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Full length article

Mitigating nutrient losses in Europe: Synergistic solutions for air and water pollution by 2050

Aslıhan Ural-Janssen [a,b,*], Erik Meers [b], Gerard H. Ros [a], Ruben Vingerhoets [b,c], Maryna Strokal [a]

[a] Earth Systems and Global Change Group, Wageningen University & Research, 6700AA Wageningen, the Netherlands
[b] Laboratory for Re-Source Recovery, Department of Green Chemistry and Technology, Ghent University, 9000 Ghent, Belgium
[c] Research Group of Sustainable Energy, Air and Water Technology, Department of Bioscience Engineering, University of Antwerp, 2020 Antwerp, Belgium

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ABSTRACT

Agriculture and urbanization often cause nitrogen (N) and phosphorus (P) losses, and associated environmental impacts in Europe. Here, we aim to quantify the effects of using recovered N from manure processing and recovered P from treated sewage sludge, increasing N and P use efficiencies in agriculture, and improving sewage treatments on reducing future nutrient emissions to the air, and losses to rivers and seas of Europe. Exploring synergistic options we show that 30 % less N is expected in the air via ReNuRe products and higher N use efficiency by 2050. Rivers are projected to receive 23–68 % less nutrients relative to the future baseline scenario. These rivers may export up to two-thirds less nutrients relative to the future baseline. Recovered P from treated sewage sludge can fulfill P fertilizer need in Europe in 2050. Our analysis supports the adoption of bio-based fertilizers to mitigate nutrient losses and contributes to circular economy.

1. Introduction

Intensive agriculture and urbanization are important sources of nutrient pollution and associated impacts in Europe (Grizzetti et al., 2021; Strokal et al., 2021; Ural-Janssen et al., 2023). Nitrogen often is released to the air from agricultural activities in the form of NH_3, N_2O, and NO_x (de Vries et al., 2024). Nutrients are transported to rivers and coastal waters from agricultural via runoff as diffuse sources and from urban areas via sewage systems as point sources (Strokal et al., 2016). European rivers exported annually 2690 Gg of N and 128 Gg of P to coastal waters during 2017–2020 (Ural-Janssen et al., 2023). This challenges nutrient pollution reduction (de Vries et al., 2024; Vigiak et al., 2023), and the recovery of European freshwater biodiversity (Haase et al., 2023). In the future, rivers may export more nutrients because of population growth, increased urbanization, and agricultural intensification unless policy interventions are implemented effectively (Ural-Janssen et al., 2024). This calls for sustainable solutions to mitigate nutrient losses and their environmental impacts.

Several European policies have been implemented for nutrient losses including the National Emission Ceilings Directive (EC, 2001) with emission targets for NH_3 and NO_x, the Nitrates Directive (EC, 1991a) and the Water Framework Directive EC (2000) with N and P limits for their loadings to waterbodies, the Paris Agreement (UN, 2015) with targets for reducing GHG emissions and the Waste Framework Directive (EC, 2008) with recommendations on recycling and recovery instead of disposal. The Green Deal Farm-to-Fork (F2F) strategy aims for sustainable food production by reducing food waste, enhancing circularity via waste recycling and improving nutrient use efficiency to mitigate nutrient losses by at least 50 % without deteriorating soil fertility, claiming that this will reduce fertilizer use by at least 20 % in 2030 (EC, 2020).

Upcycling organic wastes to BBFs could substitute synthetic fertilizers while maintaining the crop yield efficiency (Chojnacka et al., 2020). ReNuRe is one of the BBFs, being a clean end product with

Abbreviations: AD, Anaerobic digestion; AS, Ammonia stripping-scrubbing; BBFs, Bio-based fertilizers; DIN, Dissolved inorganic nitrogen; DIP, Dissolved inorganic phosphorus; DON, Dissolved organic nitrogen; DOP, Dissolved organic phosphorus; GHG, Greenhouse gas; MARINA-nutrients, Model to assess river inputs of pollutants to seas for nutrients; N, Nitrogen; NH_3, Ammonia; N_{2O}, Nitrous oxide; NO_x, Nitrogen oxide; NUE, Nitrogen use efficiency; P, Phosphorus; PUE, Phosphorus use efficiency; ReNuRe, REcovered Nitrogen from manURE; RPSS, Recovered phosphorus from treated sewage sludge; TDN, Total dissolved nitrogen; TDP, Total dissolved phosphorus.

* Corresponding author.
E-mail address: aslihan.ural@wur.nl (A. Ural-Janssen).

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comparable characteristics as synthetic N fertilizers (Huygens et al., 2020). Ammonium salts produced through stripping-scrubbing process can be used as ReNuRe fertilizer (Vingerhoets et al., 2024). Vingerhoets et al. (2023) showed that a combination of N recovery from manure by ammonia stripping-scrubbing, and P recovery from municipal wastewater by struvite precipitation could increase the circularity of N by 15 % and of P by 24 %, thereby reducing the dependence on external fertilizers. Existing studies mainly assess the characterization (Case and Jensen, 2019; Morey et al., 2023) and agronomic efficiency of BBFs (Breda et al., 2020; Saju et al., 2023; Sigurnjak et al., 2019; Ye et al., 2020). However, their environmental effects on surface waters can fully or partly offset the benefits of nutrient recycling. Studies evaluated their environmental impacts on field levels (Aguirre-Villegas et al., 2019; Albert and Bloem, 2023; Wester-Larsen et al., 2022) while focusing on specific impacts by ignoring issues like pollution swapping and impacts of site conditions. Other studies applied life cycle assessments to evaluate the environmental impacts of BBFs (Ravi et al., 2022; Rydgård et al., 2024) or the processes to create them (Yoshida et al., 2018). Nevertheless, these studies often ignore the fact that the nutrient use efficiency of applied products is highly controlled by site-specific agro-ecological conditions (You et al., 2023). Thus, there is a need for a comprehensive study assessing the effects of BBFs on air and water pollution to support their implementation.

