			1.02		0.45	
18	Grassland	Sand	D + Ev conc + MF			44.2	0.50			
19	Grassland	Sand	Ev conc + MF			44.2	0.50			
20	Grassland	Clay	D + MF	32.3			1.05		0.36	
21	Grassland	Clay	D + Ev conc + MF			44.2	0.54			
22	Grassland	Clay	Ev conc + MF			44.2	0.54			
23	Potato	Sand	D + MF	25.4			0.41		0.33	
24	Potato	Sand	D + Ev conc + MF			34.7	0.01			
25	Potato	Sand	DSFD + Ev conc + MF		1.7		0.66		0.46	
26	Potato	Clay	D + MF	25.4			0.48		0.33	
27	Potato	Clay	D + Ev conc + MF			34.7	0.08			
28	Potato	Clay	DSFD + Ev conc + MF		1.7		0.73		0.46	

AS	Ammonium sulphate solution (synthetic)
CAN	Calcium ammonium nitrate fertiliser
D	Digestate
DSFD	Dried solid fraction of digestate
Ev conc	Evaporator concentrate
K60	Potassium fertiliser with 60% K_2O
TSP	Triple Super Phosphate fertiliser

6.2.2 *Nutrients*

Table 6-5 and Figure 6-3 and Figure 6-4 show the amounts of nutrients that are applied per scenario for Am-Power. For Am-Power total S application is substantially higher in scenarios where evaporator concentrate is used as substitute to mineral fertilisers than in scenarios without evaporator concentrate. In these scenarios, the S applications are high due to higher S content in the evaporator concentrate of Am-Power, compared to e.g. the RO concentrate of GZV (Table 2-2, 12 versus 1.5 g S/kg FW). However, the S-content of the evaporator concentrate is lower compared to the ammonium sulphate produced by Acqua & Sole and BENAS. The high S application rates (as SO_4^{2-}) are allowed, but will cause sulphate losses to groundwater. Furthermore, Ca, Mg and K will also leach out because they are associated with sulphate leaching, resulting into acidification of the top soil. Consequently, additional liming is required to maintain the pH of the rootzone. Therefore high S applications above crop requirements (Table 3-4) are not recommended. If the S application is limited, less evaporator concentrate can be applied and additional nitrogen fertilisers are required.

Remarkable is the limited amount of organic matter that can be applied with the dried solid fraction of digestate. This is mainly caused by the legislative P restriction and the high P content in this product. In fact, the highest amounts of organic matter can be applied with the evaporator concentrate.

Table 6-5 Total amounts of applied nutrients as total nitrogen (TN), effective nitrogen (N eff.), total phosphorus (TP), total potassium (TK), total sulphur (TS) and as organic matter (OM) (expressed in kg ha^{-1} y^{-1}) for the defined scenarios of Am-Power (BE).

Scenario	TN	N eff.	TP	TK	TS	OM
17	442	375	42	332	32	1615
18	534	375	42	429	531	2785
19	534	375	42	429	531	2785
20	452	385	42	290	32	1615
21	544	385	42	429	531	2785
22	544	385	42	429	531	2785
23	243	190	33	250	25	1269
24	315	190	33	337	417	2188
25	218	190	33	250	20	888
26	263	210	33	250	25	1269
27	335	210	33	337	417	2188
28	238	210	33	250	20	888

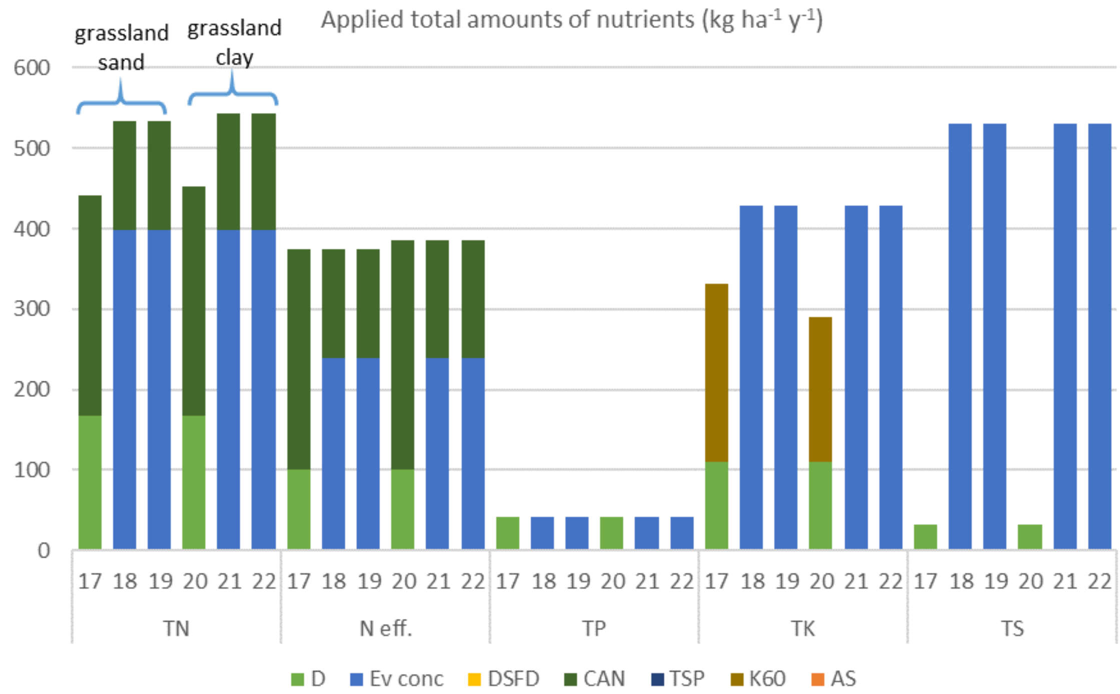

Figure 6-3 Total amounts of applied nutrients (expressed in kg ha^{-1} y^{-1}) on grassland for the defined scenarios of Am-Power (Flanders, Belgium), for sand soils (scenarios 17-19) and clay soils (scenarios 20-22).

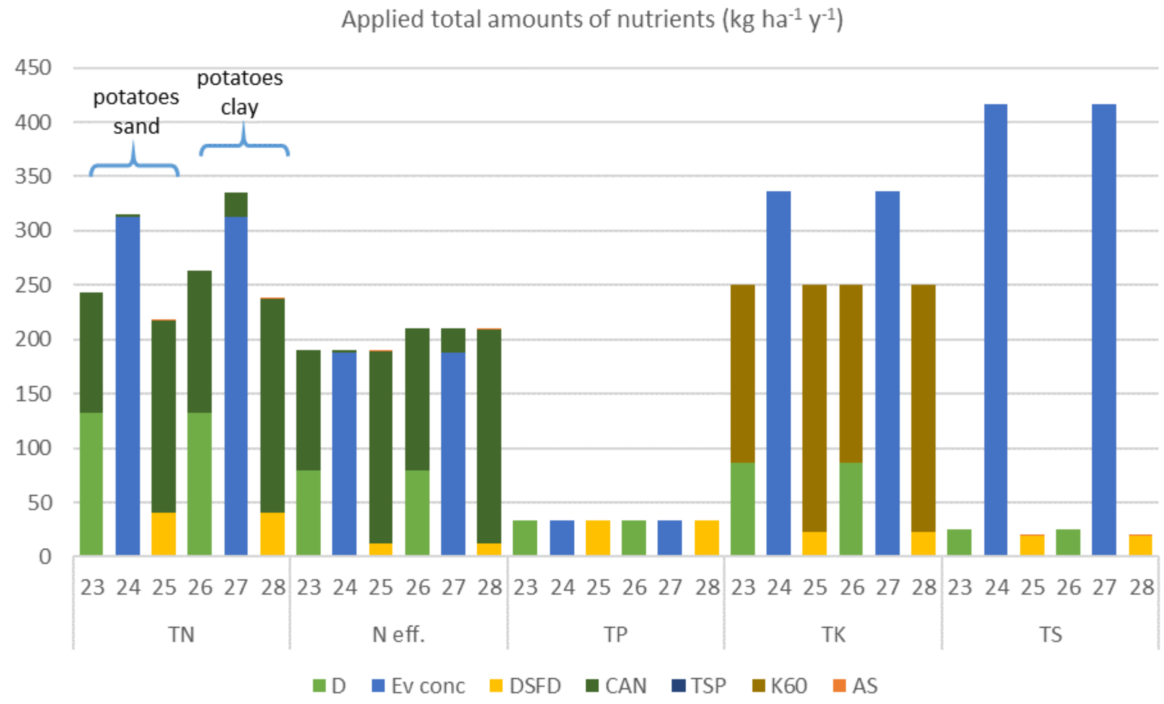

Figure 6-4 Total amounts of applied nutrients (expressed in kg ha^{-1} y^{-1}) on arable land for the defined scenarios of Am-Power (Flanders, Belgium), for sand soils (scenarios 23-25) and clay soils (scenarios 26-28).

6.2.3 Heavy metals

In Table 6-6 the total loads of heavy metals are shown for Am-Power. Applying evaporator concentrate instead of digestate decreases As, Cd, Pb, Cu and Zn loads and increases Co and Ni loads. Although the application rates of digestate are higher for Am-Power than for Groot Zevert Vergisting, the addition of heavy metals is for some of the heavy metals quite similar to the loads for the scenarios of GZV. At GZV the Cu and Zn load is higher, since both elements are additives to animal feed, while Pb and Cd are higher at Am-Power (food waste as feedstock for the digester). The heavy metals As and Hg have not been measured in digestate, evaporator concentrate or DSFD. The As and Hg loads thus could be slightly higher in practice.

Table 6-6 Total amounts of applied heavy metals as arsenic (As), cadmium (Cd), cobalt (Co), chrome (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn) (expressed in g ha^{-1} y^{-1}) for the defined scenarios of Am-Power (BE).

Scenario	As$^{1)}$	Cd	Co	Cr$^{2)}$	Cu	Hg$^{1)}$	Ni	Pb	Zn
17	0.57	3.6	5.8	40	199	0.01	39	57	915
18	0.18	2.7	17	45	164	0.01	84	37	684
19	0.18	2.7	17	45	164	0.01	84	37	684
20	0.55	3.6	5.8	40	199	0.01	39	58	916
21	0.19	2.7	17	45	164	0.01	84	38	685
22	0.19	2.7	17	45	164	0.01	84	38	685
23	0.30	2.8	4.6	31	156	0.01	31	37	703
24	0.00	2.1	13	35	129	0.00	66	21	521
25	0.45	0.2	1.9	36	119	0.01	21	16	585
26	0.33	2.8	4.6	31	156	0.01	31	38	706
27	0.03	2.1	13	35	129	0.00	66	23	524
28	0.48	0.2	1.9	36	120	0.01	21	18	588

$^{1)}$ The As and Hg contents of digestate, RO concentrate and DSFD were not measured. The reported loads are resulting from the use of mineral fertilisers. In practice, the As and Hg loads might be higher.
$^{2)}$ Cr-VI is not explicitly modelled

6.3 Waterleau NewEnergy (Flanders, Belgium)

6.3.1 Amounts

The applied amounts of digestate and mineral fertiliser in each reference scenario of grassland (45, 48) and potato (51 and 54) are quite similar for Waterleau NewEnergy, because the P maximum application standard is the limiting factor that determines the amounts of digestate to be applied. Due to high P contents in the dried solid fraction of digestate a low amount of this organic rich product can be applied (even lower compared to Am-Power [Table 6-4] and much lower compared to GZV [Table 6-1]). In all of the scenarios CAN has to be applied, but TSP or AS are in fact not required. In some of the scenarios a limited amount of K60 has to be applied to meet with crop requirements.

Table 6-7 Total amounts of applied products on grassland and arable land (expressed in tonne ha^{-1} y^{-1}) to meet with the application standards and crop requirements for the defined scenarios of Waterleau NewEnergy (Flanders, Belgium).

Scen.	**Crop**	**Soil**	**Code products**	**Biobased**			**Mineral fertilisers**			
				D	**DSFD**	**Ev conc**	**CAN**	**TSP**	**K60**	**AS**
45	Grassland	Sand	Dig + MF	39			0.83	0.01	0.36	
46	Grassland	Sand	Dig + Ev conc + MF	16		12	0.86			
47	Grassland	Sand	Ev conc + MF			20	0.90			
48	Grassland	Clay	Dig + MF	39			0.87	0.01	0.28	
49	Grassland	Clay	Dig + Ev conc + MF	23		9.1	0.88			
50	Grassland	Clay	Ev conc + MF			20	0.94			
51	Potatoes	Sand	Dig + MF	27			0.33	0.03	0.29	
52	Potatoes	Sand	Dig + Ev conc + MF	15		8.8	0.28			
53	Potatoes	Sand	DSFD + Ev conc + MF		1.3		0.64		0.46	0.02
54	Potatoes	Clay	Dig + MF	27			0.40	0.03	0.29	
55	Potatoes	Clay	Dig + Ev conc + MF	15		8.8	0.36			
56	Potatoes	Clay	DSFD + Ev conc + MF		1.3		0.72		0.46	0.02

AS	Ammonium sulphate solution (synthetic)
CAN	Calcium ammonium nitrate fertiliser
D	Digestate
DSFD	Dried solid fraction of digestate
Ev conc	Evaporator concentrate
K60	Potassium fertiliser with 60% K_2O
TSP	Triple Super Phosphate fertiliser

6.3.2 Nutrients

Table 6-8 and Figure 6-5 and Figure 6-6 show the amounts of nutrients that are applied per scenario for Waterleau NewEnergy. The limitation in P application standard determines the amount of products that can be applied. The amount of effective nitrogen is in line with the maximum amounts allowed nitrogen (Table 3-3). For Waterleau NewEnergy the total S application is substantially higher in scenarios where evaporator concentrate is used as substitute for digestate and/or mineral fertilisers than in scenarios without evaporator concentrate due to the higher S-SO_4 concentration in the evaporator concentrate compared to digestate (Table 2-2) and mineral fertilisers (no S-SO_4 except for AS). The amount of S applied is higher than at GZV (Table 6-2) but lower than Am-Power (Table 6-5). Using dried solid fraction of digestate on arable land (up to the P application limit) will lead to a reduction in total N-input but a higher dosage of CAN (Figure 6-6; scenario 53 and 56).

Table 6-8 Total amounts of applied nutrients as total nitrogen (TN), effective nitrogen (N eff.), total phosphorus (TP), total potassium (TK), total sulphur (TS) and as organic matter (OM) (expressed in kg ha^{-1} y^{-1}) for the defined scenarios of Waterleau NewEnergy (BE).

Scenario	TN	N eff.	TP	TK	TS	OM
45	475	375	42	332	33	1250
46	471	375	42	332	160	1646
47	463	375	42	440	240	1840
48	485	385	42	290	33	1250
49	484	385	42	290	129	1571
50	473	385	42	440	240	1840
51	258	190	33	250	23	850
52	266	190	33	250	118	1274
53	218	190	33	250	20	841
54	278	210	33	250	23	850
55	286	210	33	250	118	1274
56	238	210	33	250	20	841

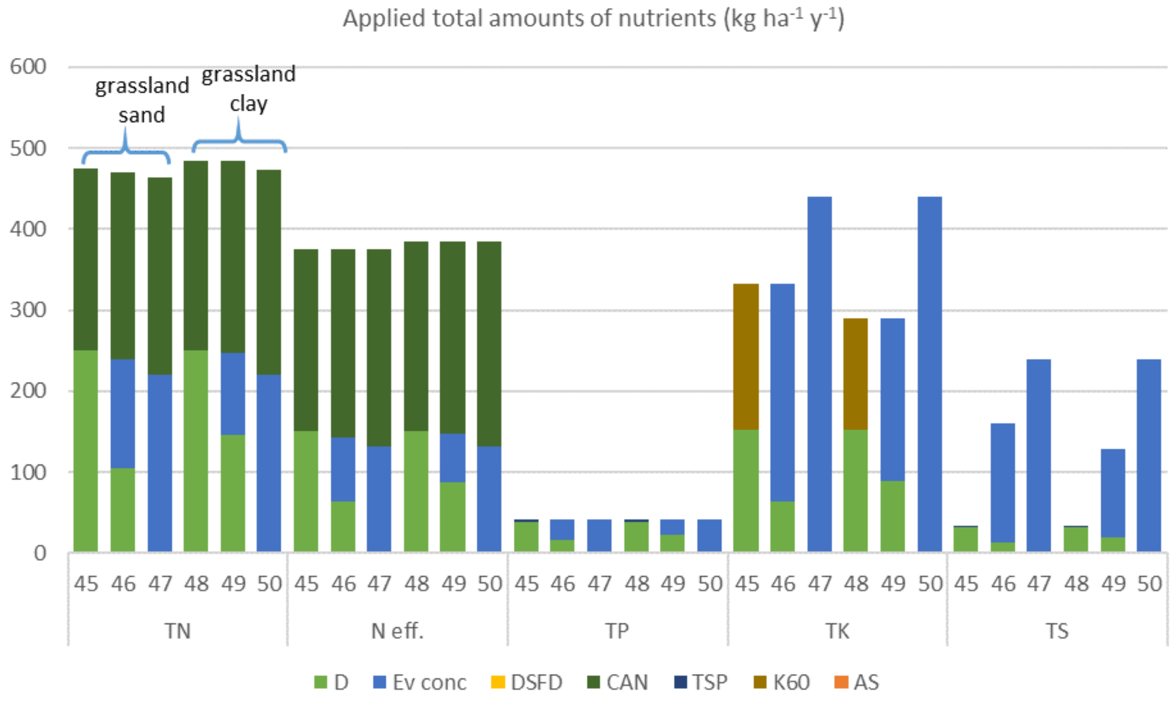

Figure 6-5 Total amounts of applied nutrients (expressed in kg ha^{-1} y^{-1}) on grassland for the defined scenarios of Waterleau NewEnergy (Flanders, Belgium), for sand soils (scenarios 45-47) and clay soils (scenarios 48-50).

