



Modelling agronomic and environmental effects of bio-based nitrogen fertilisers in Europe

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Received: 20 February 2025 / Accepted: 5 December 2025
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Abstract Biobased waste materials, rich in nutrients and carbon, are often underutilised but could be processed into valuable biobased fertilisers (BBFs). Replacing conventional mineral fertilisers with BBFs requires understanding of their agronomic and environmental performance, which is currently lacking. This study used the Daisy model to evaluate the agronomic (dry matter and nitrogen (N) yield) and environmental (N losses to air and water) performance of eight BBFs in six European cropping systems. Mineral N fertilisation in the baseline scenarios was replaced with BBF according to three different schemes of N fertiliser replacement: Agronomic (according to 1st year fertiliser N replacement value (NFRV), typically 10–90%), Environmental (same total N as in baseline, equivalent to NFRV = 100%), and Intermediate (based on average NFRV of Agronomic and Environmental). Results indicated that under the Agronomic scheme, BBFs maintained

or increased yields, but increased N losses relative to the baseline with mineral N. The Environmental scheme reduced crop yields by up to 10%, but N losses remained similar to baseline fertilisation. BBFs generally improved soil organic N or carbon stocks, indicators of soil quality. Differences in N losses and soil quality in the Agronomic scheme were mainly related to BBFs having different NFRV; a low NFRV (e.g., compost) implies higher total N inputs to maintain yields, leading to excessive N losses in the long run. This suggests that applying BBFs according to the more cautious Environmental scheme can prevent N losses from increasing above baseline levels, with only minor yield reductions (<10%) and potential soil quality improvements. Balanced BBF recommendations should also consider content of other nutrients (phosphorus, potassium) to optimise crop production and environmental protection.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10705-025-10463-z>.

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Keywords Crop yield · Gaseous N losses · Nitrate leaching · Nutrient recycling · Soil organic carbon · Soil organic nitrogen

Introduction

Mineral fertilisers are efficient in providing nutrients to crops. However, the production of mineral nitrogen (N) fertilisers is associated with a large climate impact due to the high energy use in the form of fossil fuels. Moreover, mining of phosphorus (P)

and potassium (K) result in depletion of these limited resources. The increased attention on climate- and environmental concerns has led to increased interest in circular bio-economy where organic waste- and side-streams are recovered, recycled and reused, rather than discarded as waste (EC 2015).

In the European Union, a new fertiliser regulation (EU 2019) recently entered into force and aims to enable bio-based fertilisers (BBFs) to compete with mineral fertilisers on equal regulatory terms in order to promote the substitution of mineral fertilisers with BBFs. Bio-based fertilisers were defined in Wester-Larsen et al. (2022) as “materials or products derived from biomaterials (plant, animal or microbial origin, often wastes, residues or side-streams from agriculture, industry or society) with a content of bio-available plant nutrients suitable to serve as a fertiliser for crops”. In addition, novel BBFs were defined in Wester-Larsen et al. (2022) as “a BBF produced by processes beyond simple biogas digestion of animal manures and simple composting. The processes involved in producing novel BBFs can e.g. be drying, pelletizing or mineral extraction”.

Substituting mineral fertilisers with BBFs produced from organic waste- and side streams could lower the climate- and environmental impacts from fertiliser production. However, the climate- and environmental impacts after application of traditional organic fertilisers, such as manure, have previously been shown to be higher than for mineral fertilisers. The climate and environmental impact of the use of BBFs is variable depending on the specific BBF and application conditions and location (Walling and Vaneekhaute 2020). Therefore, it is advisable to use case specific data whenever applicable. Nitrate (NO_3^-) leaching has been highlighted as a special concern when using fertilisers of organic origin (Torstensson et al. 2006). The risk of emissions of the very potent greenhouse gas nitrous oxide (N_2O) may also increase when using organic fertilisers containing readily available N and easily degradable organic matter (Hansen et al. 2019; Velthof et al. 2003; Petersen et al. 2023). The review of Walling and Vaneekhaute (2020) concluded that there is no consistency in whether application of BBFs will increase, decrease or not change the risk of N_2O emissions, compared to application of mineral N fertilisers. Other recent global meta-analyses show that substituting mineral N fertilisers with organic wastes

can improve crop yields, soil carbon, fertility, and reduce N losses (e.g., N_2O); however, the effects are not consistent and vary with substitution rates, soil types, and environmental conditions, highlighting the importance of site-specific management to optimize outcomes (Fan et al. 2023; Wang et al. 2024). Moreover, organic fertilisers with a high content of ammonium (NH_4^+) are prone to risk of ammonia (NH_3) losses. On the other hand, novel BBFs could contribute to enhanced sequestration of C in the soil, as they contain organic matter (OM), and thereby counteract climate change. These aspects are not well investigated due to the novelty of the BBFs. Furthermore, the environmental and climate impacts might differ between short- and long-term and therefore, the long-term climate- and environmental impacts of applying BBFs are crucial to assess.

For traditional organic fertilisers, the overall agronomic efficiency (yield increase per unit N applied) has been shown to increase with repeated annual applications (Gutser et al. 2005; Zavattaro et al. 2015), due to the mineralisation of residual soil organic N (SON) accumulated from previous applications (Jensen 2013). Thus, the long-term fertiliser effect of novel BBFs are likely to increase with repeated annual applications.

Long-term field trials are costly to run and results on accumulated effects would only become available after many years of trial duration. Therefore, the long-term agronomic efficiency, environmental and climate impacts cannot be easily determined experimentally. Instead, process-based agroecosystem models may be utilised to assess long-term agronomic, environmental and climate effects of BBF application. However, in order to do this, the model needs to be able to reliably simulate both crop production, cycling of carbon (C) and N in soil, water and atmosphere, including soil water transport and availability to crops as well fluxes of C and N containing gases. The Daisy model (Hansen et al. 2012) is such a process-based agroecosystem model, which has been successfully used for simulating cropping systems under variable environmental factors and management practices, especially under European conditions (Rashid et al. 2022a, b).