Environmental models are useful tools to explore future trends in air and water quality in response to projected changes in pressures and drivers, knowing that nutrient management in agricultural systems have a strong influence on the emissions of nutrients to air and waters (Young et al., 2021). Several models exist for large-scale simulations of nutrient flows from agriculture, including MITERRA-Europe (Velthof et al., 2009), INTEGRATOR (de Vries et al., 2011; 2021), GREEN (Grizzetti et al., 2012), IMAGE-GNM (Beusen et al., 2015) and MARINA (Strokal et al., 2016). These models have been used to simulate the flows of N and P in agroecosystems, and to evaluate technical or social innovations affecting the nutrient use efficiency. The models usually take a process-based approach that is combined with empirical mass balance approaches to assess annual fluxes at high spatial resolution. De Vries et al. (1998) showed that model simplification, in terms of less detailed formulations of processes (process aggregation) at low temporal resolution (temporal aggregation), is an adequate step in the upscaling of modelling results from a local to a regional scale when interested in annual average fluxes. Both MITERRA-Europe (Velthof et al., 2009) and INTEGRATOR (de Vries et al., 2011; 2021) quantifies N losses to air and water across Europe, and have been applied at various resolutions. Moreover, GREEN simulates river exports of total N and P to European seas at basin scale (Grizzetti et al., 2012). Furthermore, IMAGE-GNM simulates N and P flows to freshwaters at a 0.5° grid cell resolution globally (Beusen et al., 2022).

The MARINA-Nutrients model for Europe (Ural-Janssen et al., 2023) combines both air and water emissions and simulates N emissions to the air, and N and P flows from land to rivers and by rivers to coastal waters. It is a European version of the MARINA model family (Micella et al., 2024) running at the sub-basin scale for dissolved organic and inorganic nutrients, which makes the model different from the abovementioned examples. This model is chosen in this study because it addresses air (agriculture-associated), river, and coastal water (agriculture and sewage-associated) pollution for European basins, supporting the identification and assessment of policy-relevant strategies on reducing air and water pollution under global change. The model has been validated and used to identify required reductions to avoid future coastal eutrophication in Europe under global change (Ural-Janssen et al., 2023; 2024). In this study, we use the model to reveal new insights on the effects of BBFs on air and water pollution control in the future when considering socioeconomic developments and climate change. Scenarios such as Shared Socio-economic Pathways (SSPs, O'Neill et al. (2014)) and Representative Concentration Pathways (RCPs, van Vuuren et al. (2011)) provide various storylines to project future changes in socioeconomic developments and hydrology.

This study aims to quantify the effects of using recovered N from manure processing and recovered P from treated sewage sludge, increasing N and P use efficiencies in agriculture, and improving sewage treatments on reducing future nutrient emissions to the air, and losses to rivers and coastal waters of Europe. To our knowledge, no studies have thoroughly assessed the impact of using BBFs in European agro-ecosystems on N emissions to the air and nutrient loads to rivers and coastal waters, while accounting for variation in crop and soil types, climates, and management practices. This work was designed to fill these gaps by providing an in-depth, quantitative assessment across Europe at the basin scale under global change. We used the MARINA-Nutrients model for Europe with a baseline scenario from Ural-Janssen et al. (2024), and incorporated six alternative scenarios on nutrient management strategies.

2. Materials and methods

2.1. MARINA-Nutrients model for Europe

Our model is process-based, steady-state with a lumped approach to estimate N emissions to the air from agriculture, inputs of DIN, DIP, DON, DOP to rivers, and their river exports to seas per basin (and sub-basins of the Danube River) for 594 European rivers while accounting for nutrient retention in and export from land (e.g., P accumulation in soils, crop uptake) and rivers (e.g., damming, water removal) (Ural-Janssen et al., 2023). The model considers the following pollution sources:

- Agricultural sources include animal housing and manure storage systems, the application of synthetic fertilizers and untreated manure on land, manure deposited on land during grazing, biological N_2 fixation by crops, atmospheric N and P deposition on agricultural land, leaching of organic matter and weathering of P-contained minerals from agricultural areas to surface waters;
- Non-agricultural sources encompass human waste from populations not connected to sewage systems, biological N_2 fixation by natural vegetation, atmospheric N deposition on non-agricultural land, leaching of organic matter and weathering of P-contained minerals from non-agricultural areas;
- Urbanization-related sources include urban and rural sewage systems (human waste that is collected and treated).

We integrate the BBFs produced by N recovery from manure processing and by P recovery from treated sewage sludge into the model quantifying:

1. N emissions to the air from manure processing systems (AD+AS) and from the application of ReNuRe products on agricultural land;
2. DIN and DON inputs to rivers and their exports to seas from the application of ReNuRe products on agricultural land;
3. DIP and DOP inputs into rivers and their exports to seas from the application of recovered P from treated sewage sludge (RPSS) on agricultural land.

N emissions to the air from agricultural sources are quantified as:

$$\mathrm{Nemission}_{f.a.y.j} = \mathrm{Nexcretion}_{a.y.j} \times \mathrm{EF}_{f.a.y.j} \tag{1}$$

$$\mathrm{Nemission}_{f.y.j} = \mathrm{WSdif}_{N.y.j} \times \mathrm{EF}_{f.y.j} \tag{2}$$

where $\mathrm{Nemission}_{f.a.y.j}$ represents N emissions to the air by form f (NH_3, N_2O, NO_x), animal type a (dairy cattle, other cattle, pig, poultry, other animals), source y (animal housing, manure storage) and basin j (kg N yr^{-1}). These emissions are quantified as a function of animal N excretions ($\mathrm{Nexcretion}_{a.y.j}$, kg N yr^{-1}) and EFs ($\mathrm{EF}_{f.a.y.j}$, 0–1) per N form f, animal type a, source y and basin j. $Nemission_{f.y.j}$ represents N emissions to the air by form f (NH_3, N_2O, NO_x), by source y (synthetic fertilizer, untreated manure, ReNuRe products and effluent from manure processing, manure deposited on land during grazing, atmospheric deposition and biological N_2 fixation) and basin j (kg N yr^{-1}). These emissions are quantified as a function of N inputs to agricultural land ($WSdif_{N.y.j}$, kg N yr^{-1}) and EFs ($EF_{f.y.j}$, 0–1) per form, source y and basin j.

Nutrient inputs to rivers from agricultural diffuse sources are quantified as:

$$RSdif_{f.y.ag.j} = WSdif_{f.y.j} \times G_{f.j} \times FE_{ws.f.j} \tag{3}$$

$$RSdif_{f.y.nonag.j} = WSdif_{f.y.j} \times FE_{ws.f.j} \tag{4}$$

where $RSdif_{f.y.ag.j}$ represents annual nutrient inputs to rivers by form f (DIN, DON, DIP, DOP), diffuse source y from agricultural (ag) areas in basin j (kg N or P yr^{-1}). Nutrient inputs to rivers from agricultural diffuse sources are quantified as a function of nutrient inputs to land ($WSdif_{f.y.j}$, kg N or P yr^{-1}) that are corrected for nutrient export from agricultural land (via crop harvesting and animal grazing) ($G_{f.j}$, 0–1), and runoff from land to streams ($FE_{ws.f.j}$, 0–1) (Ural-Janssen et al., 2023).