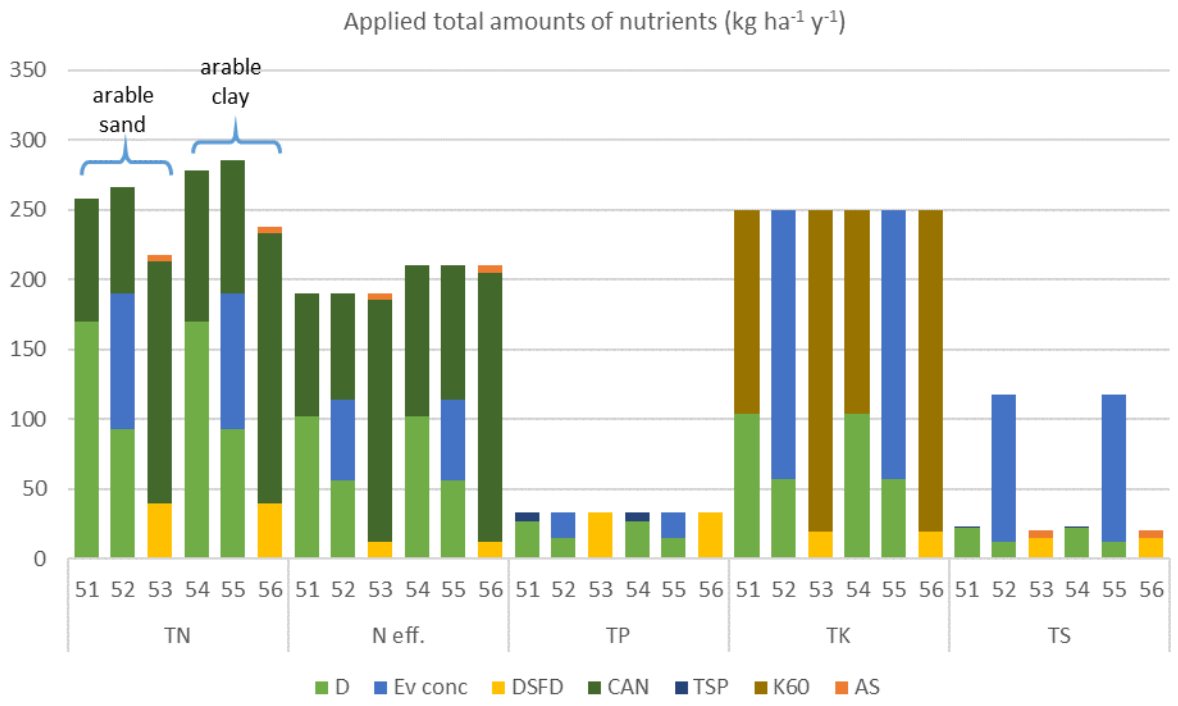

Figure 6-6 Total amounts of applied nutrients (expressed in kg ha^{-1} y^{-1}) on arable land (potatoes) for the defined scenarios of Waterleau NewEnergy (Flanders, Belgium), for sand soils (scenarios 51-53) and clay soils (scenarios 54-56).

6.3.3 Heavy metals

The total loads of heavy metals are shown in Table 6-9 for Waterleau NewEnergy. Applying evaporator concentrate instead of digestate decreases As, Cd, Cu and Zn loads and increases Co and Ni loads. The load of heavy metals are comparable to Am-Power, only Cu is somewhat higher. The heavy metal Hg has not been measured in evaporator concentrate and dried solid fraction of digestate. The Hg loads will be (slightly) higher in practice.

Table 6-9 Total amounts of applied heavy metals as arsenic (As), cadmium (Cd), cobalt (Co), chrome (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn) (expressed in g ha^{-1} y^{-1}) for the defined scenarios of Waterleau NewEnergy (BE).

Scenario	As	Cd	Co	Cr	Cu	Hg	Ni	Pb	Zn
45	3.3	15.6	6.6	37	354	0.05	36	27	1018
46	2.7	7.0	10.5	32	271	0.05	65	30	835
47	2.3	1.5	12.6	29	201	0.05	82	32	677
48	3.3	15.6	6.6	37	354	0.05	36	28	1019
49	2.8	10.	9.6	33	298	0.05	58	30	899
50	2.3	1.0	12.6	29	201	0.05	82	33	678
51	2.3	11.0	4.5	29	241	0.03	25	14	691
52	2.0	6.0	8.0	25	219	0.03	49	15	656
53	1.4	0	3.2	39	319	0.02	16	25	979
54	2.4	11.0	4.5	29	241	0.03	25	15	694
55	2.0	6.0	8.0	25	219	0.04	49	17	660
56	1.4	0	3.2	39	320	0.03	16	27	982

6.4 Acqua & Sole (Italy)

6.4.1 Amounts

Table 6-10 shows the amounts of products which can be applied for Acqua & Sole. When biobased ammonium sulphate solution is applied, no industrially produced nitrogen fertiliser has to be added. Due to differences in N-concentrations the amounts of AS_b or CAN applied differ. In all scenarios still some limited amounts of potash (K60) application is required, but there is no need to apply TSP or industrially produced AS. In the reference scenarios, CAN also needs to be applied.

Table 6-10 Total amounts of applied products on arable land (expressed in tonne ha^{-1} y^{-1}) to meet with the application standards and crop requirements for the defined scenarios of Acqua & Sole (Italy) (no limit for P application).

Scen.	Crop	Soil	Code products	Biobased		Mineral fertiliser			
				D	AS_b	CAN	TSP	K60	AS
29	Corn	Loam	D + MF	45		0.33		0.13	
30	Corn	Loam	D + AS_b + MF	45	1.2			0.13	
31	Rice	Loam	D + MF	45		0.33		0.13	
32	Rice	Loam	D + AS_b + MF	45	1.2			0.13	
33	Corn	Loam	D + MF	11		0.84		0.17	
34	Corn	Loam	D + AS_b + MF	11	3.0			0.17	
35	Rice	Loam	D + MF	7		0.90		0.18	0.01
36	Rice	Loam	D + AS_b + MF	7	3.2			0.18	

AS	Ammonium sulphate (synthetic)
AS_b	Biobased ammonium sulphate solution
CAN	Calcium ammonium nitrate fertiliser
D	Digestate
K60	Potassium fertiliser with 60% K_2O
TSP	Triple Super Phosphate fertiliser

6.4.2 Nutrients

Table 6-11 and Figure 6-7 provide details on nutrient application per scenario for Acqua & Sole. Phosphorus is only applied via digestate. Large amounts of P are applied in all scenarios due the fact that there is no limit for maximum P application and the P-N ratio of digestate. The application of P is 5 – 7 times higher than crop uptake of arable crops (Table 5-9), which will cause high P losses in the long term. Table 6-12 shows the amounts applied in case the P application limit is set to the amount of P uptake of the crop (equilibrium fertilisation), while N_{eff} is kept at the same level in all scenarios. In the situation where P becomes restrictive the amount of digestate that can be applied is limited and more N need to be applied as biobased fertiliser (biobased AS; AS_b) leading to additional load of sulphate compared to the reference scenario (from about 152 to more than 250 kg S per ha per year). In all cases, the amount of total S applied increases above crop requirements (Table 3-4) by using recovered (biobased) ammonium sulphate as substitute for mineral fertilisers. In all scenarios, mineral K fertiliser (potash; K60) also had to be applied to meet with the crop recommendations. The amount of organic matter applied is similar for biobased scenarios compared to the reference scenarios, since only digestate determines the amount of organic matter applied. In the scenarios with restricted P application the amount of digestate applied has decreased, and as such also the amount of organic matter that is applied, and not the other biobased or mineral fertilisers.

Table 6-11 Total amounts of applied nutrients as total nitrogen (TN), effective nitrogen (N eff.), total phosphorus (TP), total potassium (TK), total sulphur (TS) and as organic matter (OM) (expressed in kg ha^{-1} y^{-1}) for the defined scenarios of Acqua & Sole (IT) (no limit for phosphorus application).

Scenario	TN	N eff.	TP	TK	TS	OM
29	450	270	153	92	50	2835
30	450	270	153	92	152	2835
31	450	270	153	92	50	2835
32	450	270	153	92	152	2835

Table 6-12 Total amounts of applied nutrients as total nitrogen (TN), effective nitrogen (N eff.), total phosphorus (TP), total potassium (TK), total sulphur (TS) and as organic matter (OM) (expressed in kg ha^{-1} y^{-1}) for the defined scenarios of Acqua & Sole (IT) in case of phosphorus (P) equilibrium fertilisation.

Scenario	TN	N eff.	TP	TK	TS	OM
33	314	270	37	92	12	686
34	314	270	37	92	269	686
35	300	272	24	92	10	445
36	298	270	24	92	282	445

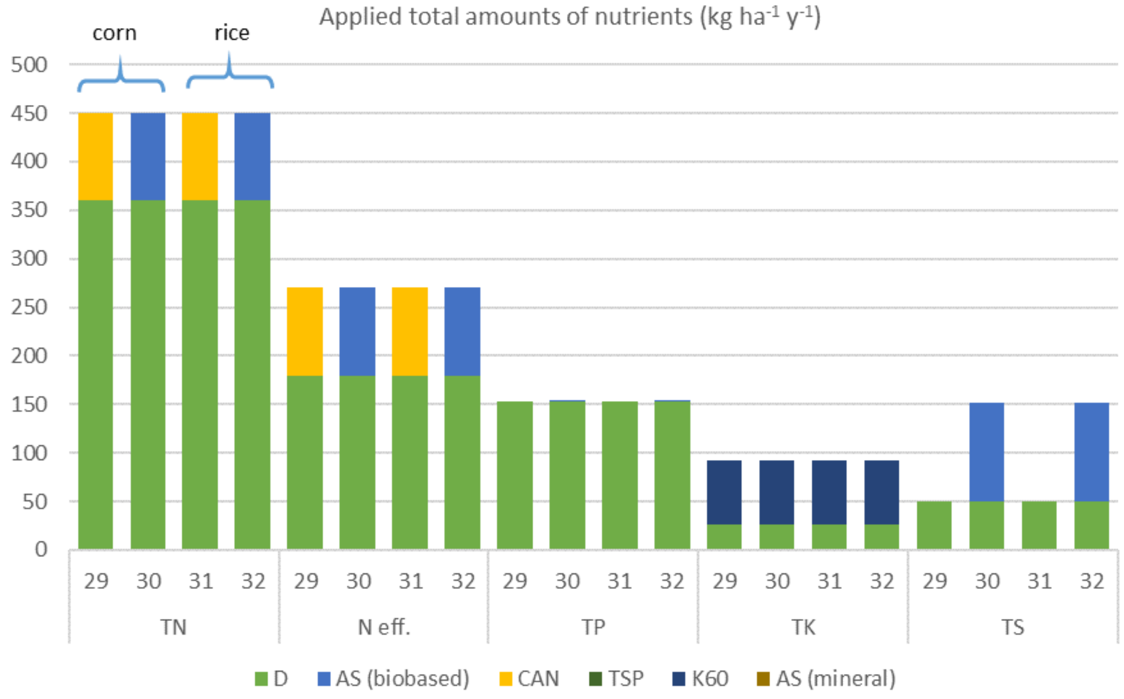

Figure 6-7 Total amounts of applied nutrients (expressed in kg ha^{-1} y^{-1}) on arable land for the defined scenarios of Acqua & Sole (Italy) without P equilibrium fertilisation, for corn (scenarios 29-30) and rice (scenarios 32-32).

6.4.3 Heavy metals

Table 6-13 shows the amounts of heavy metals that are applied per scenario for Acqua & Sole. Due to the application of similar amounts of digestate, there is almost no difference between the reference and the other scenarios. Compared to the other demonstration plants, the heavy metal loads are very high. This is caused by both high dosage of digestate and higher metal contents in the digestate, due to different feedstock of the digester, namely sewage sludge. The amount of applied digestate is higher due to less stringent rules in Italy: more N application is allowed and P application is not limited by legislation. In the case where P equilibrium fertilisation is assumed the heavy metal loads are much lower (Table 6-14).

Table 6-13 Total amounts of applied heavy metals as arsenic (As), cadmium (Cd), cobalt (Co), chrome (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn) (expressed in g ha^{-1} y^{-1}) for the defined scenarios of Acqua & Sole (IT) (no limit for phosphorus application).

Scenario	As	Cd	Co	Cr	Cu	Hg	Ni	Pb	Zn
29	37	4.2	30	356	1666	6.3	261	340	5099
30	38	4.4	30	356	1671	6.6	262	334	5095
31	37	4.2	30	356	1666	6.3	261	340	5099
32	38	4.4	30	356	1671	6.6	262	334	5095

Table 6-14 Total amounts of applied heavy metals as arsenic (As), cadmium (Cd), cobalt (Co), chrome (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn) (expressed in g ha^{-1} y^{-1}) for the defined scenarios of Acqua & Sole (IT) in case of phosphorus (P) equilibrium fertilisation.

Scenario	As	Cd	Co	Cr	Cu	Hg	Ni	Pb	Zn
33	9.3	1.0	7.3	87	404	1.5	63	98	1264
34	12	1.6	7.6	87	418	2.3	67	84	1256
35	6.2	0.7	4.7	57	263	1.0	41	71	835
36	9.0	1.3	5.1	57	277	1.8	45	56	825

6.5 BENAS (Germany)

6.5.1 Amounts

Table 6-15 shows the amounts of products from BENAS which have to be applied to meet the crop requirements and application standards. The addition of industrially produced AS in scenario 37 is negligible and will not be applied in practice. No CAN has to be used if biobased ammonium sulphate (AS_b) is used (scenarios 38 and 40).

Table 6-15 Total amounts of applied products on grassland and arable land (expressed in tonne ha^{-1} y^{-1}) to meet with the application standards and crop requirements for the defined scenarios of BENAS (Germany).

Scen.	**Crop**	**Soil**	**Code products**	**Biobased**		**Mineral fertiliser**			
				D	**AS$_b$**	**CAN**	**TSP**	**K60**	**AS**
37	Grassland	Sand	D + MF	24		0.91			0.02
38	Grassland	Sand	D + AS$_b$ + MF	24	5.4				
39	Winter wheat	Sand	D + MF	24		0.59			
40	Winter wheat	Sand	D + AS$_b$ + MF	24	3.4				
41	Grassland	Sand	D + MF	23		0.92			0.02
42	Grassland	Sand	D + AS$_b$ + MF	23	5.5				
43	Winter wheat	Sand	D + MF	17		0.69			
44	Winter wheat	Sand	D + AS$_b$ + MF	17	4.0				

AS	Ammonium sulphate solution (synthetic)
AS$_b$	Biobased ammonium sulphate solution
CAN	Calcium ammonium nitrate fertiliser
D	Digestate
K60	Potassium fertiliser with 60% K$_2$O
TSP	Triple Super Phosphate fertiliser

6.5.2 Nutrients

Table 6-16 and Figure 6-8 report the amount of nutrients that is applied in each BENAS scenario. In scenarios with application of AS$_b$, as substitute for mineral fertiliser CAN, total S applications are high, compared to the other demonstration plants as well. To avoid additional sulphate losses and therefrom resulting environmental impact, S application should be limited and, consequently, to fulfil nitrogen demand, some AS$_b$ fertiliser should be replaced with another N fertiliser. In all scenarios, substantial amounts of organic matter are supplied. However, S applications are high as well. The scenarios with or without P restriction differ minimally, because the P application is already close to equilibrium fertilisation without using restrictions (Table 6-17).

Table 6-16 Total amounts of applied nutrients as total nitrogen (TN), effective nitrogen (N eff.), total phosphorus (TP), total potassium (TK), total sulphur (TS) and as organic matter (OM) (expressed in kg ha^{-1} y^{-1}) for the defined scenarios of BENAS (DE) (no limit for phosphorus application).

Scenario	TN	N eff.	TP	TK	TS	OM
37	418	350	33	144	30	1724
38	418	350	33	144	317	1724
39	328	260	33	144	26	1724
40	328	260	33	144	211	1724

Table 6-17 Total amounts of applied nutrients as total nitrogen (TN), effective nitrogen (N eff.), total phosphorus (TP), total potassium (TK), total sulphur (TS) and as organic matter (OM) (expressed in kg ha^{-1} y^{-1}) for the defined scenarios of BENAS (DE) in case of phosphorus (P) equilibrium fertilisation.

Scenario	TN	N eff.	TP	TK	TS	OM
41	417	351	32	139	30	1669
42	416	350	32	139	320	1669
43	309	260	24	105	19	1251
44	309	260	24	105	237	1251

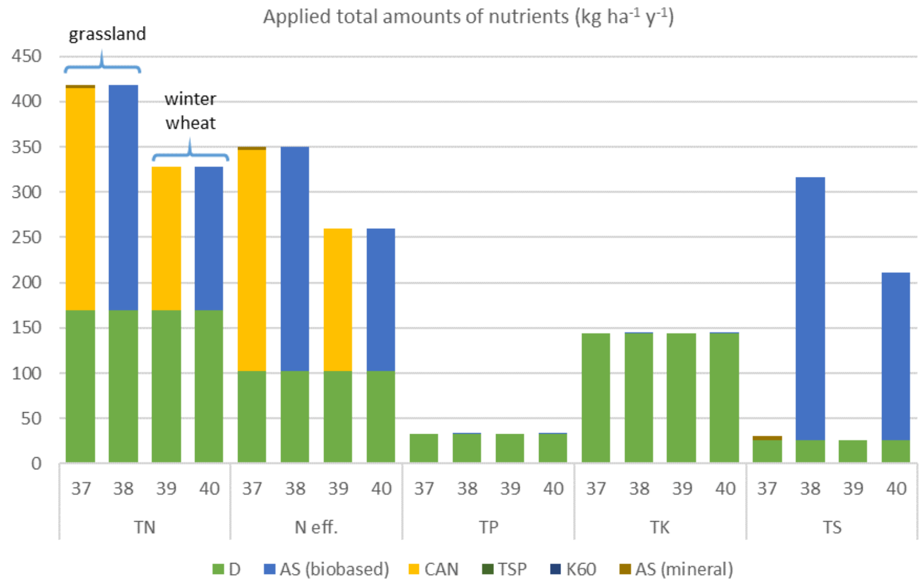

Figure 6-8 Total amounts of applied nutrients (expressed in kg ha^{-1} y^{-1}) on grassland and arable land for the defined scenarios of BENAS (Germany), for grassland (scenarios 37-38) and winter wheat (scenarios 39-40).

6.5.3 Heavy metals

In Table 6-18 the amounts of heavy metals applied are shown for BENAS. Application is similar for reference and non-reference scenarios except for Pb, which decreases slightly when CAN fertiliser is replaced with biobased AS in scenario 38 and 40. Compared to the other demonstration plants, Zn and Cu application are low. This is mainly caused by the different type of feedstock used in the BENAS digester (energy crops) which have a relatively low Zn and Cu and high Mn content (Appendix B). The As and Hg content of digestate and ammonium sulphate solution were not measured, but are expected to be very low / negligible compared to the amount applied by digestate.

Table 6-18 Total amounts of applied heavy metals as arsenic (As), cadmium (Cd), cobalt (Co), chrome (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn) (expressed in g ha^{-1} y^{-1}) for the defined scenarios of BENAS (DE) (no limit for phosphorus application).

Scenario	As	Cd	Co	Cr	Cu	Hg	Ni	Pb	Zn
37	2.2	4.3	5.9	16	131	0.06	20	35	816
38	1.9	4.4	6.0	16	130	0.05	21	16	780
39	2.1	4.3	5.9	16	131	0.05	20	28	803
40	1.9	4.3	5.9	16	130	0.05	21	15	780

Table 6-19 Total amounts of applied heavy metals as arsenic (As), cadmium (Cd), cobalt (Co), chrome (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn) (expressed in g ha-1 y-1) for the defined scenarios of BENAS (DE) in case of phosphorus (P) equilibrium fertilisation.