In the current study, we evaluated the agronomic and environmental performance of eight different organic N-rich BBFs replacing mineral N fertiliser, under different cropping and climate conditions,

using the Daisy model. The objectives of this study were to (i) assess the potential of selected BBFs to replace mineral N fertilisers, maintaining yields while minimising environmental impacts, (ii) quantify the long-term potential effects of BBFs for soil C sequestration and N supply capacity and (iii) assess the implications of using BBFs as a source of N for overall nutrient balances.

Materials and methods

This study was conducted in the following steps: (a) simulation of crop production, soil C and N dynamics for six crop production systems using mineral N as fertilisation (baseline scenarios) representing various European cropping systems, crop rotations and geo-climatic regions, (b) characterising eight different BBFs and calibrating the Daisy model using experimental lab incubation data on C and N turnover from these BBFs under standardised conditions, (c) defining three schemes (different substitution principles) for replacing mineral N fertiliser with BBFs, (d) simulating the baseline scenarios with the eight different BBFs, using three different schemes for mineral N fertiliser replacement by BBF, (e) using simulated crop, soil, and emission results to calculate dry matter (DM) yield, N yield, N losses (gaseous and aquatic), and changes in soil organic C and N stocks under baseline and BBF scenarios.

Model

This study utilised the Daisy model (version 6.22; released on 19-08-2021; <https://daisy.ku.dk/>), which is a deterministic, process-based model that can simulate crop production, and the cycling of C, N and water in the plant-soil-environment continuum. A detailed description of the model can be found in Hansen et al. (2012). In brief, soil water and solute transport are governed by the Richards' and convection–dispersion equations, respectively. Organic matter (OM) decomposition is simulated by the soil OM sub-module, dividing it into fast and slow-decomposing pools influenced by clay content, soil moisture, and temperature. Crop production simulation relies on photosynthesis, regulated by leaf area, radiation, temperature, mineral nitrogen and water availability, and plant senescence. Plant roots' water

uptake is limited by potential evapotranspiration, and is calculated using the Darcy equation and pressure potentials in the soil. N uptake occurs through both mass flow and diffusion. Daisy's groundwater component specifies the groundwater table for soil water simulation, associated with either an aquitard or free drainage. Leaching of inorganic N is described with an advection–dispersion equation, and includes transport to both tile drains (if present) and to the groundwater table (lower boundary). Gaseous N loss can be by either from ammonia (NH_3) volatilization (emission factor approach from applied fertiliser $\text{NH}_4\text{-N}$; see also below section on 'Biobased fertilisation scenarios'), N_2O from nitrification (emission factor from simulated nitrification) and N_2 from denitrification (more complex modelling, depending on water saturation, nitrate-concentration and microbial activity). Data on weather, soil characteristics, and field management activities are also required as input to run the Daisy model.

Development and simulation of baseline crop production scenarios with mineral N fertiliser

Six baseline crop production scenarios were developed, each representing distinct geo-climatic regions/cropping systems across Europe (Table 1). These scenarios were derived from six geo-climatic regions identified in Europe's environmental zones (Metzger et al. 2012), including Atlantic north (ATN), Atlantic central (ATC), Mediterranean east (MDE), Mediterranean west (MDW), continental east (CTE), and continental west (CTW). These scenarios were developed by Duan et al. (2021), where further details can be found. Table 1 details crop and field management (N fertilisation, drainage, and irrigation) obtained from field trials in each geo-climatic region. Briefly, in the baseline scenarios selected from Duan et al. (2021), only conventional mineral N fertiliser was used for all crops, at the same total N rate as in the scenarios with a combination of slurry and mineral fertiliser. The N rates in Duan et al. (2021) were based on experimental farm field practices but in most cases they correspond reasonably to local recommendations. Mineral N fertiliser applications for individual crops were split according to common practices, i.e. one-time for spring sown crops, and two- or three-time splits for winter crops; for comparability, similar timing was done for the BBFs (see below). Irrigation was applied

Table 1 Cropping systems with crop sequences and mineral N fertilisation in the baseline scenario setup, soil properties, water management (drainage, irrigation) and climate (annual average temperature and cumulative precipitation)

Cropping System ¹	Crop sequences (mineral N fertiliser rate, kg N ha ⁻¹ y ⁻¹)						Soil		Drainage (type, depth)	Irrigation	Climate (Avg. temp.; precipitation (°C; mm))
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Sand, silt, clay (%)	Organic C (%)			
ATN	Spring barley (145) ²	Winter rape-seed (215)	Winter wheat (212)	Winter wheat (212)	Spring barley (145)	Winter barley-FR ³ (194)	70, 22, 8	1.50	Tile 1.2 m	No	7.96; 655
ATC	Silage maize (198)	Potato (282)	Sugar beet (212)	Winter wheat (150)			88, 12, 0	2.20	Free	No	10.7; 771
CTE	Spring barley (145)	Winter rape-seed (215)	Winter wheat (212)	Winter wheat (212)	Spring barley (145)	Winter barley-FR (194)	70, 22, 8	1.20	Tile 1.2 m	No	8.0; 462
CTW	Spring barley (145)	Winter rape-seed (215)	Winter wheat (212)	Winter wheat (212)	Spring barley (145)	Winter barley-FR (194)	62, 25, 13	1.50	Tile 1.2 m	No	8.8; 570
MDW	Silage maize (210)	Silage maize (210)	Silage maize (210)	Silage maize (210)	Silage maize (210)	Silage maize (210)	34, 48, 18	0.83	Free	Yes, during summer	14.8; 657
MDE	Silage maize (210)	Silage maize (210)	Silage maize (210)	Silage maize (210)	Silage maize (210)	Silage maize (210)	34, 48, 18	0.83	Free	Yes, during summer	12.8; 710