Nutrient inputs to rivers from point sources are quantified as:

$$RSpnt_{f.y.j} = Pop_j \times fr_{pop.sew.j} \times WScap_{e.j} \times \left(1 - hw_{frem.e.j}\right) \times FEpnt_{f.j} \tag{5}$$

where $RSpnt_{f.y.j}$ represents annual nutrient inputs to rivers by form f (DIN, DIP, DON, DOP) point source y in basin j (kg N or P yr^{-1}). Nutrient inputs to rivers from point sources are quantified as a function of population (Pop_j, person) that is connected to sewage systems ($fr_{pop.sew.j}$, 0–1), per capita human N and P excretion rates ($WScap_{e.j}$, kg N or P $person^{-1}$ yr^{-1}), removal efficiencies of nutrients during wastewater treatment ($hw_{frem.e.j}$, 0–1) and the fraction of nutrients entering rivers by the effluent from wastewater treatment systems ($FEpnt_{f.j}$, 0–1).

River exports of nutrients from diffuse and point sources are quantified as:

$$M_{f.y.j} = \left(RSdif_{f.y.j} + RSpnt_{f.y.j}\right) \times FE_{riv.f.outlet.j} \times FE_{riv.f.mouth.j} \tag{6}$$

where $M_{f.y.j}$ represents annual exports of nutrients to seas by form f (DIN, DON, DIP, DOP), diffuse and point source y and basin j (kg N or P yr^{-1}). River exports of nutrients are quantified as a function of nutrient inputs to rivers that are corrected for removal (e.g., water consumption) and retention (e.g., damming, sedimentation) in rivers ($FE_{riv.f.outlet.j}$, 0–1),

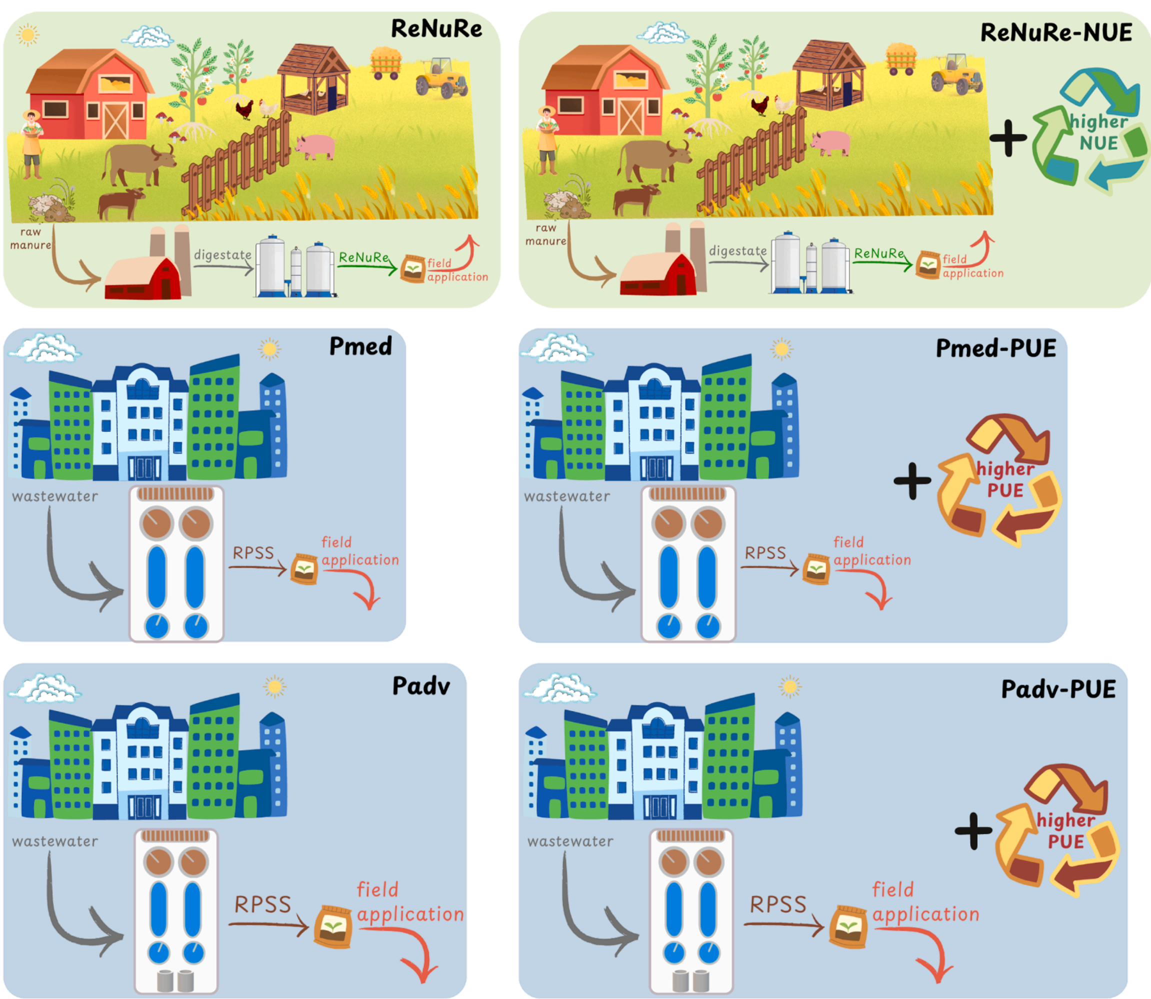

Fig. 1. Schematic overview of the six alternative scenarios for 2050. These scenarios are ReNuRe (ReNuRe products), ReNuRe-NUE (ReNuRe products + increased NUE), Pmed (RPSS + medium upgrade of WWTPs), Pmed-PUE (RPSS + medium upgrade of WWTPs + increased PUE), Padv (RPSS + advanced upgrade of WWTPs) and Padv-PUE (RPSS + advanced upgrade of WWTPs + increased PUE). ReNuRe stands for REcovered Nitrogen from manURE, NUE is short for nitrogen use efficiency, RPSS is short for recovered phosphorus from treated sewage sludge, and PUE is short for phosphorus use efficiency. The treatment box in the Pmed and Pmed-PUE scenarios represents secondary treatment, and the treatment box in the Padv and Padv-PUE scenarios represents tertiary treatment. Source: Section 2.2 and Table S4.

and the traveling distance of the nutrients to the river mouth ($FE_{riv.f.mouth.j}$, 0–1). TDN and TDP consist of the dissolved inorganic and organic forms (TDN = DIN + DON, TDP = DIP + DOP). Further details for model calculations are in Tables S1, S2 and S3, and for uncertainty and limitations in Supplementary Text 2.