Scenario	As	Cd	Co	Cr	Cu	Hg	Ni	Pb	Zn
41	2.2	4.2	5.7	16	127	0.06	19	34	792
42	1.8	4.2	5.8	15	126	0.05	21	15	755
43	1.6	3.1	4.3	12	95	0.04	15	26	594
44	1.4	3.2	4.3	11	94	0.03	16	11	566

7 Results of model applications

7.1 Nitrogen

7.1.1 Gaseous emission NH_3 and N_20

7.1.1.1 Modelled data

For the applied amounts of products in the different scenarios (section 5.4) and the associated emissions factors for NH_3 (Table 5-4) and N_2O (Table 5-5), the NH_3 and N_2O emissions were calculated and presented (and subdivided in the figures by the sources of the emissions: digestate (dig), soil conditioner (sc), N rich biobased fertilisers (BBF) and mineral fertilisers (MF)). On arable land (Figure 7-2) the NH_3 emissions are lower (about a factor 5) compared to the emissions on grassland (Figure 7-1) due to the lower N application standards for arable land compared to grassland (Table 3-3), and to differences in emission factors between grassland and arable land, which are also lower on arable land (Table 5-4). On arable land the differences between the scenarios are small; both slightly higher as well as lower losses were predicted. Only if large amounts of soil improver with a low P content are used (GZV; scenario 12 and 16) do the NH_3 emissions increase due to the higher emission factor (Table 5-4). On grassland the NH_3 emissions of the reference scenario of Water NewEnergy (scenario 45 and 48) are high compared to the other plants. Substitution of digestate by WNE evaporator concentrate result in a reduction of the NH_3 emissions due to the relatively low NH_3 - N_{tot} ratio of WNE evaporator concentrate (Table 2-2). If, on grassland, a large part of the digestate and a substantial part of the mineral fertiliser are substituted by the recovered N-rich products, the NH_3 emissions will increase, because the mineral N fertiliser (CAN) has a rather low NH_3 emission factor compared to biobased N fertilisers (Table 5-4). This is especially the case for CAN because only 50% of the total amount of N is ammonium-N (the other 50% of N is nitrate-N). If we compare the results of recovered N with urea as synthetic mineral N fertiliser, the ammonia emissions are reduced in all grassland scenarios (Figure 7-3) due to the relatively higher NH_3-emission factor (Table 5-4). On arable land the amount of urea that is applied is highly determinate of the NH_3 emissions (Figure 7-4). If biobased nitrogen fertilisers are used, a reduction is also found.

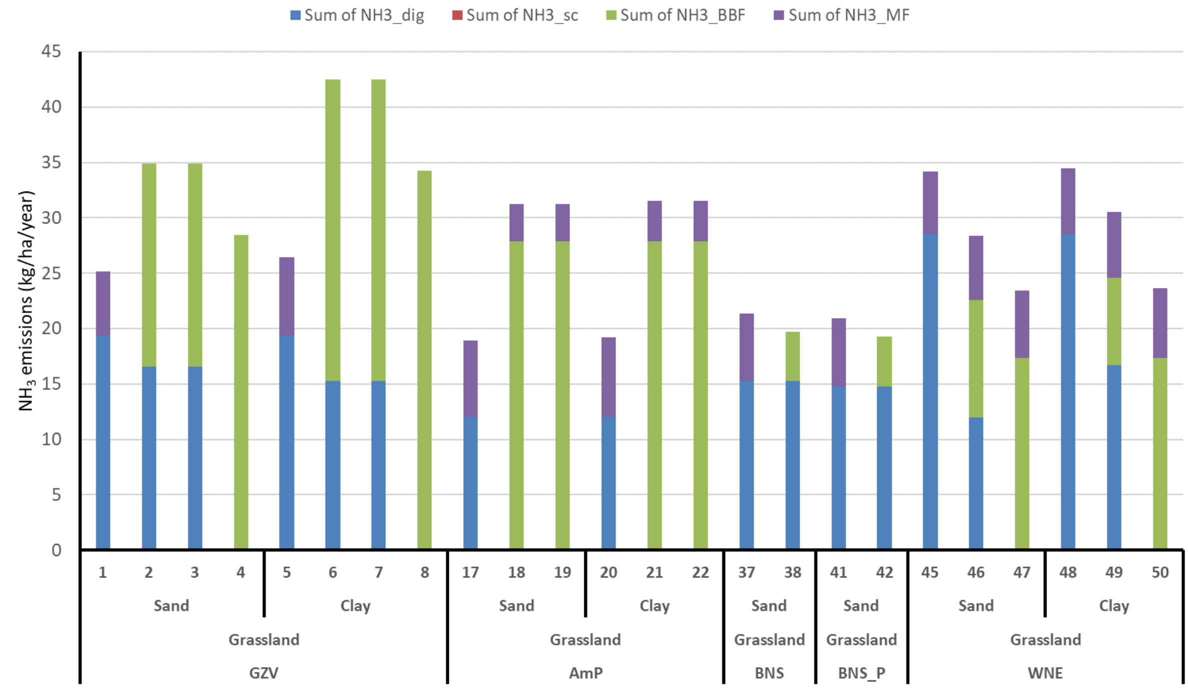

Figure 7-1 Total amounts ammonia (NH_3) emissions (expressed in kg N ha^{-1} y^{-1}) as predicted for all grassland scenarios of the demonstration Groot Zevert Vergisting (GZV), Am-Power (AmP), BENAS (BNS) and Waterleau NewEnergy (WNE) (mineral fertiliser is calcium ammonium nitrate).

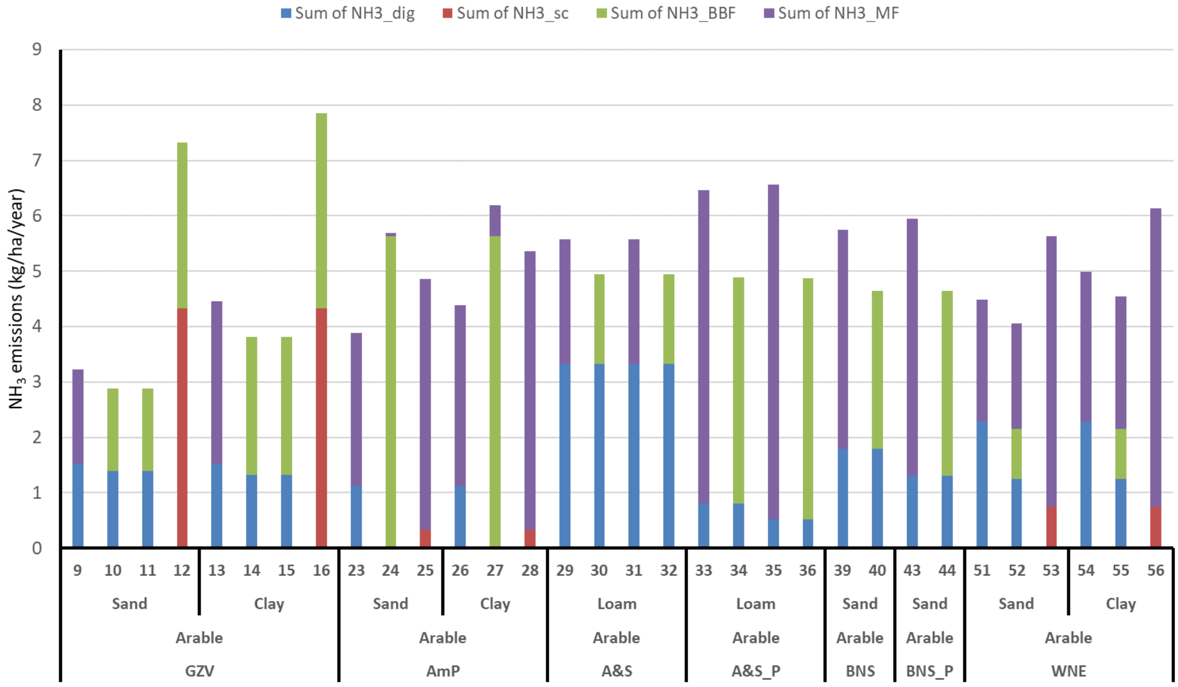

Figure 7-2 Total amounts ammonia (NH_3) emissions (expressed in kg N ha^{-1} y^{-1}) as predicted for all arable scenarios of the demonstration plants Groot Zevert Vergisting (GZV), Am-Power (AmP), Acqua & Sole (A&S), BENAS (BNS) and Waterleau NewEnergy (WNE) (mineral fertiliser is calcium ammonium nitrate).

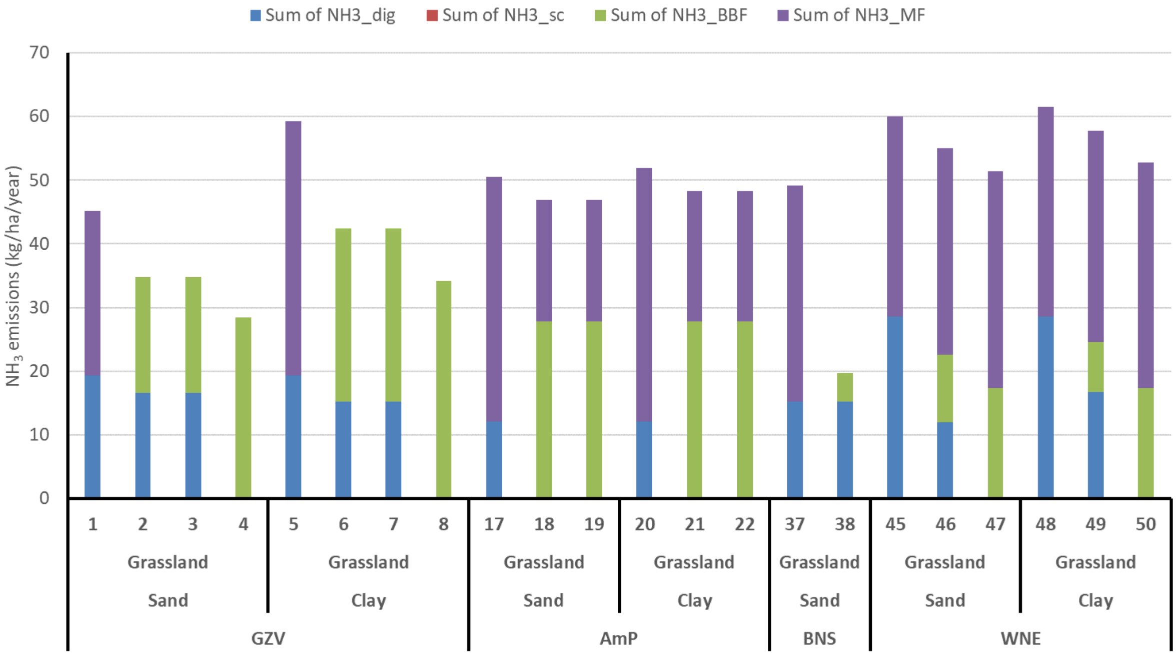

Figure 7-3 Total amounts NH_3 emissions (expressed in kg N ha^{-1} y^{-1}) as predicted for all grassland scenarios of the demonstration plants Groot Zevert Vergisting (GZV), Am-Power (AmP), BENAS (BNS) and Waterleau NewEnergy (WNE) (mineral fertiliser is urea).

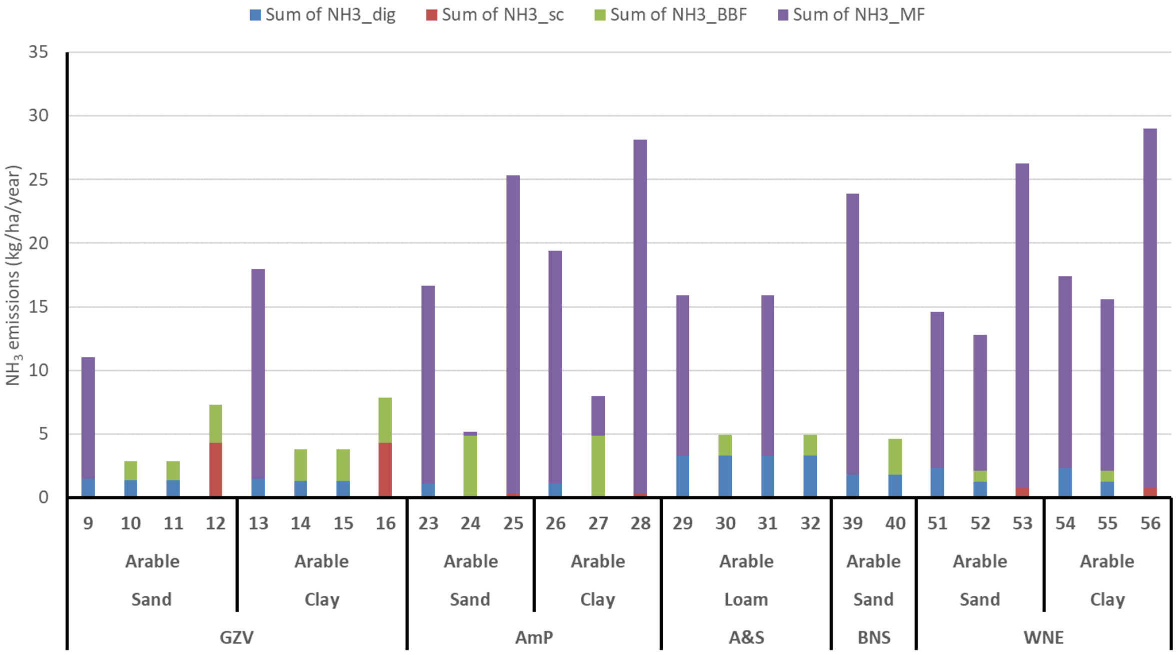

Figure 7-4 Total amounts NH_3 emissions (expressed in kg N ha^{-1} y^{-1}) as predicted for all arable land scenarios of the demonstration plants Groot Zevert Vergisting (GZV), Am-Power (AmP), Acqua & Sole (A&S), BENAS (BNS) and Waterleau NewEnergy (WNE) (mineral fertiliser is urea).

In summary, substitution of urea by recovered N-rich products (with a neutral or acid pH's) will reduce ammonia emissions both on grassland as well as on arable land. If CAN is used as reference mineral fertiliser the emissions increase when using RO concentrate (GZV) or evaporator concentrate (Am-Power) because CAN only consists of 50% ammonium and consequently has a relatively low NH_3 emission. In the environmental impact assessments, as described hereafter, CAN is kept as reference mineral N fertiliser as it is the most abundantly used mineral N fertiliser.

Regarding the N_2O-emissions, the differences are often relatively small between the scenarios and the reference scenario (1-2 kg N_2O) per ha per year both for grassland (Figure 7-5) and arable land (Figure 7-5). Reductions are predicted for GZV and GNS if large amounts of CAN are replaced by recovered N products on grassland due to the lower emission factors on grassland (Table 5-5). For Am-Power and Waterleau NewEnergy this is the case if a relatively substantial part of digestate is replaced by recovered N products on potatoes because, on arable land, digestates have higher N_2O emission factors compared biobased N fertilisers. In situations where a limited amount of digestate is replaced by recovered N-products (grassland Waterleau NewEnergy and arable GZV) the N_2O emissions are slightly increased because the differences in N_2O emissions are slightly higher for biobased N fertilisers compared digestates. Furthermore, a similar trend in results is found (not presented) if CAN is replaced by urea as reference mineral fertiliser, because the emission factor is related to total N and not to total ammoniacal nitrogen.

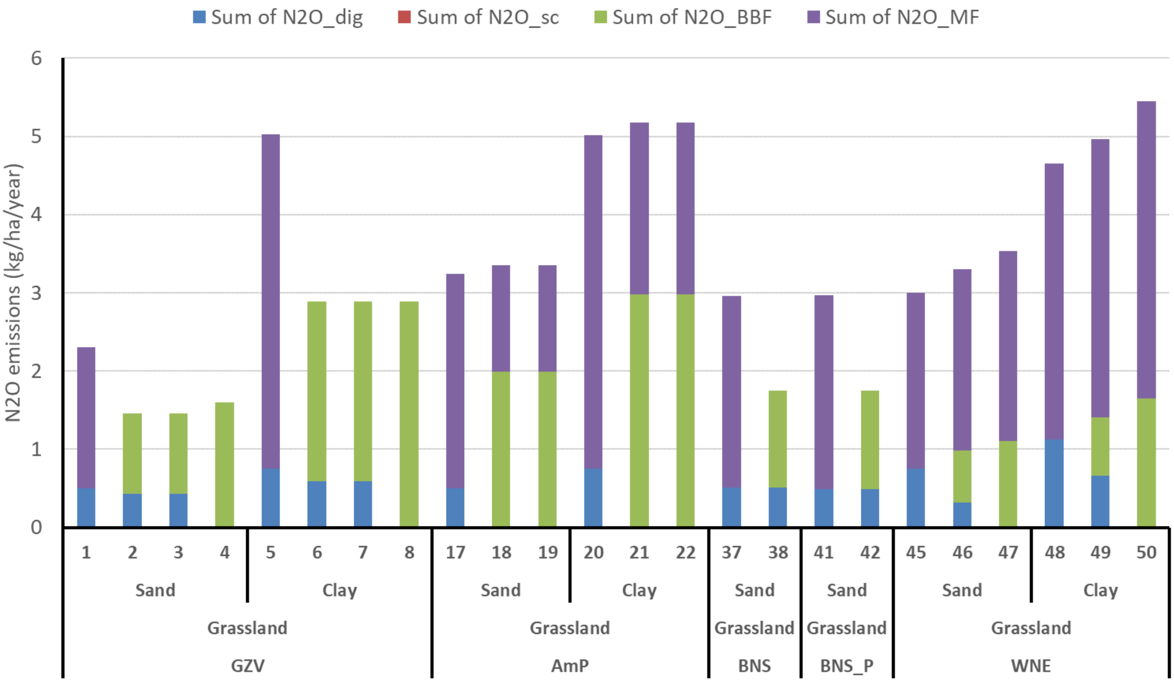

Figure 7-5 Total amounts N_2O emissions (expressed in kg N ha^{-1} y^{-1}) as predicted for all grassland scenarios of the demonstration plants Groot Zevert Vergisting (GZV), Am-Power (AmP), BENAS (BNS) and Waterleau NewEnergy (WNE) (mineral fertiliser is CAN).