¹Cropping-system names are based on geo-climatic regions in which they are embedded. The geo-climatic regions are Atlantic north (ATN, western Denmark-Foulum), Atlantic central (ATC, South-eastern Netherlands-Vredepeel), Mediterranean east (MDE, Mid-western Italy-Rome), Mediterranean west (MDW, North-eastern Spain-Girona), continental east (CTE, Central Poland-Warsaw), and continental west (CTW, eastern Denmark-Flakkebjerg)

²The values given in brackets indicate the amount of applied mineral fertiliser N for each crop (kg N ha⁻¹ y⁻¹), which was based on either recommendation or actual experimental farm practices from Duan et al. (2021)

³Catch crop of fodder radish (FR) sown after harvest of winter barley

in scenarios MD and MDW during the summer (May to Sep), at a rate of 30 mm when the soil water pressure head dropped below -600 cm in the top 30 cm soil profile. Arable crops were harvested once at maturity. For cereal crops, potatoes, and sugar beets, harvested dry matter and N yield refers to the storage organ only, meaning that straw/foilage was returned to the soil as crop residues, whereas for silage maize, yields consisted of all harvested aboveground biomass. Daisy crop modules used were calibrated using data on crop dry matter and N yields (Table S1) (Duan et al. 2021; Rashid et al. 2022a, b). The soil OM module was parameterised based on long-term field experimental data by Bruun et al. (2003). Since Daisy model has been widely used and has demonstrated robustness in simulating crop production and C and N dynamics across various scales, seasons, and crop rotations (Manevski et al. 2016, 2019; Rashid et al. 2022a, b), re-evaluation of model processes was omitted, as per common practice (Ozturk et al. 2018).

For simulation of baseline scenarios, the model was run for a 30-year spin-up period followed by 60-year simulations. Due to limited weather data availability (approximately 20 years across locations; 1999–2019 for CTE, MDE, MDW, 1992–2012 for ATN, 1992–2017 for CTW and 1995–2015 for ATC), weather data were reused, and year sequences in subsequent periods were randomised. Soil C and N balance components were logged annually on February 28, at depths of 190 cm for ATN, CTE, and CTW, 180 cm for ATC, and 100 cm for MD and MDW, reflecting variations in rooting and drainage depth.

Biobased fertilisation scenarios

The fertilisation scenarios were based on eight different BBFs (Table 2) and three different fertiliser replacement schemes (FRS).

Bio-based fertilisers and their characterisation for modelling

The eight BBFs chosen for this study were selected from a pool of about 40 high N content BBFs ($>1\%$ total N in dry matter) investigated in the EU LEX4BIO project (Wester-Larsen et al. 2022; www.lex4bio.eu). Seven of these BBFs underwent field trials at four European sites as part of the LEX4BIO research project (Müller et al. 2024), with an

additional two to three local BBFs tested at each site. For this study, three local Danish BBFs and five common BBFs from the four EU sites were selected for their contrasting C and N mineralisation, NH_3 volatilisation, and parent materials. These BBFs differ markedly in total N content, inorganic N fraction, and N:P and N:K ratios; for further details on abbreviations, raw materials, processing and characteristics, see Table 2.

In Daisy, organic matter turnover is simulated in the organic matter module (Bruun et al. 2003; Bruun and Jensen 2002). Added organic matter (AOM, e.g. BBF) is divided into slow and fast decomposing pools (AOM-slow and AOM-fast), characterised by initial OM fractions, turnover rates, and C:N ratios. These parameters were calibrated using lab incubation data on C and N mineralisation from the different BBFs (Agostini et al. 2024). Calibration utilised an automated optimisation routine employing the Nelder-Mead algorithm in Python package SciPy ver. 1.7.3 (Virtanen et al. 2020). The routine aimed to minimise root-mean-square error (RMSE) between simulated and observed values of organic C and N mineralisation fractions using an aggregated objective function. Calibrated parameters are given in Table S2.

The Daisy model also requires data on NH_3 volatilisation losses from field-applied BBFs. For the BBFs PAL and BVC (see Table 2) applied on the soil surface (i.e. in growing crops) and by soil incorporation (i.e. before seeding of spring crops), NH_3 volatilisation values were estimated directly from Wester-Larsen et al. (2022). The actual proportion of N applied lost through ammonia volatilisation was estimated from the accumulated potential ammonia volatilisation determined at day 20 in Wester-Larsen et al. (2022); as a compromise between fast and slow ammonia loss BBFs for each of the two application methods. For the remaining BBFs, values for potential ammonia volatilisation were only available for surface application to a pure sand in Wester-Larsen et al. (2022). Therefore, values for soil-surface and soil-incorporated BBFs were estimated using conversion factors calculated based on BBFs belonging to the same groups (similar material) that in Wester-Larsen et al. (2022) were tested on both soil and pure sand and with both surface application and incorporation (Table 2).