2.2. Scenario development

The future baseline scenario is taken from our previous study (Ural-Janssen et al., 2024) and the combination of SSP5-RCP8.5. This scenario assumes global warming with high economic developments, rapid urbanization, and intensified agriculture (Supplementary Text 1). Here, we develop six alternative scenarios that differ in replacing synthetic fertilizers with BBFs and enhancing nutrient use efficiency to reduce nutrient losses in Europe for 2050: two for N, and four for P (Fig. 1 and Table S4).

Two N-scenarios include:

- *The ReNuRe scenario* includes N recovery from manure via AD followed by an AS process. Combining both technologies, the raw animal slurry is converted into an ammonium salt that can be used as ReNuRe fertilizer (Sigurnjak et al., 2019), and an organic matter-rich effluent. This scenario replaces synthetic N fertilizers with the ReNuRe products produced by manure processing while maintaining the effective N inputs as in the future baseline. For this, N excretions produced by dairy cattle, other cattle, and pigs are treated via AD+AS processes (Table S4, Figs. S1 and S2). AD increases inorganic content by breaking down organic components relative to untreated manure (Meers et al., 2020). AS removes NH_3 from an NH_3-rich waste stream in a stripping reactor by using an airflow, and transfers NH_3 from liquid to the gas phase with a removal of 56 % (Vingerhoets et al., 2024) and captures the released NH_3 by a strong acid (e.g., sulfuric or nitric acid) (Sigurnjak et al., 2019). Excretions produced by poultry and other animals (i.e. sheep, goat) are considered to be applied as untreated manure on agricultural areas.
- *The ReNuRe-NUE scenario* expands the ReNuRe scenario with an assumed increase in NUE on agricultural land by 2050. NUE is considered as the overall system efficiency according to Bouwman et al. (2009), which is the ratio of N yield from crop harvesting and animal grazing to the total N input to agricultural areas (synthetic fertilizers, animal manure, atmospheric N deposition and biological N_2 fixation). We increased the NUE to 0.75 for the basins with NUE lower than 0.75 (Fig. S3) following Schulte-Uebbing and de Vries (2021), being a maximum feasible NUE for maintaining crop production while respecting environmental thresholds (i.e. N concentration in surface water to limit eutrophication). Based on the increased NUE and assuming a similar N yield as in the future baseline, we maintain the total effective N input and subsequently reduce the synthetic N fertilizer use. We assume that manure processes do not have an impact on P amount in animal manure and thus, the amount of P does not change in N-scenarios.

Four P-scenarios include:

- *The Pmed scenario* combines P recovery from treated sewage sludge and medium improvement of the WWTPs for better nutrient removal. This scenario replaces synthetic P fertilizers with RPSS while maintaining the total P inputs as in the baseline. The WWTP technologies per basin are assumed to be upgraded by one level: primary to secondary, and secondary to tertiary. Moreover, considering recently proposed technologies (> 90 % of P recovery (Huygens et al., 2019)), we assume 90 % of P recovery from these WWTPs and quantify the amount of RPSS accordingly. Finally, we identify the amount of synthetic P fertilizers that can be replaced by RPSS relative to the future baseline.
- *The Padv scenario* is similar to that of Pmed but here we assume that all the WWTPs lower than tertiary in basins will be upgraded to tertiary treatment.
- *The Pmed-PUE scenario* assumes further improvements in PUE on agricultural land in addition to the Pmed scenario. PUE is considered as the overall system efficiency according to Bouwman et al. (2009), which is the ratio of P yield from crop harvesting and animal grazing to the total P input to agricultural areas (synthetic fertilizers, animal manure, and atmospheric deposition). To increase the PUE in this scenario, we follow the approach of the NUE as the proxy in which we increase the PUE to 0.75 for the basins with the PUE lower than 0.75 (Fig. S3). Based on the increased PUE and assuming a similar P yield as in the future baseline, we maintain the total P input and subsequently reduce the synthetic P fertilizer application.
- *The Padv-PUE scenario* includes all assumptions of the Padv and Pmed-PUE scenarios.

3. Results

3.1. Reducing future N emissions to the air

In the baseline scenario, total N emissions to the air from agriculture will increase by 16 % by 2050 compared to 2017–2020 (Fig. S4). In contrast, alternative scenarios project reduced N emissions by 2050: 10 % and 19 % under the ReNuRe and ReNuRe-NUE scenarios, respectively (Fig. S4). Compared to the 2050 baseline, ReNuRe projects a 22 % reduction and ReNuRe-NUE projects a 30 % reduction in N emissions for the whole study area (Fig. S4).

Reduction potentials differ among NH_3, N_2O, and NO_x (Figs.2 and S4). Between 2050 and the period of 2017–2020, the total NH_3 emissions are projected to be 10 % and 19 % lower under the ReNuRe and ReNuRe-NUE scenarios, respectively (Fig. S4). For total N_2O, these reductions range from 7 % to 20 % under ReNuRe and from 12 % to 30 % under ReNuRe-NUE. Compared to the 2050 baseline, the ReNuRe and ReNuRe-NUE scenarios project 23–31 % reductions for the NH_3, 8–21 % reductions for N_2O and 21–37 % reductions for NO_x (Fig. 2).

Projected reductions in N emissions in the ReNuRe scenario are associated with manure processing (AD+AS) after the animal housing systems, and the application of ReNuRe products (Fig. 2). AS process has very low NH_3 emissions (no N_2O and NO_X) compared to manure storage for dairy cattle, other cattle, and pigs. The use of such closed-loop management systems reduces N emissions compared to conventional practices, providing better nutrient recycling. Moreover, ReNuRe products release less N emissions into the air relative to the untreated manure when applied on the field. Larger reductions in the ReNuRe-NUE scenario are mainly from the reduction in synthetic fertilizers (Fig. 2). Increasing the NUE lowered the total N input to agricultural land to 25,750 Gg N yr^{-1} compared to the future baseline (31,705 Gg N yr^{-1}, Fig. S5). Applying ReNuRe products in combination with increasing NUE seems to be effective in reducing N emissions from agriculture.