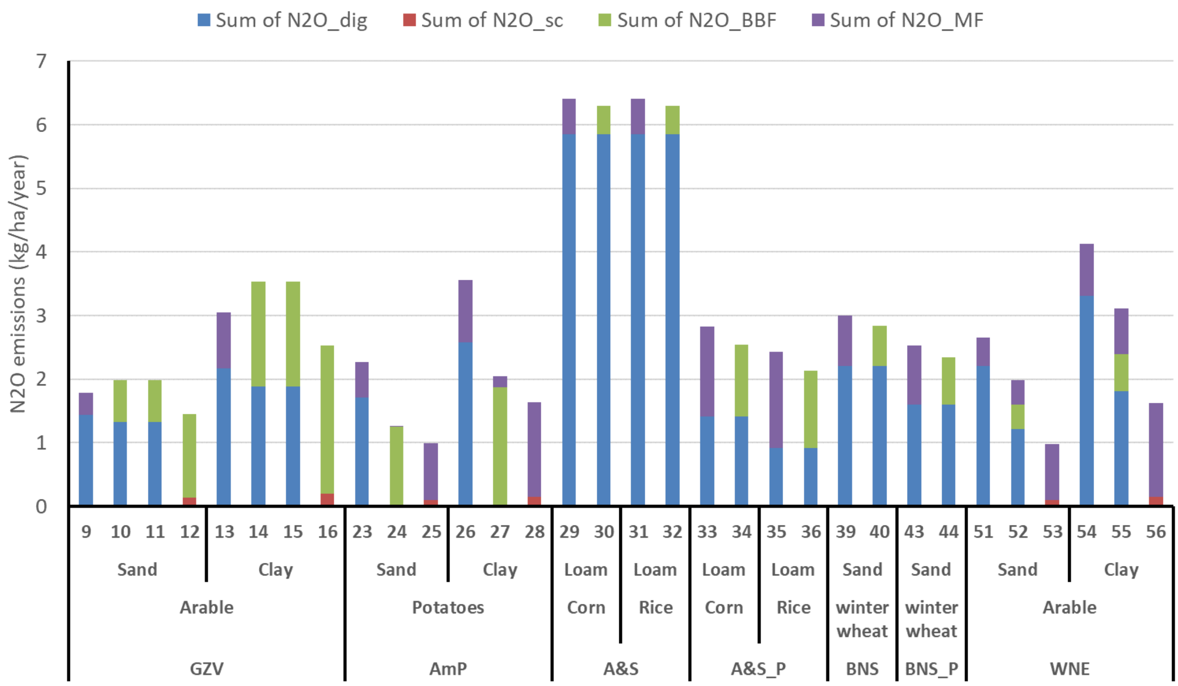

Figure 7-6 Total amounts N_2O emissions (expressed in kg N ha^{-1} y^{-1}) as predicted for all arable scenarios of the demonstration plants Groot Zevert Vergisting (GZV), Am-Power (AmP), Acqua & Sole (A&S), BENAS (BNS) and Waterleau NewEnergy (WNE) (mineral fertiliser is CAN).

In general we can conclude that the impact of the different combinations of fertilisers used in the defined scenarios is limited regarding the predicted N_2O emissions (both slightly negative/positive); only in the case where a substantial amount of mineral fertiliser (CAN/Urea) or digestate is replaced is the impact substantially positive.

7.1.1.2 Measured data Italian field trials

In Italy a three-year experiment was carried out with corn in order to measure the quantity of NH_3 emitted after pre-sowing fertilisation with digestate and urea with similar total N and N_{eff} values as used in the environmental impact study. The total measured ammonia emitted after fertilisation was 25.6 ± 9.4 kg N ha^{-1} for digestate, and 24.8 ± 8.3 kg N ha^{-1} for urea in a study in Italy for A&S (Zilio *et al.,* 2021). These values are statistically not different to each other, and both are higher than the ammonia emissions presented in Figure 7-4. However, in Figure 7-4 a combination of digestate and urea is used in the reference situation (scenario 29 with corn and 31 with rice) and in the biobased scenarios a part of the urea is substituted by biobased produced ammonium sulphate (scenario 30 and 32). If only urea would have been used (185 kg N per ha) with an estimated NH3 emission of 14.3% (Table 5-4), the annual NH_3 emissions are expected to be at 25.9 kg N per ha, which is of a similar level compared to the study of Zilio et al (2021).

The emission of N_2O was measured for corn as well, for almost a year (10 months) at the Italian experimental fields fertilised with digestate + ammonium sulphate (corresponding to scenario 30 in Figure 7-6) and urea + ammonium sulphate. The results obtained for N_2O are in line with what is reported in this study. In fact, the experimental soil fertilised with digestate + ammonium sulphate emitted a total quantity of N_2O equal to 7.59 ± 3.2 kg N ha^{-1}, a value similar to what is reported here in Figure 7-6, scenario 30 (value 6.3 kg N ha^{-1}). In the study of Zilio et al. (in prep), the measured N_2O emission from fields with digestate + ammonium sulphate is not statistically dissimilar from the measurements obtained using urea + ammonium sulphate (equal to 10.3 ± 6.8 kg N ha^{-1}). The scenario analysis in Zilio et al. does not include a scenario with urea + ammonium sulphate (without digestate), thus no comparison can be made for scenario 29 with field data.

7.1.2 Net nitrogen surplus and nitrate leaching

7.1.2.1 Modelled data

An important driver for nitrate leaching from the root zone to deeper groundwater is the net nitrogen surplus: all N total inputs including deposition and fixation, minus emissions to the air and nitrogen in crop harvest. The blue bars in Figure 7-7 show this net nitrogen surplus for all grassland scenarios. Only a part of this surplus will leach out due to denitrification in the soil. The red bars in Figure 7-7 show the modelled nitrate concentration (mg NO_3/l) leaching out via deep groundwater.

Due to the high P concentration in the digestate of GZV (pig manure) and the strict phosphate application standards, a limited amount of digestate N is applied on grassland. Synthetic mineral fertiliser or RO concentrate are applied to meet with the N requirements of grass. Since the legislative NFRV value of both products is 100%, the net nitrogen surplus is relatively low (and even negative on sandy soils) compared to the other plants. For all soil-crop scenarios of the demonstration plants, the N_{eff} applications are similar, but the amount of total N applied can differ (chapter 5). For the clay soils, modelled nitrate leaching is always below or nearby the 50 mg NO_3 per litre due to the relatively high denitrification capacity of clay soils (Figure 7-7). In sandy soils (grassland) BNS is just at this level (both reference as well as using ammonium sulphate), also if P equilibrium fertilisation is taken into account (BNS_P), while Am-Power is just above the 50 mg NO_3 per litre. Substituting all digestate by evaporator concentrate of Am-Power will lead to an increase in nitrate leaching, because about 90 kg N per ha per year extra nitrogen can be applied compared to the reference scenario (Table 6-5). This is not the case at WME when evaporator concentrate is used, because only part of the applied N is substituted by digestate and the N surplus will be at a same level (Table 6-8).

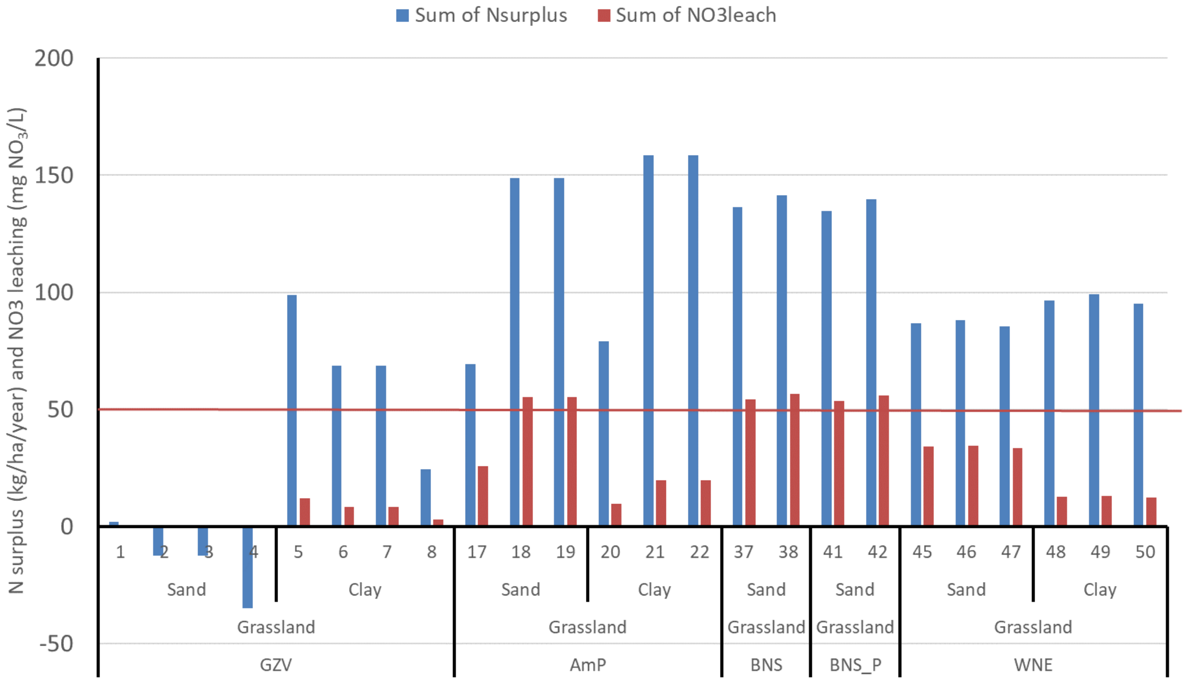

Figure 7-7 Net nitrogen surplus (kg N ha^{-1} y^{-1}; blue bars) and nitrate concentration (mg NO_3/l; red bars) leaching out from the root zone to deeper groundwater for all grassland scenarios for the demonstration plants Groot Zevert Vergisting (GZV), Am-Power (AmP), BENAS (BNS) and Waterleau NewEnergy (WNE).

Figure 7-8 shows a similar graph of the arable land scenarios. On arable land, the losses are always higher compared to grassland under the same conditions. For GZV the nitrate concentrations are below 50 mg NO$_3$ per litre, unless large amounts (10 tonne/ha) of low-P soil improver (LPSI) are applied on sandy soils (scenario 12; Figure 7-8) leading to a relatively high net nitrogen surplus on sandy soils. For Acqua & Sole, BENAS and Waterleau NewEnergy there is no difference between the reference scenario with synthetic mineral fertilisers (scenario 29, 31, 33, 35, 39, 51 and 54) and the scenarios where digestate and/or mineral fertiliser is substituted by ammonium sulphate (Acqua & Sole scenario 30, 32, 34, and 36 and BENAS scenario 40) or evaporator concentrate (Waterleau NewEnergy scenario 52 and 55). However, in both situations, a high nitrate leaching concentration can be found. In the cases where P equilibrium fertilisation is taken into account (A&S_P; scenario 33-36) the nitrate leaching will be substantially lower (compared to scenario 29-32). This is not the situation for evaporator concentrate of Am-Power (scenario 24 and 27), where the nitrate concentration will increase, because about 70 kg total N per ha per year can be applied compared to the reference situation, while the amount of N$_{eff}$ applied is always the same (Table 6-5). By using dried solid digestate of Waterleau NewEnergy (scenario 53 and 56), instead of digestate or evaporator concentrate of WNE, will also reduce nitrate leaching.

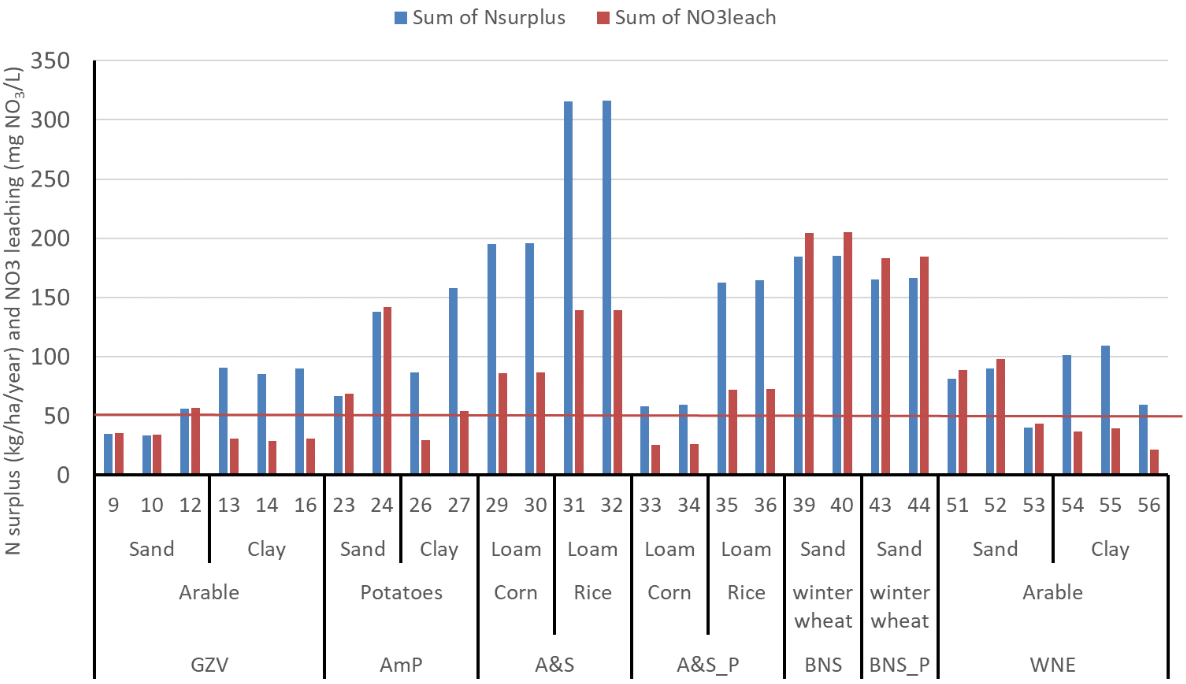

Figure 7-8 Net nitrogen surplus (kg N ha^{-1} y^{-1}; blue lines) and nitrate concentration (mg NO$_3$/l) leaching out from the root zone to deeper groundwater forall arable land scenarios for the demonstration plants Groot Zevert Vergisting (GZV), Am-Power (AmP), Acqua & Sole (A&S), BENAS (BNS) and Waterleau NewEnergy (WNE).

Although there are no differences in the amount of N$_{eff}$ applied, the amount of total N applied can differ due to differences in legislative NFRVs of the products. This will also have an effect on the amount of ammonium (N-NH$_4$) applied. Differences in total N and N-NH4 lead to differences in N-emissions to the air. Mainly the changes in total N applied in the scenarios will result in major differences in net N surplus (corrected for N-emissions and N-harvest), which are highly determinate of the nitrate losses from the root zone to deeper groundwater. Substitution of synthetic mineral fertiliser and / or digestate by biobased N-fertilisers often shows similar or lower nitrate leaching for GZV (RO concentrate), BNS, A&S (both ammonium sulphate) and WNE (evaporator concentrate), while for Am-Power (evaporator concentrate) an increase is predicted due to the high increase of total N. In fact, the higher N/P ratio of concentrate of AmPower means that more total N can be applied within the P application rate limit: total N applied as concentrate is not limited as it is a non-manure product. The NFRV of concentrate is 60% and hence, applying the maximum amount of evaporator concentrate will lead to a high N surplus and potentially leaching of nitrate. Concentrate of WNE has lower N/P ratio's due to stripping of N which reduces N dosages when applying concentrate up to the P application limit.

7.1.2.2 Measured data Italian field trials

In Italy, the risk of nitrate (NO_3^-) leaching into the soil of fields cultivated with maize was determined during two consecutive agronomic seasons. The results showed that the concentration of NO_3^- at one-meter depth in soils fertilised with digestate in pre-sowing + ammonium sulphate in topdressing has always been statistically not dissimilar to that measured in soils fertilised in parallel with urea in pre-sowing + ammonium sulphate in topdressing, nor from that measured in non-fertilised soils (no N for three years). The average content of NO_3^- in the soil at a depth of one meter during the two agronomic seasons was 6.56 ± 5.49 mg kg^{-1} dw for soil fertilised with digestate in pre-sowing + ammonium sulphate in topdressing, 7.18 ± 5.89 mg kg^{-1} dw for soil fertilised with urea + ammonium sulphate in topdressing and 5.22 ± 4.65 mg kg^{-1} dw for non-fertilised soil (complete data reported by Signurjak et al. 2022). Assuming an average content of about 6.8 mg N per kg dw in the topsoil of 1 meter (underestimation because in at the surface values will be higher) and an average bulk density of 1300 kg m^{-3}, the amount of mineral N in the soil during the year that can leach out as nitrate equals to about 88 kg mineral N per ha.

These data, although not directly quantifying the amount of NO_3^- leached (with the water flow through the soil matrix) from the experimental soils, showed that the quantities associated with the soil are similar between fertilised and non-fertilised soils. In fact, in a recent publication it was shown that N-related soil microbial populations grow in response to fertilisation with biobased or mineral fertilisers, and are able to metabolize nitrogen up to doses of 400 kg N ha^{-1} y^{-1}, denitrifying it and preventing it from being leached (Zilio *et al.,* 2020).

In the model approach, the amount of total N applied is 450 kg N per ha (360 kg N / ha as digestate and 90 kg N/ha as urea), which equals to N_{eff} of 270 kg N per ha (180 from digestate and 90 kg N/ha by urea). The estimated harvested N is about 280 kg N/ha, resulting in a total N surplus of 170 kg N/ha. Taking into account also the N_{dep} (29 kg N per ha per year), N_{fix} (2 kg N per ha per year) and correcting for NH_3-emissions (5.6 kg N per ha per year) the soil N surplus is 195.4 kg N per ha per year. The nitrate leaching is estimated as 73.3 kg N/ha (approx. 38% of the soil N surplus based on the model parameters of section 5.6; so about 62% will be denitrified). The predicted nitrate leaching 17% less compared with the estimated amount available in the soil (88 kg mineral N per year) which can leach out, but in fact quite similar estimates.

7.2 Phosphorus

The phosphorus losses over time are highly determined by the net P surplus (total application of P minus the amount of harvested P). A positive surplus P will increase the accumulation in the soil (soil P status) and sometimes the P uptake also. Due to the increase of the soil P status, the P losses from the root zone will also increase. On the other hand a negative surplus will reduce the losses in the long term and a new equilibrium will be reached. In the scenario analysis a long run of 100 years was done with the P-applications as defined in the scenarios (constant over the years) and the results of the P balance and P losses are presented at t=0 and after 100 years in Table 7-1. In many cases the P concentration leaching out of the rootzone is reduced over time as a result of a negative P balance.