Table 2 Physico-chemical characteristics of the bio-based fertilisers and mineral fertiliser replacement schemes (see footnote text for details), incl. estimated N fertiliser replacement values (N-FRV) and estimated ammonia volatilisation values (see text for more details), N:P ratios estimated from BBF chemical analysis of N and P content and N:K ratios estimated from analysed N content and product declaration informed K content. Information based on Wester-Larsen et al. (2022), Agostini et al. (2024) and Müller et al. (2024). A.D.: Anaerobic digestion for biomethane production

Bio-based Fertilisers abbreviation	Parent material/process	Dry matter (fraction)	Carbon (C _{org}) ^a fraction of DM)	Nitrogen (N _{org}) ^a fraction of DM)	NH ₄ -N (frac-tion of N)	NO ₃ -N (frac-tion of N)	C:N	N:P	N:K	Fertiliser replacement scheme (FRS) ¹		NH ₃ volatilisation		
										Agronomic (NFRV, %)	Environmental (NFRV, %)	Intermediate	Surface (% of Nt)	Incorporated
BA6	Plant residues (wheat, maize) / Bioethanol ferment-distillation	0.907	0.481	0.061	0.014	0.000	7.83	4.53	3.71	S: 67 W: 60	S: 100 W: 100	S: 84 W: 80	1.44	0.03
BIO	Meat & bone meal, apatite, vinasse, chick manure / Pelletising	0.941	0.381	0.079	0.035	0.000	4.85	1.85	3.70	S: 75 W: 64	S: 100 W: 100	S: 88 W: 82	6.84	0.14
BVC	Municipal organic food waste / Initial A.D. + sub-seq. composting	0.557	0.264	0.028	0.081	0.000	9.37	2.04	2.96	S: 12 W: 9	S: 100 W: 100	S: 56 W: 55	1.05	0.0001
FEK	Chicken manure / Drying, extru-sion	0.901	0.385	0.044	0.203	0.000	8.81	3.03	1.64	S: 83 W: 74	S: 100 W: 100	S: 92 W: 87	3.37	0.13
OG2	Horn meal (pig bristles) / Hydrolysis	0.940	0.514	0.148	0.010	0.000	3.47	46.4	1392	S: 75 W: 50	S: 100 W: 100	S: 88 W: 75	1.96	0.06
PAL	Fermented biochar, clay & rock flour / Terra Preta process	0.907	0.427	0.054	0.193	0.001	7.92	5.62	0.82	S: 97 W: 79	S: 100 W: 100	S: 99 W: 90	3.01	0.09
PCW	Potato cell water / Evaporation	0.339	0.329	0.045	0.146	0.011	7.29	3.83	0.24	S: 81 W: 88	S: 100 W: 100	S: 91 W: 94	0.06	0.04
SDG	Agro & food waste + seaweed / Two-phase A.D	0.038	0.285	0.108	0.677	0.000	2.63	6.83	3.73	S: 82 W: 77	S: 100 W: 100	S: 91 W: 89	13.0	4.82

¹Fertiliser replacement schemes (FRS) represent three different principles for substituting mineral fertiliser with bio-based fertilisers. Agronomic FRS utilises 1st year mineral N fertiliser replacement values (NFRV) based on field experimental results for the listed BBFs in both spring (S) and winter (W) sown crops (Müller et al. 2024), meaning BBF total-N > mineral N in baseline. Environmental FRS applies BBF total-N = mineral N in baseline, (assuming a theoretical NFRV = 100%), prioritising environmental considerations. In the Intermediate FRS, the BBFs were applied using NFRVs calculated as the average of the Agronomic and Environmental FRS, as a compromise between opposing interests

Fertiliser replacement schemes (FRS)

When replacing mineral N fertilisers with alternative BBFs, the N fertiliser replacement values (NFRV) indicate the proportion of BBF fertiliser N that can substitute mineral fertiliser N equivalently (Jensen 2013). Typically determined for a single cropping season, NFRV represents the initial year N fertilising effect of the BBF.

Three different fertiliser replacement schemes (FRS) were applied:

- a. **Agronomic FRS:** This assumes farmers prioritise optimising the agronomic yields; when BBFs have an expected NFRV of less than 100% in the application year, farmers may increase BBF total N application (exceeding total N application in mineral fertiliser in the baselines) to maintain yields. For five of the eight BBFs in this study, NFRV values for the Agronomic scheme were estimated from the NFRV determined in field trials at four European sites in the LEX4BIO research project (Müller et al. 2024). These field trials included several levels of mineral N fertiliser (including nil N plots) as reference response curve and BBFs were applied at an equal total N base for NFRV determination. The estimated average first-year NFRV for spring and winter crops across the four sites and two experimental years were used (Table 2). The remaining three BBFs (SDG, BVC, and PCW) were only tested at one field site in Denmark, and for these the agronomic NFRVs were estimated as the average first-year fertiliser replacement value across the two experimental years in Denmark. The NFRV values were estimated for both spring and winter sown crops (soil incorporation in spring before seeding, and surface application in spring during the growing crop, respectively).
- b. **Environmental FRS:** total N application with BBFs was equal to total N application in mineral fertiliser in the baselines (corresponding to an assumed theoretical NFRV = 100%); the expected lower immediate availability is assumed compensated by residual N value when BBFs are applied repeatedly over multiple years. This assumes farmers prioritise environmental protection, limiting the application rate either voluntarily or

adhering to legal regulations that restrict total N application when replacing mineral N with BBF.

- c. **Intermediate FRS:** To strike a balance between farmers' economic incentives and environmental protection goals, the Intermediate FRS simply utilises the average NFRV of the Agronomic and Environmental schemes. This means that the BBF total N application rate will be expected to be in order: Agronomic > Intermediate > Environmental FRS = Baseline.

Because the Daisy model does not simulate the cycling of other plant nutrients such as P and K or the effect of pests and weeds, simulated crop growth and development is only controlled by the global radiation, temperature, soil water and N availability. For the current analysis, we therefore assume that all selected cropping systems are not limited by other nutrients, as the focus was only on the effects and fate of C and N. For P this is a generally valid assumption, as Recena et al. (2022) has shown that 72% of European cropland soils are not limited by soil P status. For K this assumption depends on the local soil and fertilisation legacy conditions, which are outside the scope of the current study.