3.2. Reducing future nutrients in rivers

Between 2050 and the period of 2017–2020, TDN and TDP in European rivers are projected to increase by 11 % and 30 %, respectively under the baseline scenario (Fig. 3). This is mainly associated with more nutrients from point sources (sewage systems) as a result of future urbanization (Ural-Janssen et al., 2024). However, alternative scenarios project different trends. For TDN, the most effective scenario is combination of adopting ReNuRe products with increased NUE (ReNuRe-NUE) projecting a 14 % reduction by 2050 relative to the period of 2017–2020 (Fig. 3). For TDP, the Pmed and Padv-PUE scenarios project 39–58 % reductions relative to 2017–2020 (Fig. 3). Compared to the future baseline, ReNuRe-NUE projects 23 % reductions for TDN and Padv-PUE projects 68 % reductions for TDP in 2050 (Fig. 3). By upgrading the WWTPs in the Pmed (one level up) and Padv (to tertiary treatment)

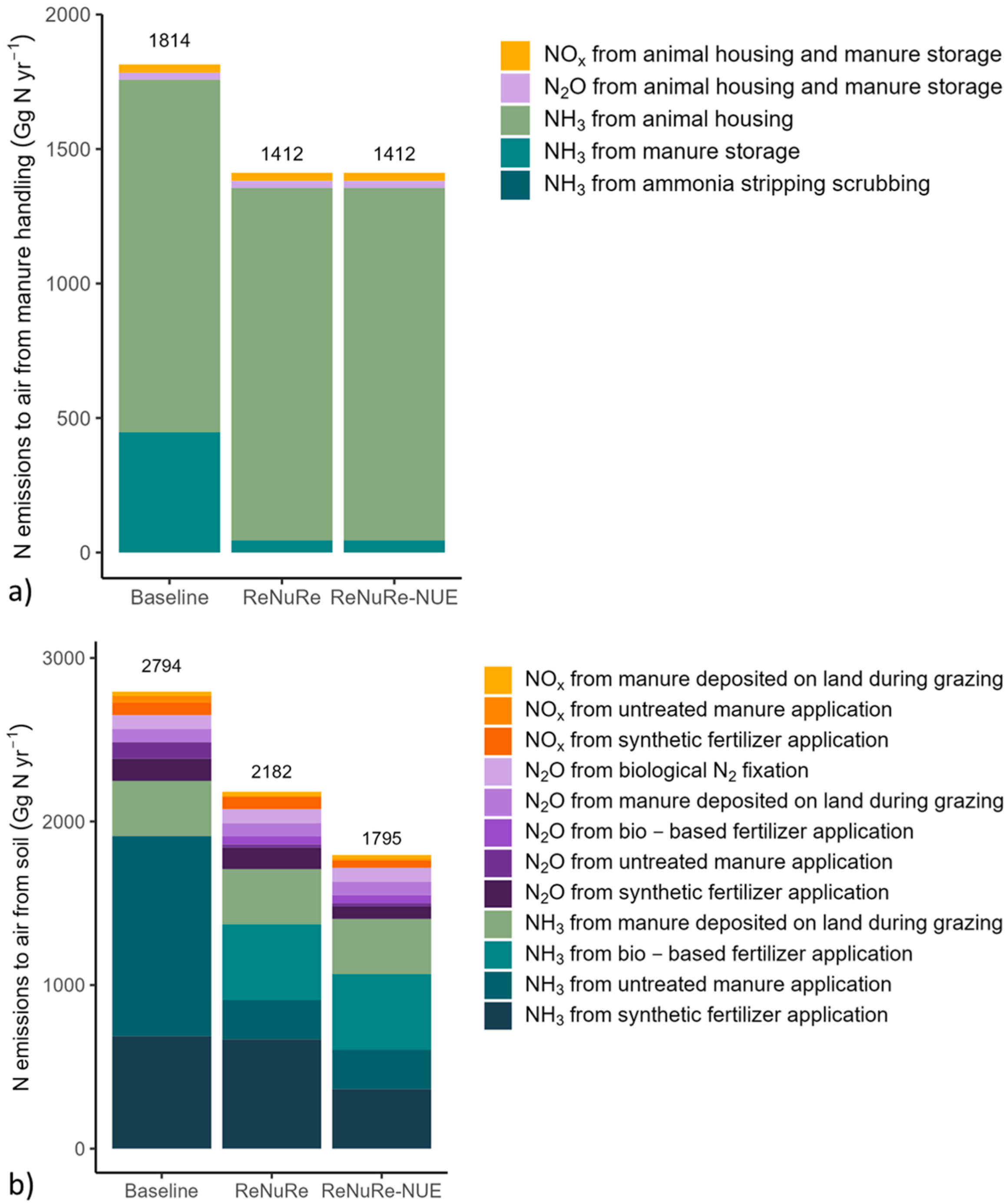

Fig. 2. Nitrogen (N) emissions to the air from agricultural systems under the baseline and two alternative scenarios in 2050 (Gg N yr^{-1}). The baseline is based on the combination of SSP5-RCP8.5 (Shared Socioeconomic Pathway 5 and Representative Concentration Pathway 8.5). The two alternative scenarios are ReNuRe (ReNuRe products) and ReNuRe-NUE (ReNuRe products + increased NUE). ReNuRe stands for REcovered Nitrogen form manURE and NUE is short for nitrogen use efficiency. a) N emissions to the air from manure handling. b) N emissions to the air from agricultural soils. Source: The MARINA-Nutrients model for Europe.

scenarios could help reduce not only TDP (53–65 %) but also TDN (11–13 %) in rivers relative to the baseline (Fig. 3).

Compared to the future baseline, 46 % less DIN and 12 % less DON inputs to all studied rivers from agriculture are projected in the ReNuRe-NUE scenario (Figs. 3 and S6). This is due to the decline in synthetic fertilizer use (39 %) and atmospheric N deposition (24 %) compared to the future baseline (Fig. S5). Lower fertilizer use is associated with higher NUE, and less atmospheric N deposition is associated with reduced volatilization from manure storage, processing, and application (Fig. 2).

In P-scenarios, RPSS can fulfill fertilizer needs in Europe for 2050 and reduce DIP and DOP in rivers (Figs. 3 and S5). DIP and DOP pollution in European rivers can be reduced by 25 % and 8 %, respectively, by implementing RPSS and increased PUE compared to the future baseline (Fig. S6). This is because of the reduced fertilizer application under the Pmed-PUE and Padv-PUE scenarios relative to the future baseline (Fig. S5).