Table 7-1 Phosphorus balance (expressed in kg ha^{-1} *y*$^{-1}$*) at t=0 and t= 100 years for all defined scenarios in this study.*

Scen.	Demoplant	Soil type	Crop type	root-zone	Yield (DM)	P input	P harvest (t=0)	P surplus	P conc. Leaching (t-0)	P conc. Leaching (t-100)
				cm	kg/ha/y	kg/ha/y	kg/ha/y	kg/ha/y	g/m^3	g/m^3
1	GZV	Sand	Grassland	10	11.0	39.3	47.3	-8.9	0.27	0.08
2	GZV	Sand	Grassland	10	11.0	39.3	47.3	-8.9	0.27	0.08
3	GZV	Sand	Grassland	10	11.0	37.5	47.3	-10.7	0.27	0.08
4	GZV	Sand	Grassland	10	11.0	39.3	47.3	-8.9	0.27	0.08
5	GZV	Clay	Grassland	10	11.0	39.3	47.3	-8.8	0.25	0.08
6	GZV	Clay	Grassland	10	11.0	39.3	47.3	-8.8	0.25	0.08
7	GZV	Clay	Grassland	10	11.0	36.7	47.3	-11.5	0.25	0.08
8	GZV	Clay	Grassland	10	11.0	39.3	47.3	-8.8	0.25	0.08
9	GZV	Sand	Arable	30	46.7	26.2	27.2	-1.9	0.27	0.10
10	GZV	Sand	Arable	30	46.7	26.2	27.2	-1.9	0.27	0.10
11	GZV	Sand	Arable	30	46.7	25.6	27.2	-2.6	0.27	0.09
12	GZV	Sand	Arable	30	46.7	26.2	27.2	-1.9	0.27	0.10
13	GZV	Clay	Arable	30	47.6	26.2	26.4	-1.1	0.25	0.19
14	GZV	Clay	Arable	30	47.6	26.2	26.4	-1.1	0.25	0.19
15	GZV	Clay	Arable	30	47.6	25.1	26.4	-2.1	0.25	0.15
16	GZV	Clay	Arable	30	47.6	26.2	26.4	-1.1	0.25	0.19
17	AmP	Sand	Grassland	10	13.0	42.0	50.0	-8.9	0.27	0.08
18	AmP	Sand	Grassland	10	13.0	42.0	50.0	-8.9	0.27	0.08
19	AmP	Sand	Grassland	10	13.0	42.0	50.0	-8.9	0.27	0.08
20	AmP	Clay	Grassland	10	13.0	42.0	50.0	-8.8	0.25	0.08
21	AmP	Clay	Grassland	10	13.0	42.0	50.0	-8.8	0.25	0.08
22	AmP	Clay	Grassland	10	13.0	42.0	50.0	-8.8	0.25	0.08
23	AmP	Sand	Potatoes	30	12.1	33.0	25.0	7.1	0.27	0.52
24	AmP	Sand	Potatoes	30	12.1	33.0	25.0	7.1	0.27	0.52
25	AmP	Sand	Potatoes	30	12.1	33.0	25.0	7.1	0.27	0.52
26	AmP	Clay	Potatoes	30	12.1	33.0	25.0	7.2	0.25	0.31
27	AmP	Clay	Potatoes	30	12.1	33.0	25.0	7.2	0.25	0.31
28	AmP	Clay	Potatoes	30	12.1	33.0	25.0	7.2	0.25	0.31
29	A&S	Loam	Corn	30	13.0	153.0	37.0	115	0.26	37.7
30	A&S	Loam	Corn	30	13.0	153.0	37.0	115	0.26	34.8
31	A&S	Loam	Rice	30	7.0	153.0	24.0	128	0.26	5.8
32	A&S	Loam	Rice	30	7.0	153.0	24.0	128	0.26	6.1
33	A&S_P	Loam	Corn	30	13.0	37.0	37.0	-1.0	0.26	0.17
34	A&S_P	Loam	Corn	30	13.0	37.0	37.0	-0.9	0.26	0.17
35	A&S_P	Loam	Rice	30	7.0	24.0	24.0	-1.0	0.26	0.17
36	A&S_P	Loam	Rice	30	7.0	24.0	24.0	-0.9	0.26	0.17
37	BNS	Sand	grassland	10	9.0	33.1	32.0	0.2	0.27	0.29
38	BNS	Sand	grassland	10	9.0	33.1	32.0	0.3	0.27	0.29
39	BNS	Sand	winter wheat	30	7.0	33.1	24.0	8.2	0.27	0.57
40	BNS	Sand	winter wheat	30	7.0	33.1	24.0	8.2	0.27	0.57
41	BNS_P	Sand	grassland	10	9.0	32.0	32.0	-0.8	0.27	0.10
42	BNS_P	Sand	grassland	10	9.0	32.0	32.0	-0.8	0.27	0.10
43	BNS_P	Sand	winter wheat	30	7.0	24.0	24.0	-0.8	0.27	0.15
44	BNS_P	Sand	winter wheat	30	7.0	24.0	24.0	-0.8	0.27	0.15
45	WNE	Sand	Grassland	10	13.0	42.0	50.0	-8.8	0.27	0.08
46	WNE	Sand	Grassland	10	13.0	42.0	50.0	-8.8	0.27	0.08
47	WNE	Sand	Grassland	10	13.0	42.0	50.0	-8.8	0.27	0.08
48	WNE	Clay	Grassland	10	13.0	42.0	50.0	-8.8	0.25	0.08
49	WNE	Clay	Grassland	10	13.0	42.0	50.0	-8.8	0.25	0.08
50	WNE	Clay	Grassland	10	13.0	42.0	50.0	-8.8	0.25	0.08
51	WNE	Sand	Arable	30	12.1	33.0	25.0	7.2	0.27	0.52
52	WNE	Sand	Arable	30	12.1	33.0	25.0	7.2	0.27	0.52
53	WNE	Sand	Arable	30	12.1	33.0	25.0	7.2	0.27	0.52
54	WNE	Clay	Arable	30	12.1	33.0	25.0	7.2	0.25	0.31
55	WNE	Clay	Arable	30	12.1	33.0	25.0	7.2	0.25	0.31
56	WNE	Clay	Arable	30	12.1	33.0	25.0	7.2	0.25	0.31

Since Acqua & Sole as well as BENAS had no P restrictions in applications, high P concentrations will leach out after 100 years of such surpluses. Therefore, model runs were also taken into account with P equilibrium fertilisation (A&S_P and BNS_P).
Figure *7-9* and Figure 7-10 show the average P concentration at t=0 and after 100 years resp. for grassland and arable crops assuming P equilibrium fertilisation for Acqua & Sole and BENAS. However, the data of Acqua & Sole were not presented in Figure 7-10 because it couldn’t presented very well due to the very high P losses in the long term (reaching P surplus values; Table 7-1).

In all scenarios where the P surplus is negative at t=0 (GZV grassland and arable land, Am-Power grassland, Waterleau NewEnergy grassland) the P leaching will decrease over time. In situation were the P-concentration in soil solution will become very low also the harvested P will decline, resulting in a less negative surplus and eventually a new equilibrium (zero surplus) and an equilibrium concentration of 0.08 mg P l^{-1}; Table 7-1). In the situation where the P surplus is slightly positive (Am-Power potatoes, BENAS grassland and winter wheat, Waterleau NewEnergy arable land), the amount of P harvested will not change and after 100 years, but the P leaching will increase (up to twice as high). After 100 years, high P concentrations are predicted to leach out of the rootzone in Italy (A&S) due to the high P application rates for corn (maize) and rice (section 5.4.4 Acqua & Sole and Table 7-1). This is also expected in Germany (BNS) for grassland as well as winter wheat as already mentioned in section 5.4.5 BENAS. However if P equilibrium fertilisation is applied for Acqua & Sole and BENAS (resp. A&S_P and BNS_P), the P losses will still be reduced compared to the situation without P equilibrium fertilisation / legislation.

The model predictions show that a high P surplus (P applications minus P harvest by crop) will lead to an increase of P losses in the long term, which has to be prevented from an environmental point of view to minimise eutrophication of surface waters. However, the predictions also showed that the differences between the scenarios with recovered nutrients are minimal compared to the reference scenario. So, changing digestate of synthetic mineral fertilisers will have no or a very limited effect on P losses. Furthermore, P equilibrium fertilisation is an efficient measure to control P losses from agricultural land to surface waters.

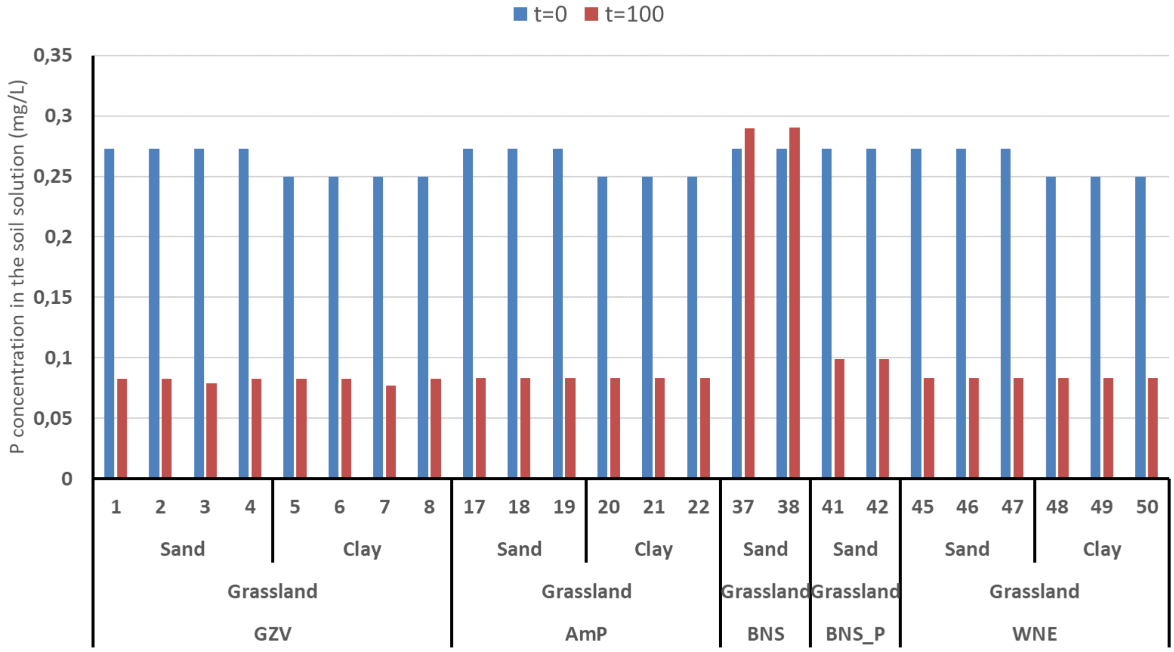

Figure 7-9 Phosphorus (P) concentration leaching out from the rootzone at t=0 and after 100 years for all grassland scenarios) for demonstration plants Groot Zevert Vergisting (GZV), Am-Power (AmP), BENAS (BNS) and Waterleau NewEnergy (WNE).

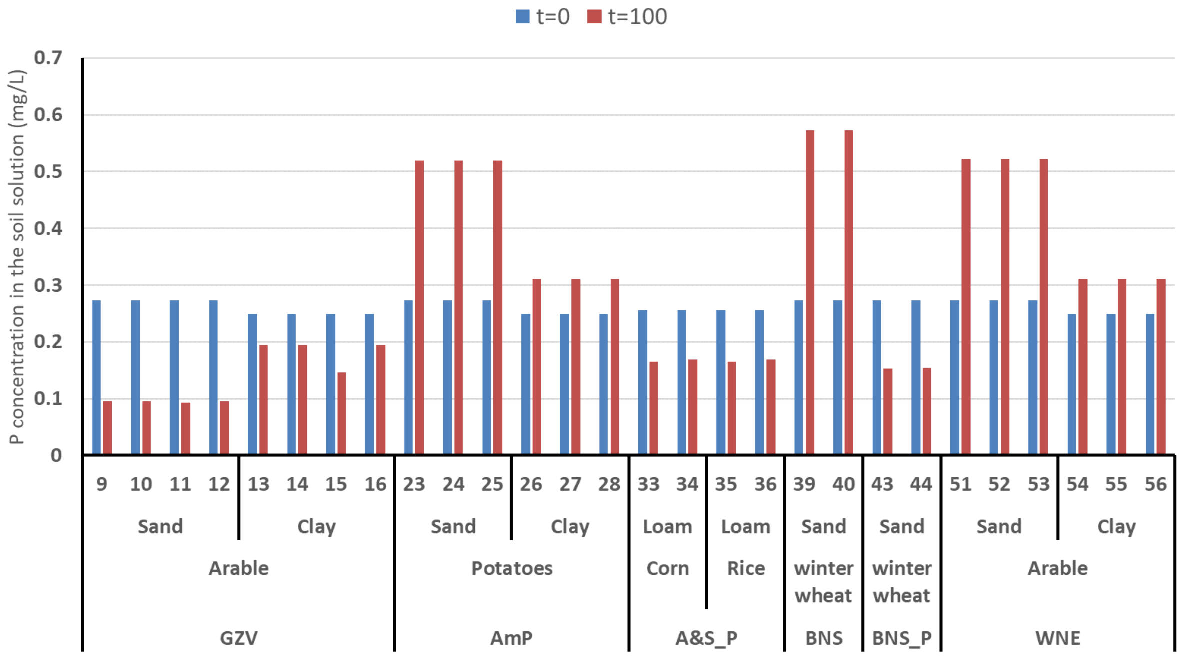

Figure 7-10 Phosphorus (P) concentration leaching out from the rootzone at t=0 and after 100 years for all arable crops scenarios) for demonstration plants Groot Zevert Vergisting (GZV), Am-Power (AmP), Acqua & Sole (A&S), BENAS (BNS) and Waterleau NewEnergy (WNE).

7.3 Heavy metals

The changes in heavy metal content in the soils, and consequently the leaching of heavy metals, are caused by the amount of heavy metals applied (section 5.4) and the amount of harvested metals in the yields, which are highly linked to the amount of heavy metals accumulated in the soil and the crop type. Similar to phosphorus, a surplus in a heavy metal will increase the heavy metal leaching, while a negative heavy metal balance will reduce heavy metal leaching.

For heavy metal accumulation and leaching of heavy metals from the rootzone, there are no target values available. Therefore, at first an overview is shown of the average increase/decrease of each of the heavy metals after 100 years compared to the initial situation. Both the heavy metal content and heavy metal leaching are given together with average change of each of the scenario (Table 7-2). Scenarios with a strong decrease of increase of a certain heavy metal will be discussed separately.

Table 7-2 Average heavy metal content and leaching at t=0 and t=100 years of chrome (Cr), arsenic (As), lead (Pb), nickel (Ni), cadmium (Cd), zinc (Zn) and copper (Cu) and the average percentage change over the 100 years (all scenarios).

		Heavy metal content soil						
		Cr	**As**	**Pb**	**Ni**	**Cd**	**Zn**	**Cu**
		mg kg^{-1} dw						
t=0	Average	19.4	8.6	24.4	11.0	0.3	48.4	13.1
	St.Dev	12.0	6.7	7.0	9.3	0.1	23.3	4.8
t=100	Average	21.3	8.6	25.0	12.7	0.4	61.2	19.9
	St.Dev	13.4	6.9	8.1	9.9	0.2	51.3	13.6
change	Average	0.02	-0.01	0.01	0.34	0.12	0.25	0.44
	St.Dev	0.02	0.02	0.06	0.53	0.74	0.92	0.47

		Heavy metal leaching						
		Cr	**As**	**Pb**	**Ni**	**Cd**	**Zn**	**Cu**
		g ha^{-1} y^{-1}						
t=0	Average	3.3	3.2	21.3	9.7	2.2	167.3	29.7
	St.Dev	0.5	1.2	10.0	7.6	2.0	81.7	15.1
t=100	Average	3.4	3.2	21.7	11.6	2.0	204.1	44.7
	St.Dev	0.5	1.2	10.6	8.1	1.8	242.7	35.3
change	Average	0.11	-0.01	0.10	0.35	0.06	0.10	0.44
	St.Dev	0.09	0.03	0.69	0.53	0.46	0.69	0.46

Chrome (Cr), Arsenic (As), Lead (Pb) and Cadmium (Cd)

These heavy metals Cr, As, Pb and Cd cause small changes in the amounts of accumulation in the soil and consequently relatively small changes in heavy metal leaching. After 100 years the heavy metal content and leaching are of a similar level in most of the scenarios (*Table 7-2*). A relatively high change was found for Cd at Waterleau NewEnergy grassland on sandy soils due to the relatively high Cd input (by digestate), however after 100 year the Cd losses were still quite similar compared with the other scenarios.

Nickel (Ni)

Regarding nickel a limited average increase of leaching is mentioned, mainly caused by the relative high nickel concentration and input to the soil by the digestate of Acqua & Sole compared to other digestates (Appendix B).

Zinc (Zn) and Copper (Cu)

The main changes in heavy metal leaching are observed zinc (Table 7-2 and Figure 7-11 grassland and Figure 7-12 arable crops) and Cu (Figure 7-13 grassland and Figure 7-14 arable crops). For zinc, strong reductions are observed in the long term for grassland on all sandy soils, while an increases of Zn leaching occurred for most grassland scenarios on clay soils (Figure 7-11). Apparently, on grassland the initial zinc content of soils was not in line with the zinc load due to the high changes in all scenarios. For all scenarios on arable land (Figure 7-12) an increase is predicted after 100 years, especially in Italy due to the high zinc concentrations in digestate (appendix B). However, the most important conclusion is that in all cases (grassland and arable land on all soil types) the introduction of BBFs are comparable to the reference scenario (digestate + mineral fertiliser) or (slightly) better, i.e. less leaching occurs. Zn leaching can significantly minimised by implementing P equilibrium fertilisation in Italy on arable land (Figure 7-12; A&S compared to A&S_P).