Simulation of baseline cropping systems with biobased fertilisers

For the scenario analysis, the mineral N fertilisation in all baseline-cropping systems was entirely substituted with BBFs during the entire simulation period. Additionally, simulations were run where BBFs replaced mineral N only in the first 6-years of simulations (one rotation for all cropping systems, except for ATC), after which mineral N fertiliser was used for the subsequent 54 years. This temporary replacement was tested exclusively with the Agronomic and Environmental FRS to examine the long-term trends of BBFs residual effects on yield and N leaching. For the primary analysis, a total of 144 scenarios, i.e. 8 BBFs (Table 2) × 3 FRS × 6 cropping systems (Table 1), were evaluated. For the analysis targeting the residual effects of BBFs, a total of 96 scenarios, 8 BBFs × 2 FRS × 6 cropping systems, were evaluated.

Calculations and compilation of results

The simulated crop and soil C and N dynamics were utilised to calculate: (i) crop N harvested (output N yield), (ii) Gaseous N losses, (iii) Non-gaseous N losses (leaching), (iv) Total N losses (gaseous + non-gaseous), (v) Soil organic C (SOC) and soil organic N (SON) stock changes. Crop N harvested comprised the total N in harvested plant biomass, excluding crop residues and stubble left on the field, which then enter the models soil organic pools. Gaseous losses included NH_3 volatilisation, N_2O from nitrification, total denitrification to N_2O and N_2 , and non-gaseous losses included N leaching through the soil matrix and any tile drains, if present. Changes in soil organic C (ΔSOC) and N (ΔSON) represents annual changes in the entire soil profile's organic C and N stocks.

For the baseline scenarios, average annual values of the abovementioned variables over the 60-year simulation period are presented. To assess the impact of BBFs, results for individual fertilisation scenarios are presented as responses relative to their respective baselines. The relative responses were calculated as follows

$$\text{Relative response} = \frac{\text{value with biobased fertilisation}}{\text{value with baseline fertilisation}}$$

A relative response value of 0.9 or 1.1 under a specific fertilisation scenario therefore indicate a 10% decrease or increase, respectively, relative to the baseline scenario.

Results

Model calibration for C and N mineralisation of added bio-based fertilisers

The calibration results showed good agreement between observed and simulated values of N and C mineralisation, expressed as a percentage of added organic-N and organic-C in the BBF remaining in the soil after application (Fig. 1A, B). For most BBF remaining organic-N declines, indicating net N mineralisation, but for BVC it increases initially, indicating net N immobilisation.

The RMSE values for simulated remaining BBF N were 7.84 for BA6, 6.45 for BIO, 1.91 for BVC, 4.90 for FEK, 3.14 for OG2, 5.67 for PAL, 17 for PCW,

and 31 for SDG (Fig. 1A). Similarly, the RMSE values for simulated remaining BBF C were 3.0 for BA6, 4.1 for BIO, 2.7 for BVC, 2.42 for FEK, 3.3 for OG2, 2.8 for PAL, 14.6 for PCW, and 4.7 for SDG (Fig. 1B). The only exception to the good fit was PCW, where the C mineralisation was underestimated (remaining C simulated higher than measured), but N mineralisation was overestimated (remaining N simulated lower than measured) within the 84-day incubation period of the measured data. For further reflections on this, see [Discussion](#).

Crop production, carbon and nitrogen dynamics with baseline mineral N fertilisation

The simulated C and N dynamics across the crop rotations of the scenarios, including crop N harvest (N yield), DM yield, gaseous and leaching N losses and SOC and SON stock changes, showed considerable variability among cropping systems under baseline fertilisation (Table 3). Individual simulated crop DM and N yields in the different scenarios can be found in the suppl. mat. (Table S1). The MDE and ATN cropping systems had the highest and lowest N harvest, respectively, while the highest and lowest DM yields were simulated for MDE and CTE, respectively. Gaseous N losses were highest from the cropping systems with maize monocultures (MDE and MDW), and least from CTE. In contrast, N leaching was highest from ATC. All cropping systems resulted in decrease of SOC and SON stocks (Table 3), indicating depletion of soil organic matter. The highest depletion of SOC and SON stocks was observed for ATC, -22 and $-313 \text{ kg N and C ha}^{-1} \text{ y}^{-1}$, respectively, while the smallest depletion (stable stocks) of SON and SOC stocks was observed for CTE and MDE, respectively. The N use efficiency ($\text{NUE} = \text{harvested N}/\text{total N input}$) was relatively high for all cropping systems, varying from 71% (ATC) to 82% (CTW).

The MDE and MDW cropping systems, which had the same maize monoculture cropping, but different climates (temperature and precipitation), exhibited differences in N and C dynamics. Compared to MDW, MDE had slightly higher N and DM yields but lower or similar N losses and SON and SOC stock depletion rates. Likewise, the CTW, when compared to CTE, resulted in higher N and DM yields but higher gaseous N losses and SON and SOC depletion rates.