There is a large spatial variability in future nutrient inputs to rivers (Fig. S8), and their reductions relative to the future baseline. In a third of the studied basins, TDN inputs to rivers could be reduced by more than

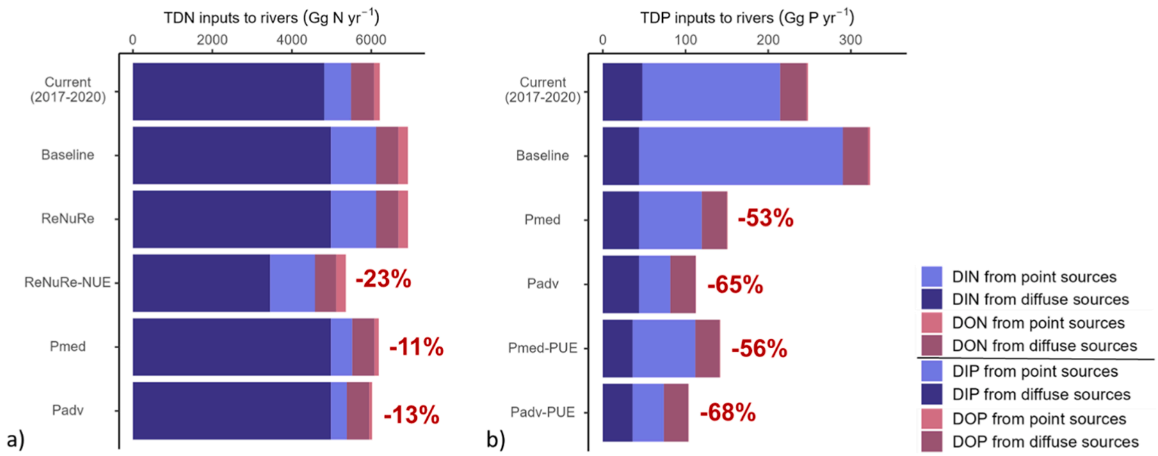

Fig. 3. Inputs of nutrients to rivers from diffuse (agricultural, non-agricultural) and point (sewage systems) sources under current (2017–2020), the baseline, and six alternative scenarios in 2050 (Gg N or P yr^{-1}). a) Total dissolved nitrogen (TDN) consisting of dissolved inorganic and organic forms. b) Total dissolved phosphorus (TDP) consisting of dissolved inorganic and organic forms. The percentages are estimated relative to the baseline. The baseline is based on the combination of SSP5-RCP8.5 (Shared Socioeconomic Pathway 5 and Representative Concentration Pathway 8.5). The six alternative scenarios are ReNuRe (ReNuRe products), ReNuRe-NUE (ReNuRe products + increased NUE), Pmed (RPSS + medium upgrade of WWTPs), Pmed-PUE (RPSS + medium upgrade of WWTPs + increased PUE), Padv (RPSS + advanced upgrade of WWTPs) and Padv-PUE (RPSS + advanced upgrade of WWTPs + increased PUE). ReNuRe stands for REcovered Nitrogen from manURE, NUE is short for nitrogen use efficiency, RPSS is short for recovered phosphorus from treated sewage sludge, WWTPs is short for wastewater treatment plants, and PUE is short for phosphorus use efficiency. Source: The MARINA-Nutrients model for Europe.

46 % under the ReNuRe-NUE scenario, while TDP inputs to rivers could decline by more than 68 % under the Padv-PUE scenario compared to the future baseline (Fig. 4). The simultaneous decrease in TDN and TDP inputs to rivers is mainly projected for eastern and southern basins (Fig. 4), and basins with the highest inputs are expected in central and western Europe with intensively farmed regions and dense population (Fig. S8). The main drivers of the reductions are less fertilizer inputs to agricultural land (Fig. S5) due to the increased overall nutrient use efficiencies, and less nutrient losses from point sources (Fig. S7) due to the improved wastewater treatment technologies relative to the future baseline.

Adopting ReNuRe products and improving NUE is a promising solution for reducing future N losses to air and waters from agriculture synergistically. For a third of the studied basins, more than 58 % of TDN inputs to rivers and more than 34 % of NH_3 emissions to the air are expected to reduce under the ReNuRe-NUE scenario (Fig. 4). The decreasing N losses are projected for most of the basins across Europe implying that combining the use of BBFs with the measures increasing NUE on agricultural land can reduce N emissions to the air and water simultaneously (Fig. 4). Nevertheless, certain relatively small basins in

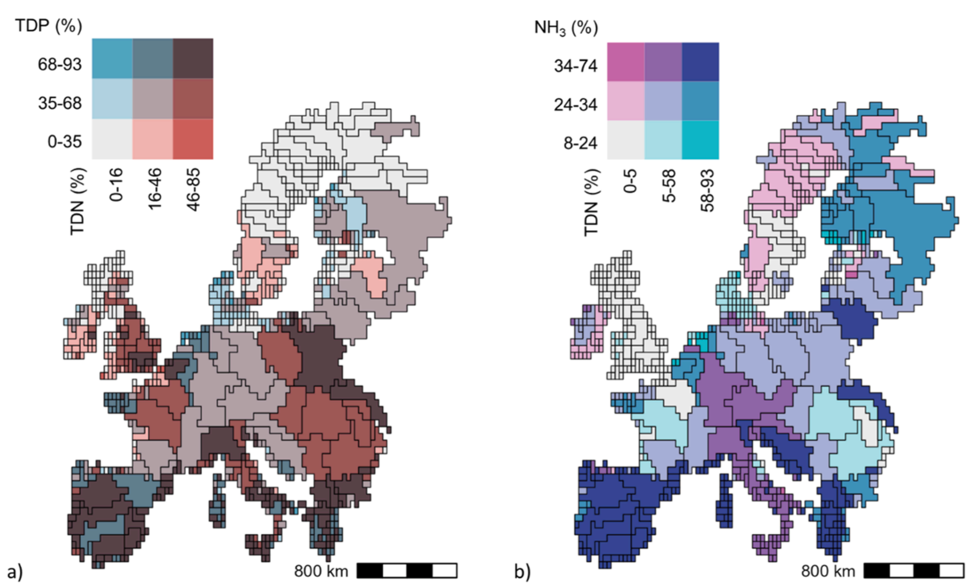

Fig. 4. Air and water pollution reductions in alternative scenarios relative to the baseline scenario in 2050 (%). a) Future reductions in total dissolved N (TDN) vs. future reductions in total dissolved phosphorus (TDP) inputs to rivers from agricultural, non-agricultural and urbanization-related sources under the ReNuRe-NUE (ReNuRe products + increased NUE) and Padv-PUE (RPSS + advanced upgrade of WWTPs + increased PUE) scenarios, respectively, relative to the baseline (%). b) Future reductions in ammonia (NH_3) emissions to the air vs. future reductions in total dissolved nitrogen (TDN) inputs to rivers from agriculture under the ReNuRe-NUE scenario (ReNuRe products + increased NUE) relative to the baseline (%). The baseline is based on the combination of SSP5-RCP8.5 (Shared Socioeconomic Pathway 5 and Representative Concentration Pathway 8.5). ReNuRe stands for REcovered Nitrogen from manURE, NUE is short for nitrogen use efficiency, RPSS is short for recovered phosphorus from treated sewage sludge, WWTPs is short for wastewater treatment plants, and PUE is short for phosphorus use efficiency. Percentage reductions were calculated using loads for NH_3 emissions, TDN and TDP inputs to rivers. Source: The MARINA-Nutrients model for Europe.

western Europe are projected to release the highest levels of NH_3 (Group 5, Fig. S8) primarily due to intensive livestock regions.