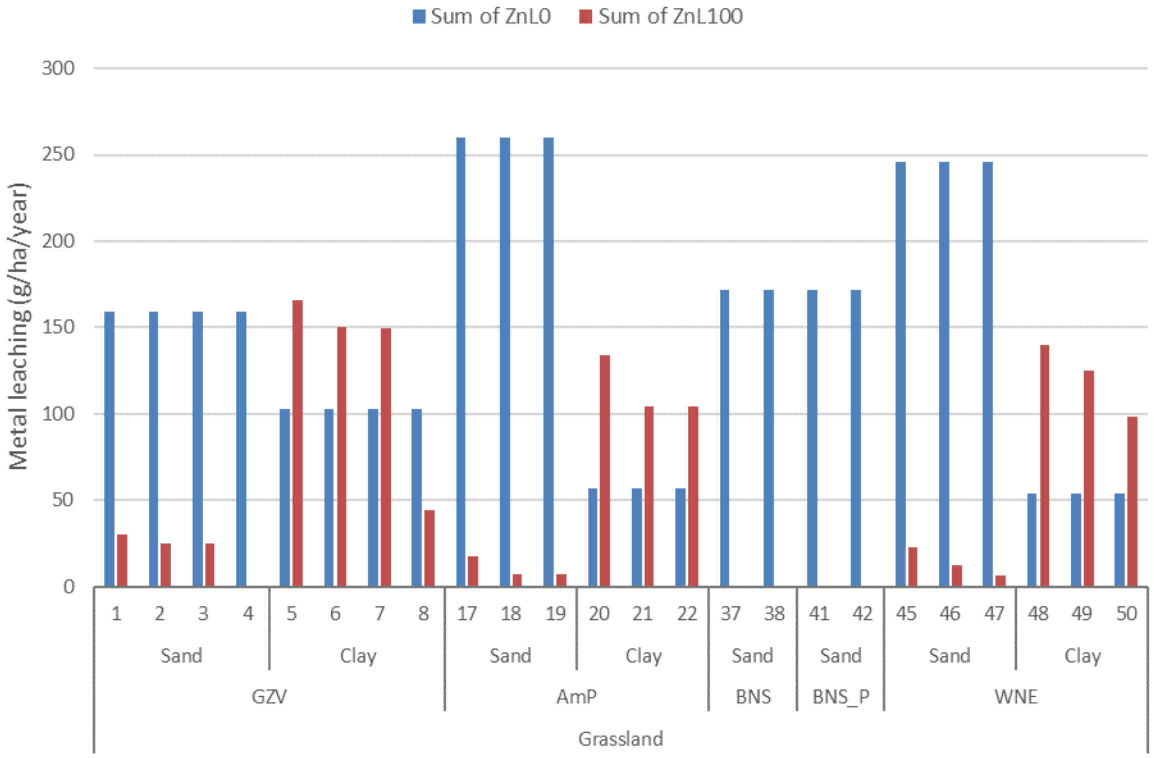

Figure 7-11 Leaching of zinc (Zn) (g ha^{-1} y^{-1}) for all grassland scenarios at t=0 (ZnL0; blue bars) and after 100 years (ZnL100; red bars) for demonstration plants Groot Zevert Vergisting (GZV), Am-Power (AmP), BENAS (BNS) and Waterleau NewEnergy (WNE).

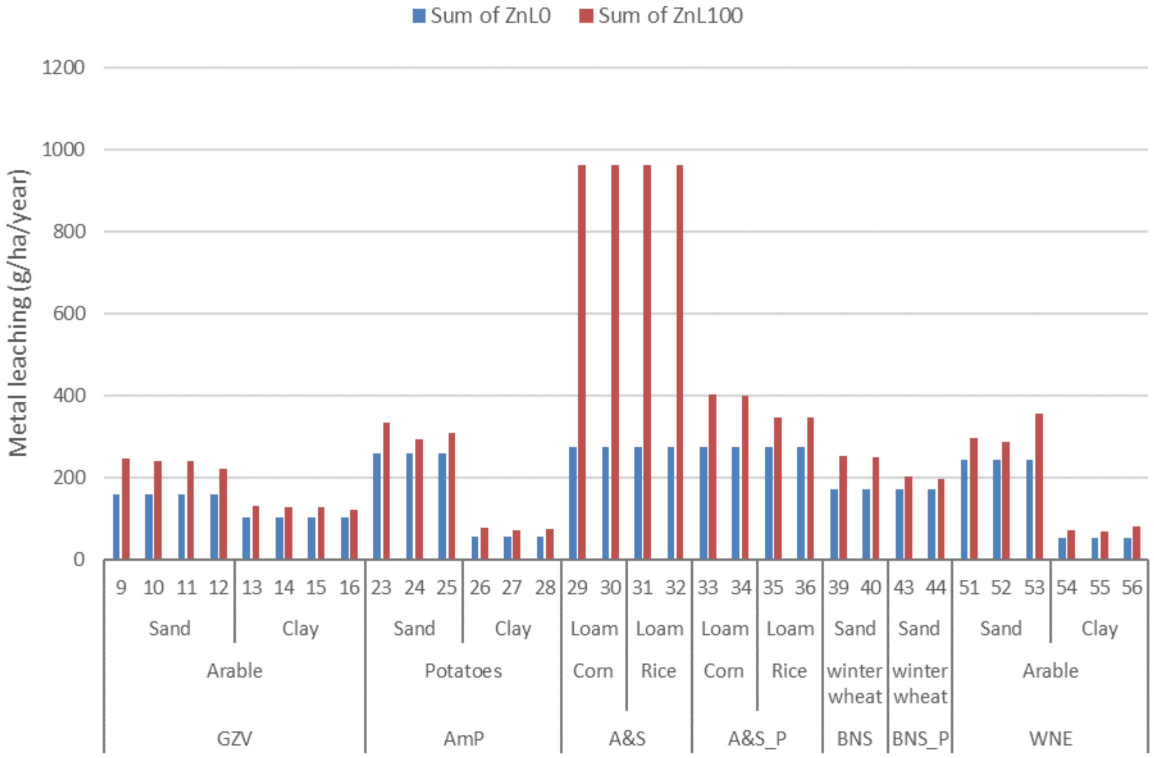

Figure 7-12 Leaching of zinc (Zn) (g ha^{-1} y^{-1}) for all arable crops scenarios at t=0 (ZnL0; blue bars) and after 100 years (ZnL100; red bars) for demonstration plants Groot Zevert Vergisting (GZV), Am-Power (AmP), Acqua & Sole (A&S), BENAS (BNS) and Waterleau NewEnergy (WNE).

For copper in almost all scenarios there is a (limited) increase of the leaching after 100 years (Figure 7-13 grassland and Figure 7-14 arable crops). Introduction of BBFs always gives a better performance compared to the reference (digestate + mineral fertilisers) except if soil conditioners are used at WNE on arable land a small increase is predicted (scenario 53 and 54). The increase of Cu leaching is relatively high for Acqua & Sole in all scenarios due to the relatively high amounts of copper applied in combination with the relatively low initial Cu content in the soil based. However, both the reference situation as well as the scenario with BBF are high. This is caused by the same amount of digestate used. In this case P equilibrium fertilisation will also have a huge effect on the Cu losses by leaching. A substantial decrease of Cu leaching is also predicted on arable land (GZV) in the case where digestate is substituted by organic matter which a low P content (after P recovery; scenario 4 and 8).

It can be concluded that the impact of heavy metals on losses does not change much by introducing BBFs as substitute for digestate or synthetic mineral fertilisers if P equilibrium fertilisation is applied. Even for Zn and Cu, important heavy metals that are often added as nutrients to feed, the changes are limited or show a positive effect on the losses. However, high inputs of these elements can increase leaching in the long term, but this also occurs in the reference situation.

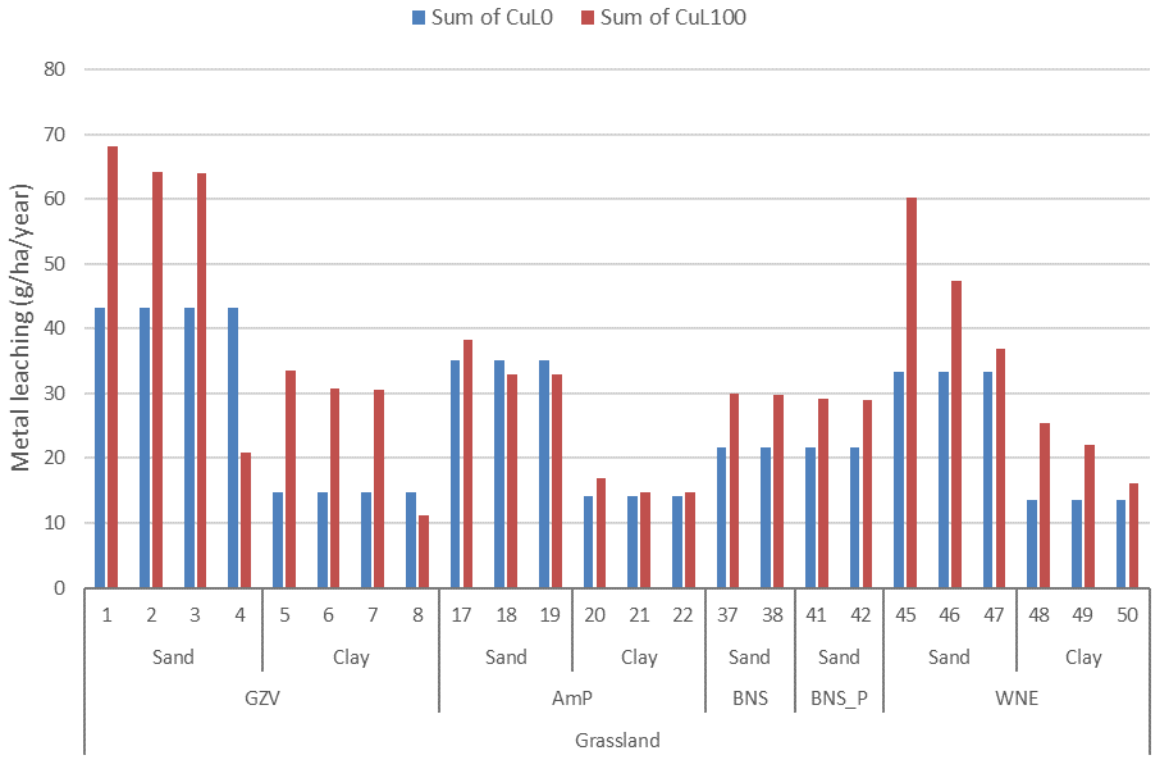

Figure 7-13 Leaching of copper (Cu) (g ha^{-1} y^{-1}) for all grassland scenarios at t=0 (CuL0; blue bars) and after 100 years (CuL100; red bars) for all scenarios for demonstration plants Groot Zevert Vergisting (GZV), Am-Power (AmP), BENAS (BNS) and Waterleau NewEnergy (WNE).

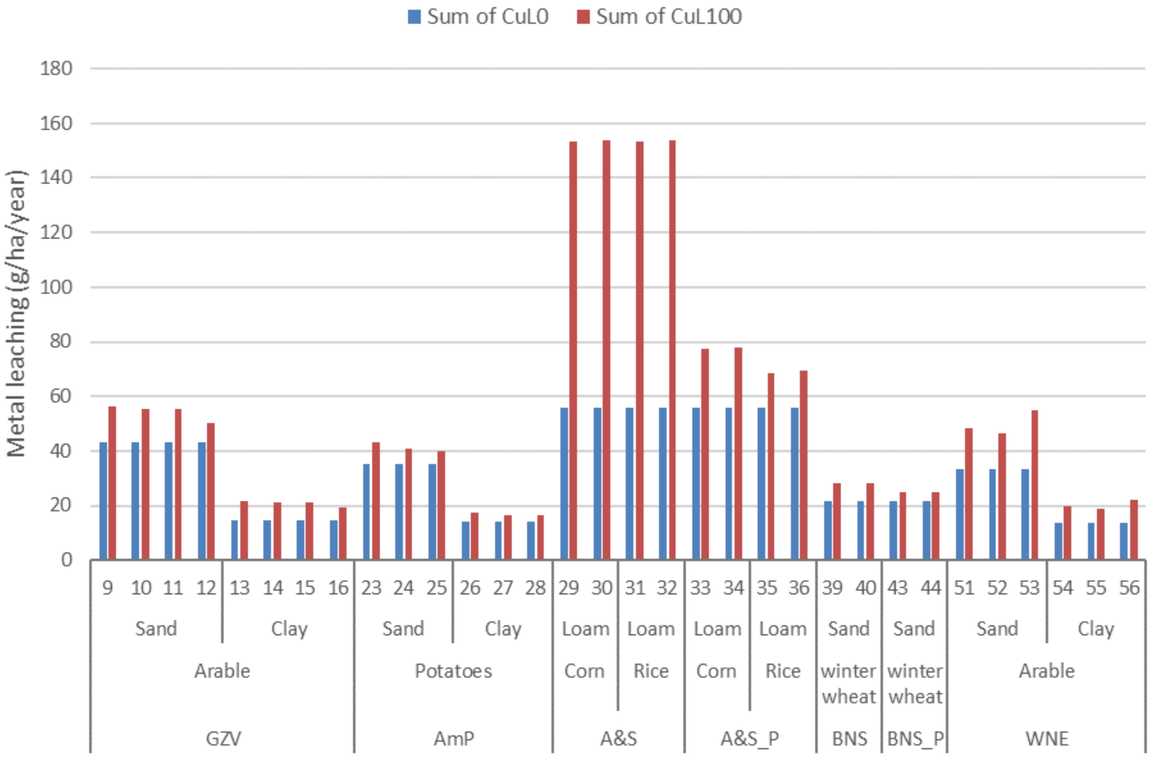

Figure 7-14 Leaching of copper (Cu) (g ha^{-1} y^{-1}) for all arable crops scenarios at t=0 (CuL0; blue bars) and after 100 years (CuL100; red bars) for demonstration plants Groot Zevert Vergisting (GZV), Am-Power (AmP), Acqua & Sole (A&S), BENAS (BNS) and Waterleau NewEnergy (WNE).

7.4 Carbon sequestration

For each scenario, the change in soil carbon stock of the rootzone (25 cm) over time was evaluated. In all grassland scenarios, regardless of the demonstration plant or the products used, the soil organic carbon (SOC) content is expected to increase (Figure 7-15). The highest increase of the carbon stock is simulated on soils with the lowest carbon content. However, differences between reference scenarios and scenarios with biobased fertilisers are minimal. This is most likely due to the fact that most organic carbon comes from crop residues (below and above soil level), reducing the impact of carbon from fertilisers (Figure 7-17). Grassland is covered by grass the whole year round, resulting in more residues remaining in the soil and contributing to the soil organic carbon stock than usually occurs in arable land.

For most arable land scenarios of Groot Zevert Vergisting, AmPower and Waterleau NewEnergy, the model results show a decrease in SOC (Figure 7-16). Usually, thus, more SOC breaks down than *effective* OC is applied. For Acqua & Sole and BENAS and one of the scenarios of GZV (number 12), a (slight) increase in SOC is predicted. This is partly due to larger applications of organic carbon via fertilisers in addition to crop residues (Figure 7-18) and for some scenarios also due to lower initial SOC contents: the lower the initial organic carbon content of the soil, the less OC needs to be applied to maintain or increase the SOC stock. Again, often the difference between reference scenarios and scenarios with biobased fertilisers is limited, although somewhat more for arable scenarios than for the grassland scenarios. In the scenarios where 10 tonne of low P soil conditioner of GZV is used on arable land (scenario 12 and 16), there is a clear positive effect on SOC compared to the reference (Figure 7-16). For BENAS the SOC remains stable, while for Acqua & Sole the SOC increases due to the relatively high OC inputs (Figure 7-18).

When looking into the model results, one should however take into account that, like for all models, the RothC model is a simplification of reality and that therefore results may differ in practice. The model results mainly indicate that differences between reference and biobased scenarios are limited, because the contribution of crop residues to the SOC stock is more important than the contribution of BBFs.

Overall, the modelling results show that attempts to increase soil SOC content by using low-N digestates (BENAS, Aqua&Sole) or low-P soil improvers (GZV) have some effect on SOC content, but the difference with the reference (digestate) is limited for BENAS and Acqua & Sole and more clearly for low-P soil improvers of GZV.

The amounts of CO_2 emissions to the air due to decomposition of the organic materials (including crop residues) varies between 2.4 and 6.0 ton C ha^{-1} (at t=0; all scenarios). After 100 years the values varies between 2.2 and 6.4 ton C ha^{-1}.

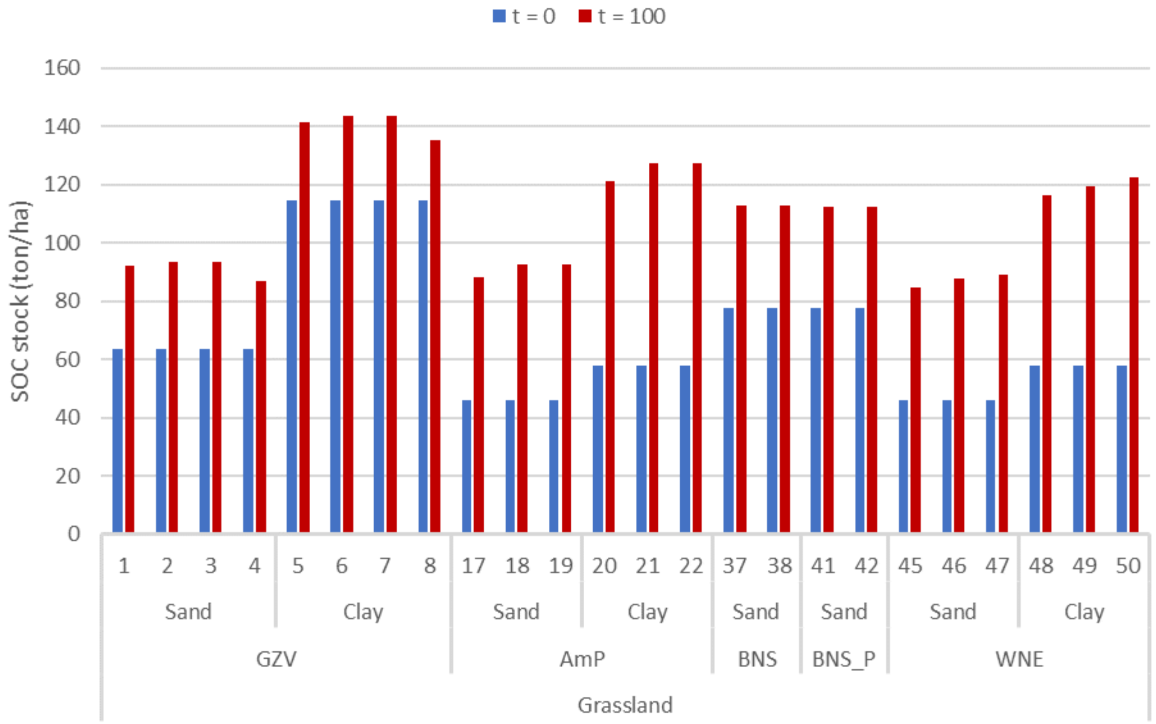

Figure 7-15 The soil organic carbon (SOC) stock (tonne ha^{-1}) for all grassland scenarios at t = 0 (blue bars) and t = 100 year (red bars), for demonstration plants Groot Zevert Vergisting (GZV), Am-Power (AmP), BENAS (BNS) and Waterleau NewEnergy (WNE).