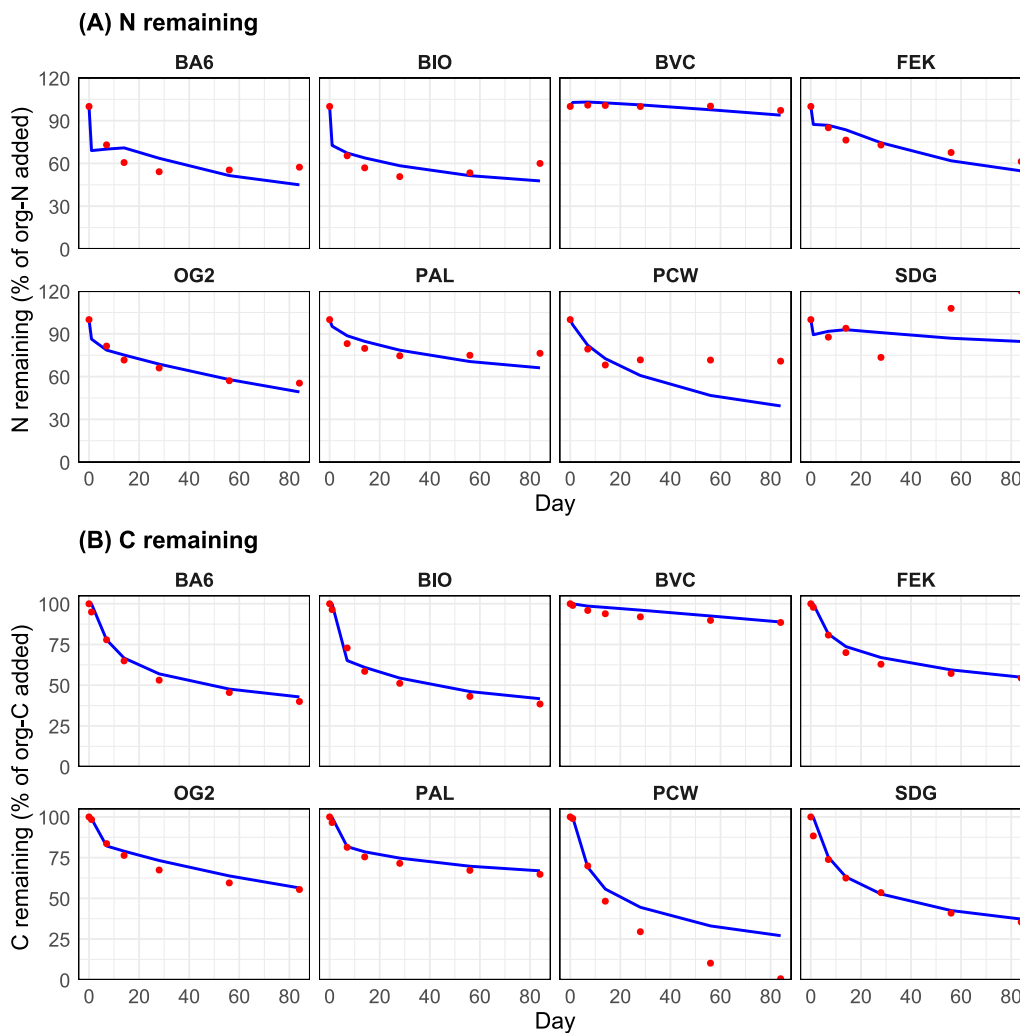


Fig. 1 Simulated (blue line) and observed (red dots) patterns of the fraction of added organic-N (**A**) and organic-C (**B**) remaining from the eight bio-based fertilisers (please refer to Table 2 for BBF descriptions), i.e. the declining curves indicates N or C mineralisation, respectively. Observed values

were determined in laboratory incubation experiments (Agostini et al. 2024). Calibration of Daisy parameters for each BBF (Table S2) utilised an automated optimisation routine (Nelder-Mead algorithm) minimising root-mean-square error (RMSE)

Effects of bio-based fertilisers compared to baseline fertilisation

The results for the effects of BBFs on N and DM yields, and gaseous and leaching N losses, are presented as the average of all cropping systems relative to baseline fertilisation (Figs. 2; 3).

Crop N and DM yield

When applied according to Agronomic FRS (NFRV < 100%, see NFRV values for individual BBFs in Table 2), all BBFs either increased or maintained crop N and DM yields relative to the baseline fertilisation, with the highest increase observed under BVC (30% and 15% increase of N and DM yields, respectively) (Fig. 2, top pane). However, when BBFs were applied according to the Environmental FRS (NFRV assumed = 100% for all BBF, resulting in

Table 3 Simulated nitrogen and soil organic carbon balance of the six cropping systems (please refer to Table 1 for cropping system descriptions) with baseline fertilisation (mineral N fertiliser). Total N input is the sum of N in fertilisers, atmospheric N deposition, and seed N. NUE: N use efficiency = har-

vested N/total N input, Δ SON and Δ SOC: annual change in soil total N and C stocks, respectively. The majority of gaseous N loss in the baselines stems from denitrification and nitrification (N_2 and N_2O)

Cropping system	N input (kg ha ⁻¹ y ⁻¹)	N harvest (kg ha ⁻¹ y ⁻¹)	Dry matter yield (Mg ha ⁻¹ y ⁻¹)	NUE (%)	Gaseous N loss (kg ha ⁻¹ y ⁻¹)	N leaching (kg ha ⁻¹ y ⁻¹)	Δ SON (kg ha ⁻¹ y ⁻¹)	Δ SOC (kg ha ⁻¹ y ⁻¹)
ATC	239	170	14.5	71	16	75	-22	-313
ATN	204	146	10.7	72	9	54	-5	-71
CTE	201	156	9.5	78	7	43	-1	-31
CTW	202	166	11.4	82	14	26	-5	-55
MDE	235	190	21.3	81	21	29	-5	-16
MDW	235	187	19.3	80	21	34	-7	-42