3.3. Reducing future river exports of nutrients to seas

Between 2050 and the period of 2017–2020, river exports of TDN and TDP to European seas are estimated to increase by 14 % and 28 %, respectively (Fig. S9). This is mainly driven by increased sewage systems and moderate treatment improvement (Ural-Janssen et al., 2024). Alternative scenarios project different trends. Compared to the period of 2017–2020, the ReNuRe-NUE projects a 9 % reduction in the river export of TDN by 2050, which is much higher for TDP (36–51 %) under the P-scenarios (Fig. S9). Compared to the future baseline, rivers may export up to two-thirds less nutrients to all studied seas in 2050 (Fig. S9). This depends on the scenarios (Figs. 5 and S8). For instance, 62 % less TDP export by European rivers is expected due to the implementation of upgraded treatment technologies and the use of RPSS together with higher PUE (Fig. S9). When ReNuRe products are combined with higher NUE, 20 % less TDN export by rivers is projected compared to the future baseline (Fig. S9).

Total DIN export by rivers from agriculture and sewage systems is projected to reduce by 14–33 % under the Pmed and ReNuRe-NUE scenarios, respectively, relative to the future baseline (Fig. 5). The reduced DIN export under the P-scenarios mainly occurs as a result of upgraded WWTPs and associated nutrient removal (Fig. S7). Relatively lower reduction in the ReNuRe-NUE, but higher reductions in the Pmed and Padv scenarios are estimated for DON export by all studied rivers (Fig. 5).

Among P forms, overall more than 60 % reductions are projected for total DIP export by all studied rivers, up to 78 % under the Padv-PUE scenario relative to the future baseline (Fig. 5). Relatively lower reductions in total DOP export by rivers (11–20 %) are estimated (Fig. 5). All reductions are caused by improving WWTPs (69–85 % less TDP inputs to rivers, Fig. S7) and increasing PUE (less fertilizer inputs to agricultural land, Fig. S5) relative to the future baseline.

4. Discussion

4.1. Comparisons

Minimum one-third of surface waters (i.e. 36 % of rivers, 31 % of coastal waters) of the European Union are reported eutrophic (EC, 2021). Thus, achieving the targets of “good ecological and chemical status” according to the Water Framework Directive is still challenging without effective measures (EC, 2021). In our study, we found that nutrient exports by the European rivers to the coastal waters could be reduced by 14–51 % in 2050 relative to the current period (2017–2020), when ReNuRe products and RPSS are widely implemented and combined with management practices leading to higher nutrient use efficiencies in the field (Fig. S9).

Moreover, gaseous N losses could be reduced up to 19 % by 2050 compared to 2017–2020, when ReNuRe products combined with higher NUE (Fig. S4). On the other hand, Rashid et al. (2025) found that when ammonium sulphate is applied as BBF with equivalent total N input, gaseous N losses were comparable to those from conventional fertilizers. They used the Daisy model to simulate N dynamics, including gaseous losses (e.g., NH_3, N_2O) based on fertilizer type, application rate, and environmental conditions. This could be explained by the choices of EFs for production and application of BBFs. Our study considers the ReNuRe products produced by AD and AS which prevents gaseous N losses, and lower EFs for their land application relative to synthetic fertilizers and untreated manure regardless of application type and environmental conditions (Table S3).

The use of BBFs did not negatively affect the N and P yields – defined as nutrient exported from agricultural land through crop harvesting and grazing since the total effective nutrient input level remained the same or the decline was compensated with an increase in nutrient use efficiency. Our findings align with literature regarding the agronomic performance of BBFs (Huygens et al., 2020; Rashid et al., 2025; Sigurnjak et al., 2019; Ye et al., 2020). On the other hand, while mineral-like BBFs can balance N supply with plant uptake and reduce N losses, they do not contribute to long-term soil fertility. Whereas, BBFs with higher organic