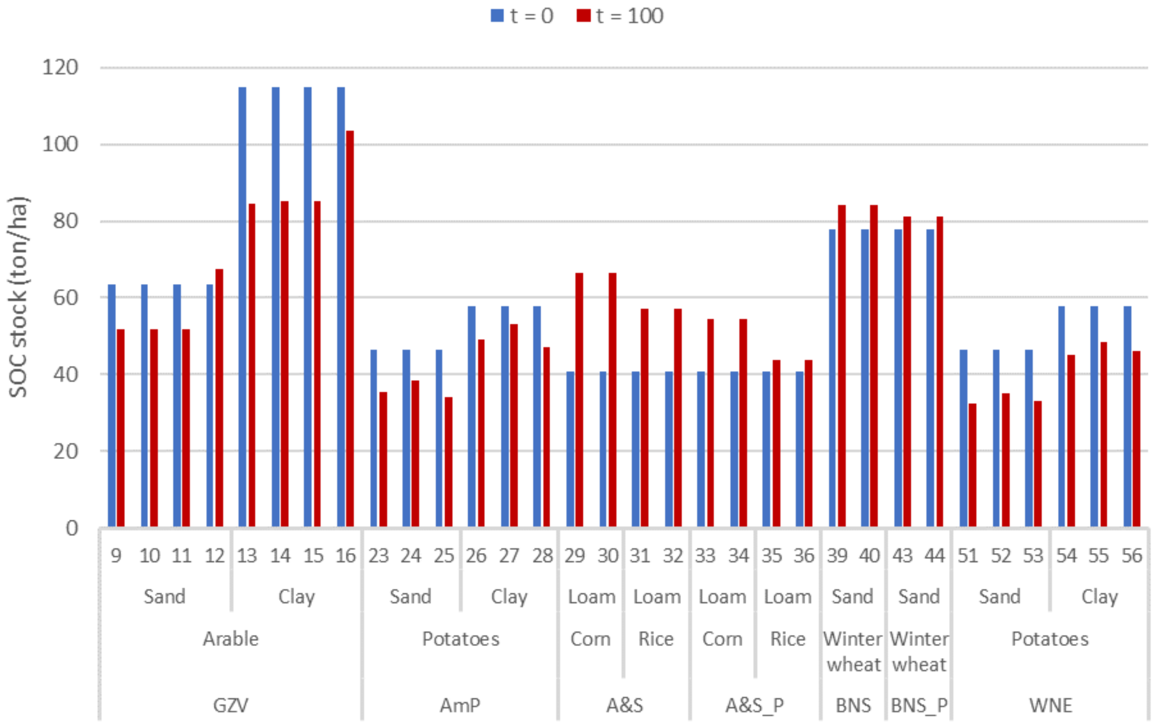

Figure 7-16 The soil organic carbon (SOC) stock (tonne ha^{-1}) for all arable land scenarios at t = 0 (blue bars) and t = 100 year (red bars), for demonstration plants Groot Zevert Vergisting (GZV), Am-Power (AmP), Acqua & Sole (A&S), BENAS (BNS) and Waterleau NewEnergy (WNE).

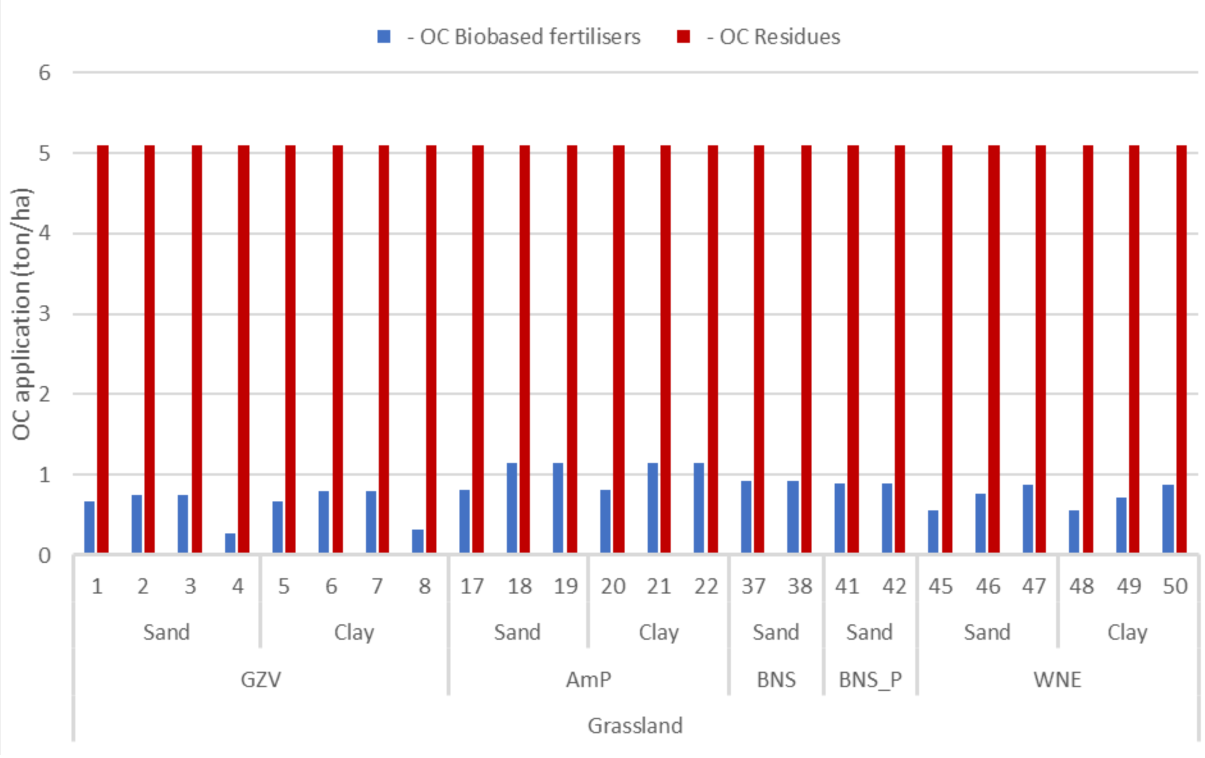

Figure 7-17 The application of organic carbon (OC) (tonne ha^{-1}) resulting from organic fertilisers (blue bars) and crop residues (red bars) for all grassland scenarios, for demonstration plants Groot Zevert Vergisting (GZV), Am-Power (AmP), BENAS (BNS) and Waterleau NewEnergy (WNE).

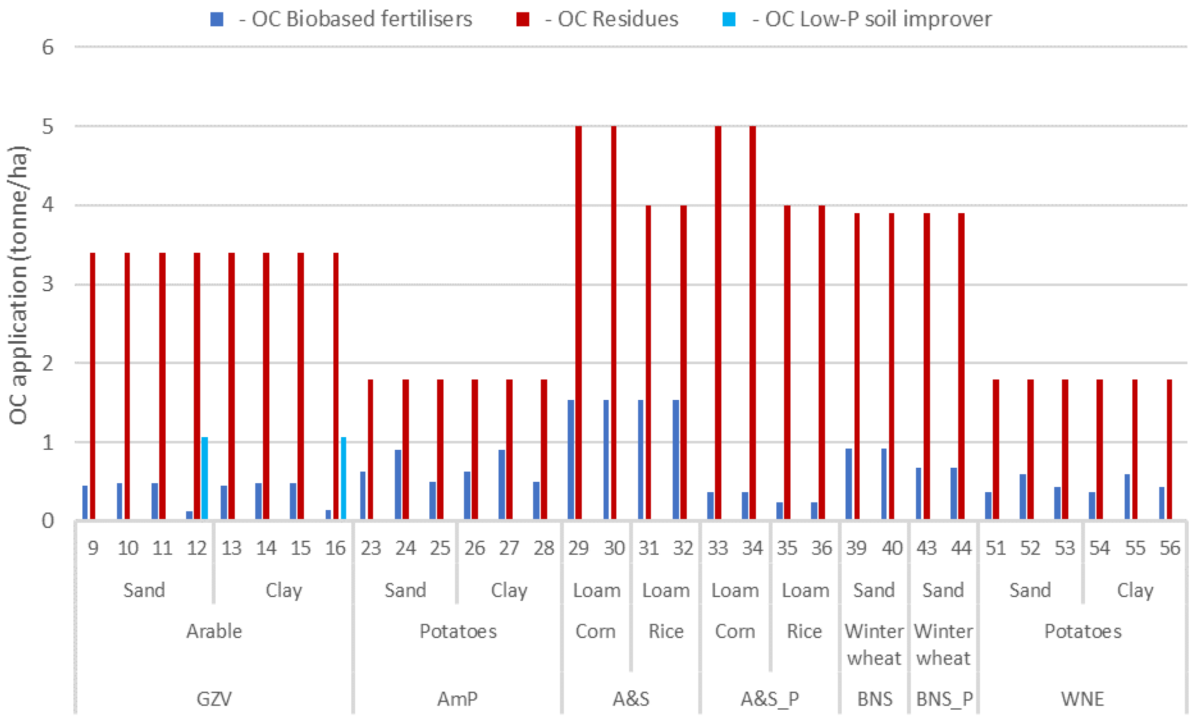

Figure 7-18 The application of organic carbon (OC) (tonne ha^{-1}) resulting from organic fertilisers (blue bars), crop residues (red bars) and Low-P soil improver (light blue bars) for all arable land scenarios, for demonstration plants Groot Zevert Vergisting (GZV), Am-Power (AmP), Acqua & Sole (A&S), BENAS (BNS) and Waterleau NewEnergy (WNE).

8 Discussion

The defined scenarios, where both synthetic mineral fertilisers and digestate are partly or completely substituted by biobased fertilisers produced by the demonstration plants, will always cause changes in load of nutrients (including forms of nutrients) and heavy metals to the soil due to differences in product composition. Consequently, there will be a change in losses to the air, accumulation or depletion in the soil and losses from the rootzone to deeper groundwater. The results of the scenarios with BBFs are compared to the reference scenarios where just a combination of digestate and mineral fertilisers are used.

The amounts of nitrogen applied in each of the scenarios is always in line with legislation. For manure based products the amount of total N in terms of manure or manure-based digestate is clearly set in the EU Action Plans of the Nitrates Directive for Nitrate Vulnerable Zones. The total amounts of nitrogen that effectively can be applied (by taken into account the legislative nitrogen fertiliser replacement values) are also defined in these Action Plans. However for the non-manure based fertilisers, such limitations had to be taken from other sources/references, and this has resulted in different NFRV values of digestates from different feedstock varying from 50% – 80%, soil improvers 10% – 30% and finally 100% for ammonium sulphate and RO concentrate, while in Flanders 60% is used for evaporator concentrate (as presented in Table 3-2). Changes in these values will directly impact the amounts of products applied and the additional amount of synthetic mineral fertiliser needed to meet with the soil-crop requirements. As a result, the predicted values of emissions have to be compared with the reference of a similar soil-crop combination, since, for example, the reference conditions between the same soil-crop combination will differ between countries/demonstration pilot. This is clearly illustrated in section 5.4 regarding the applied amounts of nutrients and heavy metals.

The calculated amounts of phosphorus (P), potassium (K) and sulphur (S) are often not limited by legislative application standards and minimum values were set in order to meet with the crop requirements. In the whole of the Netherlands and a part of Belgium (phosphate saturated areas, in Flanders) legislative limits are set for P. In all Dutch and Flemish scenarios these P limits are set a maximum. Due to the omission of P limits in Italy and Germany, high P loads of the soil are calculated to meet with crop N requirements and/or N-limits. In Italy, especially, the P applications can be 5-7 times higher compare to P harvested. It is clear that that, in the long term, soils will be loaded with P and extreme high P losses can occur, like is already the case in the Netherlands and Belgium. Therefore, additional P equilibrium scenarios were included in the study for Italy and Germany (indicated as A&S_P and BNS_P), although the impact on changes in P load in Germany is limited. In the Netherlands and Flanders, P restrictions determine the amount of digestate that can be applied due to the high P-N ratio of digestate. If P equilibrium fertilisation is included in Italy and Germany, the amount of digestate that can be applied is also restricted. On grassland, the P losses to groundwater will decrease over time due to the negative P balances (P application minus amount of P in harvested crops). A new equilibrium will be reached with lower P harvest and lower P leaching. A positive P balance will increase the P accumulation over time, and as a result the P losses will increase. However, in all cases the differences with the reference scenario are minimal. So, replacing synthetic mineral fertiliser or digestate by recovered products has a negatable impact on the P losses.

The ammonia (NH_3) emission factions highly depend on the application technology used on the fields. In this study, best application technologies with lowest emission are assumed for all products, which has been defined for all demonstration plants in all countries (section 4.4; Table 5-4). The NH_3-emissions calculated for the biobased scenarios are reduced on grassland compared to the reference scenarios, except when RO concentrate of GZV or evaporator concentrate of Am-Power is applied. However in the reference scenarios synthetic fertiliser CAN is used, which contains 50% NO_3, reference scenarios have relatively low NH_3-emissions. In the case where urea is used as reference mineral fertiliser, introduction of BBFs will always give a reduction in NH_3 emission compared to the reference scenario. On arable land the NH_3-emissions are lower compared to grassland and small differences are calculated between the scenarios, both slightly positive as well as negative. Only soil improver application could lead to an increase of NH_3-emissions. It can be expected that the produced N-rich biobased fertilisers will not lead to additional NH_3-emission: in most situations the emissions will be lower compared to urea.

Based on the nitrous oxides (N_2O) emission factors of different types of products (see section 4.5) and the composition and amount of product applied, the modelled results shows that N_2O emissions differ between the scenario's. Both positive and negative effects are found for BBFs compared to the reference scenario with digestate and CAN as mineral N fertiliser. A positive effect (fewer emissions) is predicted in cases where large amounts of synthetic fertiliser CAN or digestate are replaced by the biobased fertilisers due to differences in emission factors and amounts of total N applied. In cases where the substitution of digestate is limited, an increase in N_2O emissions is predicted, although the changes are limited Figure 7-5 and Figure 7-6.

The rootzone nitrogen surplus (all N_{inputs} minus $N_{NH3\text{-}emissions}$ minus N_{crop}) determines the potential N losses to groundwater in the form of nitrates. The fraction of N that will leach from the rootzone to groundwater depends on land use (f_{lu}), precipitation (f_p), rooting depth (f_r), temperature (f_t), and organic C content of the soil (f_c). Nitrate leaching concentrations (mg NO_3 per litre) are relatively low in grassland fields compared to arable fields, and the nitrate concentrations in clay soils are also lower compared to sandy soils (and loamy soils are in-between). Low nitrate losses under grassland are caused by the high denitrification capacity in grassland fields (large amounts of easily decomposable organic matter available; e.g. exudates). Clay soils often have a higher moisture content during the year, which causes higher denitrification compared to sand or loam. On grassland, no severe NO_3 leaching changes are modelled by replacing synthetic mineral fertiliser or digestate by recovered BBF fertilisers, although a substitution of mineral N fertiliser by evaporator concentrate in the case of Am-Power can lead to an increase of applied N and a subsequent substantial increase in nitrate leaching. On the other hand, evaporator concentrate of Waterleau NewEnergy reduces nitrate leaching on grassland slightly. On arable land, the nitrate losses are relatively high. However, the differences between the reference scenario and scenario with biobased fertilisers are often small. However, introducing evaporator concentrate of Am-Power causes an increase in nitrate leaching on arable land because, in that specific situation, about 70 kg total N per ha per year can be more applied compared to the reference situation, while the amount of N_{eff} applied is always the same (Table 6-5).

Many parameters determine the leaching of each heavy metal (section **Error! Reference source not found.**). In this study the heavy metals that have been parametrised for the model were taken into. The scenarios do not show substantial changes in Chrome (Cr), Arsenic (As), Lead (Pb) and Cadmium (Cd). The changes of nickel (Ni) content in the soil and leaching over 100 years are small, except for Italian scenarios on loamy soils with relatively high Ni loads in applied digestate. The heavy metals zinc and copper, which are also micronutrients for crops, show the most important changes in losses in the long term, both positive as well as negative, but the changes are limited except for Acqua & Sole (negative impact; Zn) due to the high inputs both in the reference conditions as well in other scenarios. Zinc leaching can be significantly minimised by implementing P equilibrium fertilisation (Figure 7-14; A&S compared to A&S_P). In most of the scenarios there is a small increase in Cu accumulation, and consequently in copper leaching after 100 years. Introducing P equilibrium fertilisation will substantially reduce the input of heavy metals and the associated leaching from soils to groundwater. However, in almost all cases (grassland and arable land on all soil types) substitution of digestate and/or mineral fertilisers by produced biobased fertilisers result in lower leaching of heavy metals.

The impact of changing the amount of fertilisers has a limited effect on soil organic carbon (SOC) content in the rootzone because the organic matter supply is often limited compared to the amount of crop residues. On grassland, the SOC increases over 100 years, because relatively large amounts of root residues are accumulating in the rootzone, but differences between the biobased fertiliser scenarios and the reference scenario are relatively small in all situations. On arable land the results vary, both increases (low-N digestates of Acqua & Sole and BENAS; low-P soil improver on sandy soils) as well as decreases are modelled since the organic supply by fertilisation is relatively more important compared to crop residues, but, also in these scenarios, the difference between the reference scenario and the scenario of BBFs is small. Only in the case where low-P soil improvers (GZV) are used is SOC predicted to be substantially higher compared to the reference scenario.

The emissions and accumulation of nutrients potassium (K) and sulphur (S) are not modelled in our study, but the loads have been assessed and compared to crop requirements. The surpluses of potassium are limited in our scenarios and no severe environmental aspects are expected. However, high sulphate loads are calculated in situations where ammonium sulphate is used as nitrogen source (section 5.4). There are no legal restrictions on S with respect to agricultural applications, but high levels should be avoided because high concentrations will leach out together with associated Ca and Mg, leading to acidification of the top soil layer and subsequently to an additional liming requirement . Sulphate losses can also have a negative impact on drinking water extraction and can contribute indirectly to eutrophication of surface waters.

Sulphate concentrations of between 500 and 1000 mg/l in drinking water may cause a laxative effect in adults and children (WHO, 2004) and it is advised to avoid concentrations above 500 mg SO_4/l. However, no human toxicological threshold for sulphate in drinking water has been set. The EU has set a drinking water standard of 250 mg/l for sulphate. This standard is not based on toxicity levels, but on technical and organoleptic requirements to produce drinking water (EU Directive 98/83/EC). In permanent groundwater (anaerobic conditions) where decomposable organic material is available, sulphate will be reduced into sulphide (S^{2-}). Sulphide is a well-known natural toxin for both plants and aquatic organisms (macrofauna). However, in the deeper layers, sulphides can react with available iron(hydr)oxides or iron precipitates (e.g. $FeHPO_4$) resulting into poorly soluble pyrite (FeS_x). As a site effect, extra phosphate can leach out which can contribute to eutrophication of fresh water systems. Although there are no direct legal limitations for the use of sulphur/sulphate on agricultural land, excessive loads should be prevented by applying according to crop requirements, which vary between crops (e.g. maize 12 kg S/ha, cereals 20 kg S /ha, leek 24 kg S/ha, grass 20 – 40 kg S/ha, cauliflower 50 kg S/ha, Rapeseed 20 – 40 kg S/ha, Brussels sprouts 50 to 80 kg/ha).