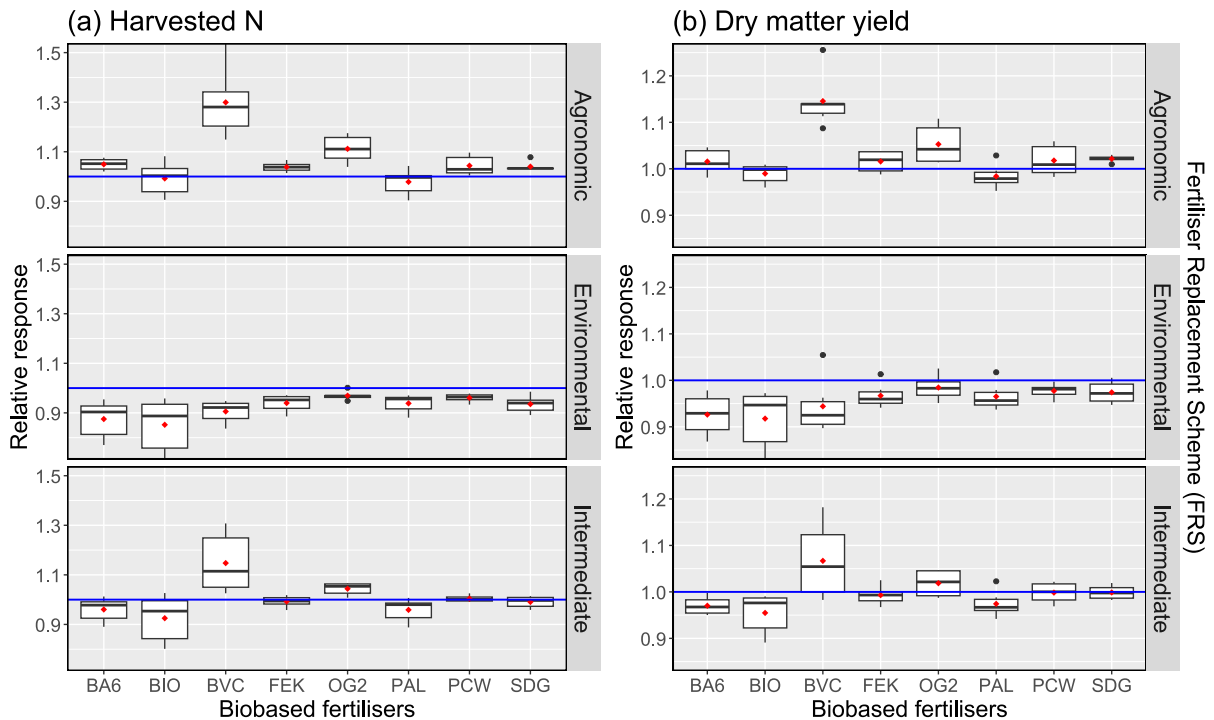


Fig. 2 Effect of different bio-based fertilisers (please refer to Table 2 for BBF descriptions) on **a** harvested N and **b** dry matter yield in the different fertiliser replacement schemes (Agronomic, Environmental, and Intermediate, see [Materials & Methods](#) for definition). The results are shown relative to the baseline fertilisation, which was mineral N fertiliser. The

boxplots are showing the variation due to different cropping systems. The red point inside the boxplots represents the mean of all cropping systems. The blue line serves as the reference baseline, with values above and below this line indicating an increase or decrease, respectively, relative to the baseline. A change from 1.0 to 1.1 indicates a 10% increase

lower total N input), all BBFs resulted in lower crop N and DM yield, with the highest reduction under BA6 and BIO (Fig. 2, middle pane). When BBFs were used to replace baseline fertilisation according

to the Intermediate FRS (an average of agronomic and environmental NFRVs), all BBFs, except BVC tended to maintain crop N and DM yields at the same level as the baseline (Fig. 2, lower pane). BVC increased