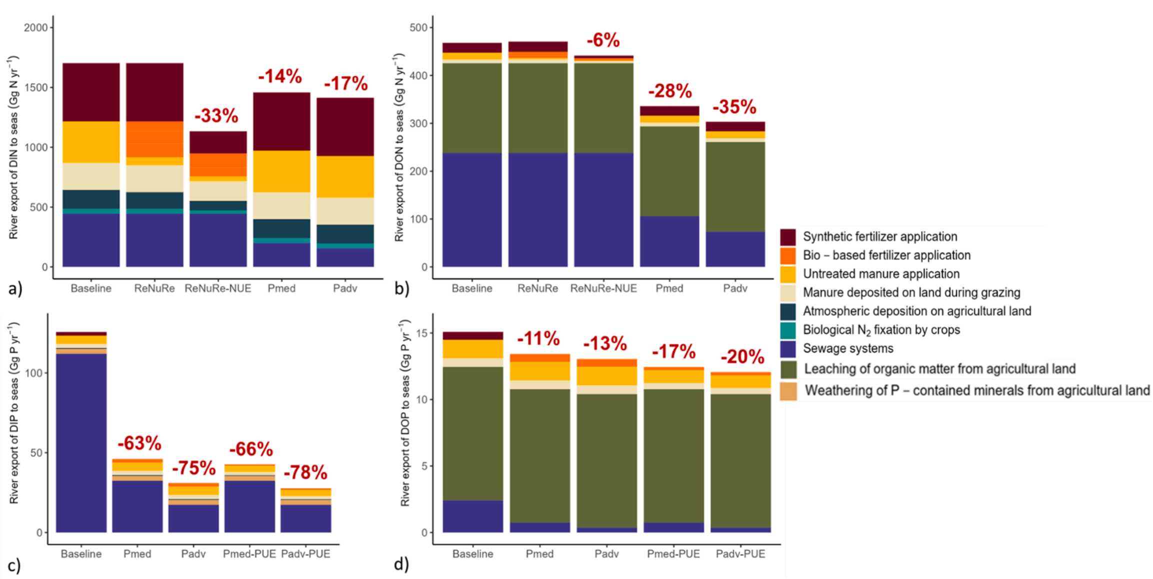

Fig. 5. River exports of nutrients to seas from agriculture and sewage systems under the baseline and six alternative scenarios in 2050 (Gg N or P yr^{-1}). a) Dissolved inorganic nitrogen (DIN). b) Dissolved organic nitrogen (DON). c) Dissolved inorganic phosphorus (DIP). d) Dissolved organic phosphorus (DOP). The percentages are estimated relative to the baseline. The baseline is based on the combination of SSP5-RCP8.5 (Shared Socioeconomic Pathway 5 and Representative Concentration Pathway 8.5). The six alternative scenarios are ReNuRe (ReNuRe products), ReNuRe-NUE (ReNuRe products + increased NUE), Pmed (RPSS + medium upgrade of WWTPs), Pmed-PUE (RPSS + medium upgrade of WWTPs + increased PUE), Padv (RPSS + advanced upgrade of WWTPs) and Padv-PUE (RPSS + advanced upgrade of WWTPs + increased PUE). ReNuRe stands for REcovered Nitrogen from manURE, NUE is short for nitrogen use efficiency, RPSS is short for recovered phosphorus from treated sewage sludge, WWTPs is short for wastewater treatment plants, and PUE is short for phosphorus use efficiency. Source: The MARINA-Nutrients model for Europe.

N content like anaerobic digestate can enhance N supply capacity and soil fertility over time (Rashid et al., 2025). Therefore, future research should understand these implications and long-term benefits based on regional needs and barriers.

4.2. Future implications

Our model results account for spatially explicit analysis of air and water pollution, and contribute to developing synergistic solutions to mitigate nutrient losses from agriculture and sewage systems. Some nutrient management measures might have trade-offs known as pollution swapping (Velthof et al., 2014). However, synergetic options still receive relatively less attention in research and policy (Kanter et al., 2020). We show that the F2F target "reduction of nutrient losses by at least 50 %" (EC, 2020) could be achieved for P inputs to rivers under the P-scenarios, and more than 20 % decline in N fertilizer use can be possible by 2050 under the ReNuRe-NUE scenario providing reduced N emissions to the air and waters. Our analysis also supports the River Basin Management Plans (EC, 2000) by basin-specific analysis for opportunities reducing air and water pollution simultaneously, and minimizing the risk of pollution swapping to help solve N crisis in Europe.

We chose animal manure and sewage sludge as relatively larger organic waste streams to produce BBFs. ReNuRe products produced from manure processing are promising alternatives to synthetic N fertilizers mainly due to the reduced NH_3 emissions. On the other hand, P recovery and recycling are inevitable to sustain agricultural production while maintaining water quality, in particular in areas where soil P pools are below agronomic thresholds. The Urban Waste Water Treatment Directive urges to re-use the sludge arising from WWTPs whenever appropriate (EC, 1991b), although using the recovered products derived from treated sewage sludge remains restricted/prohibited in most EU countries. High P recovery from municipal sewage sludge-derived ash is a sustainable alternative for circular economy (Fournie et al., 2022; Liu et al., 2021; Zhu et al., 2023). Our study shows that RPSS can provide a circular solution to meet P fertilizer demand in Europe for 2050. This helps close nutrient cycles at the basin scale and contributes to the EU zero pollution goals and legislation for P recovery. However, limitations such as heavy metal contamination (Husek et al., 2022) and regional surplus/deficiency (Panagos et al., 2022) should be considered while selecting processes. Thus, nutrient recovery and recycling from sewage sludge after sufficient treatment and heavy metal removal not only promises economic benefits, but also leads to reduced nutrient inputs to rivers and coastal waters from point sources.

BBFs have a large potential for resource recovery and circular economy, especially for manure-surplus countries, though their benefits are largely controlled by the enhanced use efficiency for both N and P. Their adoption with higher nutrient use efficiency in agriculture supports the F2F strategy and the United Nations Sustainable Development Goals (SDGs 2 and 6) by simultaneously mitigating air and water pollution, and improving agronomic efficiency. However, even if the environmental benefits of BBFs are underscored, marketing and usage are highly influenced by their cost and social perception (Garmendia-Lemus et al., 2024; Moshkin et al., 2023). ReNuRe products offer potential solution by providing the use of local nutrients and reducing dependency on imported fertilizers (Vingerhoets et al., 2025). Future studies should delve into cost-benefit analyses for the production and use of different BBFs, and explore the intricate relationship between stakeholders vs. agronomic and environmental impacts for a comprehensive assessment of implementing BBFs and introducing them to the market.

5. Conclusions

We analyze the potential of synergetic options for reducing future nutrient losses from agriculture and urbanization-related sources in Europe under six scenarios considering improved nutrient recovery, recycling, and efficiency. Our study is the first attempt to model the effects of adopting BBFs and improving nutrient use efficiencies in agriculture on N emissions to the air and nutrient inputs to waters, and the effects of enhancing sewage treatments on nutrient inputs to waters by 2050 while accounting for the spatial drivers of nutrient pollution. Adopting ReNuRe products and increasing NUE is found to be synergistic option to reduce N emissions to the air, and N inputs to rivers and seas of Europe. By combining optimized use of ReNuRe products with higher NUE, 30 % less N in the air and 23 % less N inputs to rivers are expected by 2050 compared to the future baseline. By combining enhanced sewage treatment, use of RPSS and higher PUE, 68 % less P inputs to rivers are projected relative to the future baseline. Consequently, these rivers are predicted to export up to two-thirds less nutrients to seas compared to the future baseline. Besides, the recovered P from treated sewage sludge can provide P fertilizer demand in Europe by 2050. Our findings help achieve the F2F target on mitigating nutrient losses by 50 % and reducing fertilizer use by 20 %, and support circular economy.

CRediT authorship contribution statement

Aslıhan Ural-Janssen: Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization. **Erik Meers:** Writing – review & editing, Supervision, Funding acquisition. **Gerard H. Ros:** Writing – review & editing, Methodology, Conceptualization. **Ruben Vingerhoets:** Writing – review & editing. **Maryna Strokal:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2025.108472.

Data availability

The main model results supporting Figs. 2-5 generated in this study have been deposited in the DANS Easy repository under the Digital Object Identifier: 10.17026/PT/AWTUAM.

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