In a sustainable circular economy, and also a linear economy!, the application of each of the required nutrients should not go beyond the crop requirement of that specific nutrient, because the nutrient accumulation and losses will always increase in the long term if no additional measures are taken.

9 Conclusions

Based on the described methodology and results of the environmental impact assessment of produced biobased fertilisers on soil, water and climate, the following main conclusions can be made:

- Although there are no differences in the amount of effective nitrogen applied in the soil-crop combinations among assessed scenarios, the amount of total nitrogen (N) and ammonium (N-NH_4) applied may differ due to differences in legislative Nitrogen Fertiliser Replacement Values (NFRVs) of the products and the composition of the products. Mainly, the differences in total N and N-NH_4 application lead to differences in N emissions as ammonia (NH_3) and nitrous oxides (N_2O) to the air, and losses from the rootzone as nitrate, since these two parameters are the main driving forces of N losses.

- If there is no limit regarding maximum phosphorus (P) total applications (Italy and Germany), high P surpluses can occur up to 5-7 times higher than the amount of harvested P in crops (Italy), which will cause severe P leaching problems in the long term as modelled in this study. Therefore, additional scenarios were implemented to showcase the impact of P equilibrium fertilisation for demonstration plants Acqua & Sole (Italy) and BENAS (Germany). These show that P losses can be reduced, especially in Italy.

- Using ammonium sulphate as nitrogen source will often lead to sulphur (S) applications above crop requirements, which should be avoided to minimise S losses. Since in none of the countries S fertilisation application restriction are used, this is not included within the scenario analysis reported here. High S loads can occur if large amounts of ammonium sulphate are used, but also evaporator concentrate can increase S losses as well as low-P soil conditioner.

- It is expected that the application of produced nitrogen rich biobased fertilisers will not lead to additional ammonia (NH_3) emission, especially not if fully ammonium based mineral fertilisers are used as reference (urea) instead of calcium ammonium nitrate (CAN) (which contains 50% N-NO).

- In general, the impact of the different combinations of fertilisers used in the defined scenarios is also limited regarding the predicted nitrous oxides (N_2O) emissions (both slightly negative/positive); only in the case where a substantial amount of mineral fertiliser (CAN/urea) or digestate is replaced by N-rich biobased fertilisers (BBFs) is the impact is substantially positive (lower N_2O emissions predicted).

- Substitution of synthetic mineral fertiliser by biobased nitrogen fertilisers often shows similar or lower nitrate leaching for the demonstration plants GZV (RO concentrate), BNS, A&S (both ammonium sulphate) and WNE (evaporator concentrate), while for Am-Power (evaporator concentrate) an increase is predicted due to the high increase of total N applied. In fact, differences in composition of evaporator concentrate between Am-Power and Waterleau NewEnergy is highly determinate of what can be applied (amount total N) linked to national application limits, and consequently the main differences on nitrate leaching.

- The leaching of heavy metals chrome (Cr), arsenic (As), lead (Pb) and cadmium (Cd) don’t change much over time. Both slightly positive and negative effects are predicted for zinc (Zn), and almost always limited negative effects for copper (Cu) and nickel (Ni). The scenarios with digestate of sewage sludge shows relative high losses of Ni, Cu and Zn compared to the other scenarios.

However, in almost all cases (grassland and arable land on all soil types) substitution of digestate and/or mineral fertilisers by produced biobased fertilisers result in lower leaching of heavy metals.

- Overall, the modelling results show that, on grassland, the soil organic carbon content will increase, which is mainly caused by high attempts to increase on grassland the soil organic carbon (SOC) content, which is mainly caused by the large contribution of crop residues on grassland compared to the inputs of organic carbon via fertilisation. On arable land, the results for SOC vary. Using low-N digestates (BENAS, Aqua&Sole) or low-P soil improvers (Groot Zevert Vergisting) have some positive effect on SOC content, but the difference with the reference (digestate) is limited for BENAS and Acqua & Sole and more clearly for low-P soil improvers of GZV.

In general it can be concluded that application of produced biobased fertilisers of the demonstration plants as substitute for digestate and/or mineral fertilisers (reference conditions) give often quite similar results in terms of emissions to the air, nitrate and phosphate losses and heavy metal losses. Sometimes the performance is better, and sometimes a negative impact is predicted depending on the soil-crop combination and the composition of the biobased fertilisers (which differ remarkably).

In none of the situations all crop-requirements can be exactly met, even not in the reference scenarios, which can cause, in some cases, over-fertilisation in terms of phosphate, sulphate and/or heavy metals. In the cases where P equilibrium fertilisation is taken into account together with the N recommendations, situations with additional P losses and heavy metal losses were solved. If ammonium sulphate is used as biobased fertiliser, it is recommended to consider crop specific sulphur recommendations in order to limit sulphate losses.

In a sustainable circular economy, and also a linear economy!, the application of each of the required nutrients should not go beyond the crop recommendations of that specific nutrient, because in the long term the nutrient loss will always increase if no additional measures are taken. Under these conditions, there are no negative impacts expected of the produced biobased fertilisers by the demonstration plants.

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Appendices

Appendix A MITERRA-Europe model application

Table A.1 Recent model applications

Project	**Financier**	**Period**	**Description**
Carbon impact biomass use	EU DG ENER	2013-2015	The principal objective of this study is to deliver a qualitative and quantitative assessment of the direct and indirect GHG emissions associated to different types of solid and gaseous biomass used in electricity and heating/cooling in the EU under a number of scenarios. In this study MITERRA-Europe is used to quantify the GHG impact of agricultural biomass use.
AnimalChange	EU FP7	2011-2015	AnimalChange focusses on the integration of mitigation and adaptation options for sustainable livestock production under climate change. In this FP7 project the MITERRA-Europe model is used to assess the LCA based emissions of livestock production for the EU-27, Africa and Latin America.
SmartSOIL	EU FP7	2011-2015	SmartSOIL focuses on arable and mixed farming systems in Europe and will develop an innovative approach using the soil C flow and stocks concept to assess the impact of C management on crop productivity, soil organic C stocks and other ecosystem services. In this project the soil carbon RothC model was incorporated in MITERRA-Europe for the assessment of soil carbon stock changes.
Bioenergy potential assessment	EEA	2010-2012	This project assessed the agricultural biomass potential in EU taking account of sustainability criteria, including GHG mitigation levels and iLUC factors, and assesses environmental effects in relation to water, air, soil using the MITERRA-Europe model.
EUruralis	Dutch gov.	2004-2010	The Eururalis project (http://www.eururalis.eu) provides a tool to examine the impact of policies on rural areas for the EU-27. In one of the studies the MITERRA-Europe model was linked to assess the effect of future climate and policy scenarios on GHG emissions (Lesschen et al., 2009).
PICCMAT	EU DG Agri	2007-2008	The PICCMAT (Policy Incentives for climate change mitigation techniques) project assessed the effectiveness for climate change mitigation of a range of possible changes to land management practices. In this project the MITERRA-Europe model was extended with a soil organic carbon module.

Appendix B Heavy metal composition of biobased fertilisers produced by the SYSTEMIC demonstration plants.

Table B.1 Heavy metal compositions of digestate, mineral fertilisers and biobased end products produced by the SYSTEMIC demoplants (n.m. = not measured), including zinc (Zn)*, lead (Pb), nickel (Ni), manganese (Mn), mercury (Hg), copper (Cu), chrome (Cr), cobalt (Co), cadmium (Cd) and arsenic (As), expressed in dry weight contents.*

Parameters		Groot Zevert Vergisting	Am-Power	Waterleau NewEnergy	Acqua & Sole	BENAS
Digestate		*Digestate*	*Digestate*	*Digestate*	*Digestate*	*Digestate*
Zn	(mg/kg DM)	693	337	772	1060	328
Pb	(mg/kg DM)	<5	<13	9.7	70	6.0
Ni	(mg/kg DM)	15	15	14	54	8.7
Mn	(mg/kg DM)	470	246	506	464	774
Hg	(mg/kg DM)	<0.05	n.m.	0.017	<1.3	0.020
Cu	(mg/kg DM)	325	76	266	347	54
Cr*	(mg/kg DM)	16	16	33	74	6.9
Co	(mg/kg DM)	1.5	2.4	2.5	6.2	2.6
Cd	(mg/kg DM)	<0.4	<1.3	0.50	0.87	<1.5
As	(mg/kg DM)	<1	n.m.	1.2	7.7	1.0
(Organo-) Mineral Nitrogen		*RO concentrate*	*Evaporator Concentrate*	*Evaporator Concentrate*	*Ammonium sulphate*	*Ammonium sulphate*
Zn	(mg/kg DM)	<550	118	772	<23	0.5
Pb	(mg/kg DM)	<5.1	<5.1	9.7	<2.8	0.1
Ni	(mg/kg DM)	14	15	14	<3.0	1.0
Mn	(mg/kg DM)	<110	105	506	6.7	1.2
Hg	(mg/kg DM)	<0.058	n.m.	0.017	<0.69	n.m.
Cu	(mg/kg DM)	<100	30	266	<14	0.2
Cr*	(mg/kg DM)	<5.1	7.3	33	<0.64	0.1
Co	(mg/kg DM)	<2	3.0	2.5	<0.28	0.0
Cd	(mg/kg DM)	<0.41	<0.51	0.50	<0.56	<0.090
As	(mg/kg DM)	<1.1	n.m.	1.2	<2.7	n.m.
Organic products		*Low-P soil improver*	*Dried SF of digestate*	*Dried SF of digestate*		
Zn	(mg/kg DM)	268	405	772		
Pb	(mg/kg DM)	<5	<1.7	9.7		
Ni	(mg/kg DM)	7.0	15	14		
Mn	(mg/kg DM)	130	322	506		
Hg	(mg/kg DM)	<0.05	n.m.	0.017		
Cu	(mg/kg DM)	70	86	266		
Cr*	(mg/kg DM)	7.0	25	33		
Co	(mg/kg DM)	<1	1.4	2.5		
Cd	(mg/kg DM)	<0.4	<0.17	0.50		
As	(mg/kg DM)	<1	n.m.	1.2		

*Cr-VI is not explicitly modelled

Table B.1 Heavy metal compositions of digestate, mineral fertilisers and biobased end products produced by the SYSTEMIC demonstration plants (n.m. = not measured), including zinc (Zn), lead (Pb), nickel (Ni), manganese (Mn), mercury (Hg), copper (Cu), chrome (Cr), cobalt (Co), cadmium (Cd) and arsenic (As), expressed in fresh weight contents

Parameters		Groot Zevert Vergisting	Am-Power	Waterleau NewEnergy	Acqua & Sole	BENAS
Digestate		*Digestate*	*Digestate*	*Digestate*	*Digestate*	*Digestate*
Zn	(mg/kg FW)	54	27	25	113	33
Pb	(mg/kg FW)	<0.4	<1.1	0.2	7.4	0.7
Ni	(mg/kg FW)	1.2	1.2	0.9	5.8	0.9
Mn	(mg/kg FW)	37.5	20	16	50	78
Hg	(mg/kg FW)	<0.004	n.m.	<0.001	<0.14	0.0
Cu	(mg/kg FW)	15	6.0	9.0	37	5.5
Cr*	(mg/kg FW)	1.2	1.7	0.8	7.9	0.7
Co	(mg/kg FW)	0.1	0.2	0.2	0.7	0.3
Cd	(mg/kg FW)	<0.03	<0.11	<0.39	0.1	<0.18
As	(mg/kg FW)	<0.08	n.m.	0.1	0.8	0.1
(Organo-) Mineral Nitrogen		*RO concentrate*	*Evaporator Concentrate*	*Evaporator Concentrate*	*Ammonium Sulphate*	*Ammonium sulphate*
Zn	(mg/kg FW)	<5	15	32	<8.5	0.1
Pb	(mg/kg FW)	<0.18	<0.6	0.7	<1	0.0
Ni	(mg/kg FW)	0.5	1.9	4.1	<1.1	0.2
Mn	(mg/kg FW)	<1	12	19	2.4	0.3
Hg	(mg/kg FW)	<0.0018	n.m.	0.0	<0.25	n.m.
Cu	(mg/kg FW)	<1	4.3	10	<5	0.0
Cr*	(mg/kg FW)	<0.18	1.0	1.4	<0.23	0.0
Co	(mg/kg FW)	<0.035	0.4	0.6	<0.1	0.0
Cd	(mg/kg FW)	<0.014	<0.06	0.1	<0.2	<0.021
As	(mg/kg FW)	<0.036	n.m.	0.1	<0.98	n.m.
Organic products		*Low-P soil improver*	*Dried SF of digestate*	*Dried SF of digestate*		
Zn	(mg/kg FW)	57	321	721		
Pb	(mg/kg FW)	<1.2	<1.2	8.8		
Ni	(mg/kg FW)	1.7	12	12		
Mn	(mg/kg FW)	30.0	256	456		
Hg	(mg/kg FW)	<0.012	n.m.	0.0		
Cu	(mg/kg FW)	14	70	241		
Cr*	(mg/kg FW)	1.7	20	29		
Co	(mg/kg FW)	<0.24	1.1	2.4		
Cd	(mg/kg FW)	<0.09	<0.12	0.3		
As	(mg/kg FW)	<0.24	n.m.	0.7		

*Cr-VI is not explicitly modelled

Appendix C Heavy metal content of crops

1) Cd, Cu and Zn

$HM_{content,\ crops} = 10 \wedge (\gamma_0 + \gamma_1 * \text{pH-KCL} + \gamma_2 * \text{LOG}(\%\text{OM}) + \gamma_3 * \text{LOG}(\%\text{clay}) + \gamma_4 * \text{LOG}(HM_{soil,tot}))$
With
$HM_{soil,tot}$ = total amount in soil (mg.kg^{-1} ds extractable by Aqua Regia or equivalent)

Table C.1 Cd, Cu and Zn content of crops. Source: Römkens et al. (2007)

HM	Crop	γ_0	γ_1	γ_2	γ_3	γ_4
Cd	potatoes	0.970	-0.210	-0.410	-0.200	0.810
	sugarbeets	1.330	-0.220	0.000	-0.130	0.620
	wheat	0.220	-0.120	-0.330	-0.040	0.620
	maize	0.900	-0.210	0.000	-0.320	1.080
	grassland	0.17	-0.12	-0.28	0.000	0.49
	winter wheat	0.220	-0.120	-0.330	-0.040	0.620
	corn	0.900	-0.210	0.000	-0.320	1.080
	Rice	0.926	-0.212	-0.511	0.000	0.832
	Arable	1.408	-0.205	-0.461	-0.196	0.768
Cu	potatoes	0.22	-0.02	0.000	0.000	0.43
	sugarbeets	0.73	-0.03	0.000	0.000	0.30
	wheat	0.65	-0.03	0.000	0.000	0.16
	maize	0.07	0.06	0.000	-0.11	0.19
	grassland	1.41	-0.18	-0.65	0.000	0.83
	winter wheat	0.65	-0.03	0.000	0.000	0.16
	corn	0.07	0.06	0.000	-0.11	0.19
	Rice	0.512	-0.001	-0.126	0.000	0.136
	Arable	0.07	0.06	0.000	-0.11	0.19
Zn	potatoes	1.23	-0.09	-0.07	-0.15	0.34
	sugarbeets	2.69	-0.41	-0.71	-0.37	1.13
	wheat	1.32	-0.06	0.000	-0.24	0.45
	maize	1.35	-0.17	-0.14	-0.25	0.81
	grassland	2.06	-0.09	1.09	-1.05	0.41
	winter wheat	1.32	-0.06	0.000	-0.24	0.45
	corn	1.35	-0.17	-0.14	-0.25	0.81
	Rice	1.670	-0.078	-0.043	0.000	0.100
	Arable	1.35	-0.17	-0.14	-0.25	0.81

2) Pb

$Pb_{content,\ crops} = (10 \wedge (\delta 0 + \delta 1\ \text{LOG}(Pb_{soil,\ tot}))) * Pb_{soil,\ tot}$
With
$Pb_{soil,\ tot}$ = total amount in soil (mg.kg^{-1} ds)

Table C.2 Pb content of crops Source: (Otte, 2011)

Crop	δ0	δ1
Grassland	0.002	-0.8778
Arable	0.178	-1.1759
Potatoes	-1.511	-0.6859
Sugarbeets	0.318	-0.9049
Wheat	-1.392	-0.5541
Maize	0.178	-1.1759
Winter wheat	-1.392	-0.5541
Onion	-0.668	-0.916
Corn	0.178	-1.1759
Rice (all data on grains)	-1.042	-0.7066
Other (mais)	0.178	-1.1759

3) Cr, Ni, and As

Table C.3 Average Cr, Ni and As content of crops (mg kg^{-1} DS).
Source: (Van der Bolt, 2021, In Press.), for Ni and Cr: (Chu et al., 2009)

Crop	Cr	Ni	As
Grassland	0.25	0.60	0.08
Potatoes	0.25	0.60	0.05
Sugar beets	0.25	0.60	0.20
Wheat	0.25	0.60	0.05
Maize	0.25	0.60	0.10
winter wheat	0.25	0.60	0.05
Onion	0.25	0.60	0.20
Corn	0.25	0.60	0.10
Rice	0.21	2.68	0.08
Other	0.25	0.60	0.08

Appendix D Composition of mineral fertilisers.

Table D.1 Composition of CAN, TSP, K60, As and Urea content of crops.

Element	unit	CAN	TSP	K60	AS	Urea
TN	g kg^{-1}	270 a)			210 d)	460 e)
NH4-N	g kg^{-1}	135 a)			210 d)	
NO3-N	g kg^{-1}	135 a)				
TP	g kg^{-1}		197 b)			
TK	g kg^{-1}			498 c)		
TS	g kg^{-1}		18 XX)		240 d)	
Ca	g kg^{-1}		172 XX)			
Cu	mg kg^{-1}	1.47 f)	31 b)	0.74 f)	0.82 f)	0.83 f)
Zn	mg kg^{-1}	40.9 f)	407 b)	2.26 f)	0.41 f)	3.67 f)
Cd	mg kg^{-1}	0.05 f)	20 b)	0.01 f)	0.01 f)	0.01 f)
Ni	mg kg^{-1}	0.03 f)	32 b)	0.62 f)	0.27 f)	0.27 f)
Pb	mg kg^{-1}	21.2 f)	4 b)	0.29 f)	0.06 f)	0.35 f)
Cr	mg kg^{-1}	0.88 f)	197 b)	0.58 f)	0.82 f)	0.61 f)
As	mg kg^{-1}	0.35 f)	7 b)	0.49 f)	0.15 f)	0.09 f)

a) Triferto
b) (Smolders & Nziguheba, 2005)
c) K60: 60% K_2O (kali granulate)
d) Ammonium sulphate
e) Triferto
f) (Dittrich & Klose, 2008)

SYSTEMIC

Circular solutions for biowaste

Systemic large-scale eco-innovation to advance circular economy and mineral recovery from organic waste in Europe

Consortium

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