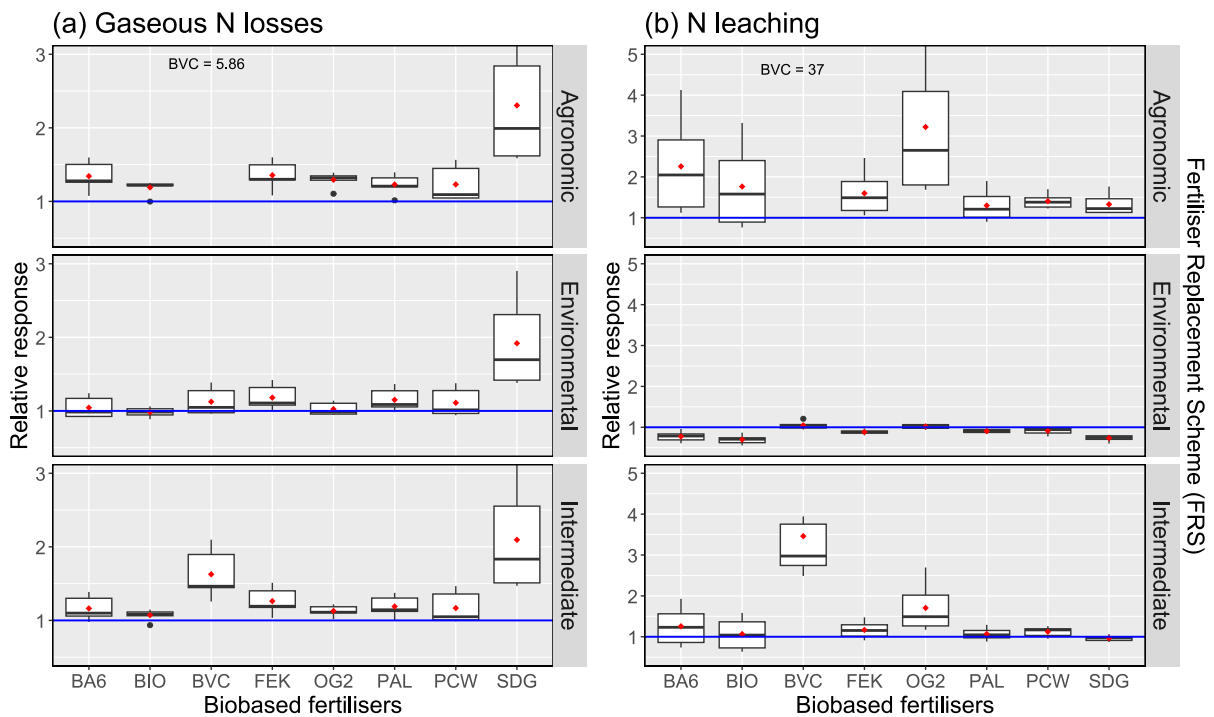


Fig. 3 Effect of different bio-based fertilisers (please refer to Table 2 for BBF descriptions) on gaseous N losses (a) and N leaching (b) in the different fertiliser replacement schemes (Agronomic, Environmental, and Intermediate, see Materials & Methods for definition). The results are shown relative to the baseline fertilisation, which was mineral N fertiliser. The

red point inside the boxplots represents the mean of all cropping systems. The blue line serves as the reference baseline, with values above and below this line indicating an increase or decrease, respectively, relative to the baseline. A change from 1.0 to 1.1 indicates a 10% increase. Note that BVC is out of scale (value given) for the Agronomic FRS

N (7%) and DM yields (15%) even in Intermediate FRS. However, BVC also showed much higher variation across the different cropping systems in the Agronomic and Intermediate fertiliser replacement schemes, than any of the other BBFs. BIO showed the second largest variation across cropping systems, in all fertiliser replacement schemes. The results for BBFs effects on crop N and DM yields of individual cropping systems are given in Fig. S1 and Fig. S2.

Gaseous and N leaching losses

For the Agronomic FRS gaseous and N leaching losses were higher with BBFs (Fig. 3), especially BVC (compost), which increased gaseous and leaching N losses on average by 5.9 and 37 times, respectively. SDG also increased gaseous N losses on average by 2.3 times, while OG2 increased N leaching on average by 3.2 times (Fig. 3, top pane). In contrast, with the Environmental FRS, N losses were either

lower than the baseline (N leaching) or the increase in gaseous N losses was much less than under the Agronomic FRS (Fig. 3, middle pane). The highest increase in gaseous N losses was observed for SDG (digestate, 1.9 times higher than the baseline), which is also the BBF with the highest estimated NH_3 volatilisation risk (Table 2), and the vast majority of this increase in gaseous N loss stems from NH_3 volatilisation. Under the Intermediate FRS, SDG and BIO (meat & bone meal) resulted in the highest (110%) and lowest (7%) increases in gaseous N losses, respectively. The highest increase in N leaching (around 250%) was observed for BVC (Fig. 3, lower pane). However, SDG showed by far the highest variation in gaseous losses across cropping systems in all fertiliser replacement schemes. BA6, BIO BVC and OG2 showed the largest variation in N leaching across cropping systems, in all fertiliser replacement schemes. The results for BBF effects on N losses in

individual cropping systems are given in Fig. S3 and Fig. S4.

SOC and SON stock changes

In the Agronomic FRS (Fig. 4a), all BBFs had a positive effect on SOC stocks, especially BVC (compost), with a SOC rate of change of $> 1500 \text{ kg C ha}^{-1} \text{ y}^{-1}$ over the 60-year simulation period, due to the relatively high BVC application rate in this FRS, around 70–80 ton of dry matter $\text{ha}^{-1} \text{ y}^{-1}$. For other BBFs, the average SOC rate of change ranged from $-16 \text{ kg C ha}^{-1} \text{ y}^{-1}$ (OG2, horn meal) to $+239 \text{ kg C ha}^{-1} \text{ y}^{-1}$ (BA6, bioethanol residue), which can be compared to the more negative SOC rate of change with baseline fertilisation ($-88 \text{ kg C ha}^{-1} \text{ y}^{-1}$). BBFs also increased SOC stocks under the Environmental and Intermediate FRS, although the effect magnitude was smaller. The SOC rate of change varied from $-47 \text{ kg C ha}^{-1} \text{ y}^{-1}$ (OG2) to $+117 \text{ kg C ha}^{-1} \text{ y}^{-1}$ (BA6) in the Environmental FRS and from -34 kg C ha^{-1}

y^{-1} (OG2) to $+165 \text{ kg C ha}^{-1} \text{ y}^{-1}$ (BA6) in the Intermediate FRS, compared to the baseline ($-88 \text{ kg C ha}^{-1} \text{ y}^{-1}$). In all the FRS, a negative ΔSOC for most BBFs (except BA6) is evident from one cropping system, namely the ATC as can be identified in Fig. S5 (suppl. mat). The reason is that the ATC crop rotation includes potatoes and sugar beet (2 out of 4) crops in the rotation, which leave relatively less crop residues than cereals dominating other scenarios; furthermore, ATC does not include catch crops like ATN, CTE and CTW, which also contributes to maintaining SOC. Still, even in ATC all the BBFs result in a more positive ΔSOC than the baseline mineral N fertiliser, see Fig. S5.

The effect of BBFs on SON stock changes is presented in Fig. 4b. Compared to the cropping systems' average with baseline fertilisation ($-7.7 \text{ kg N ha}^{-1} \text{ y}^{-1}$), BBFs exhibited positive effects under all FRS. Under the Agronomic FRS, the SON rate of change ranged from $-1 \text{ kg N ha}^{-1} \text{ y}^{-1}$ for OG2 to $+140 \text{ kg N ha}^{-1} \text{ y}^{-1}$ for BVC. Similarly, the SON rate of change

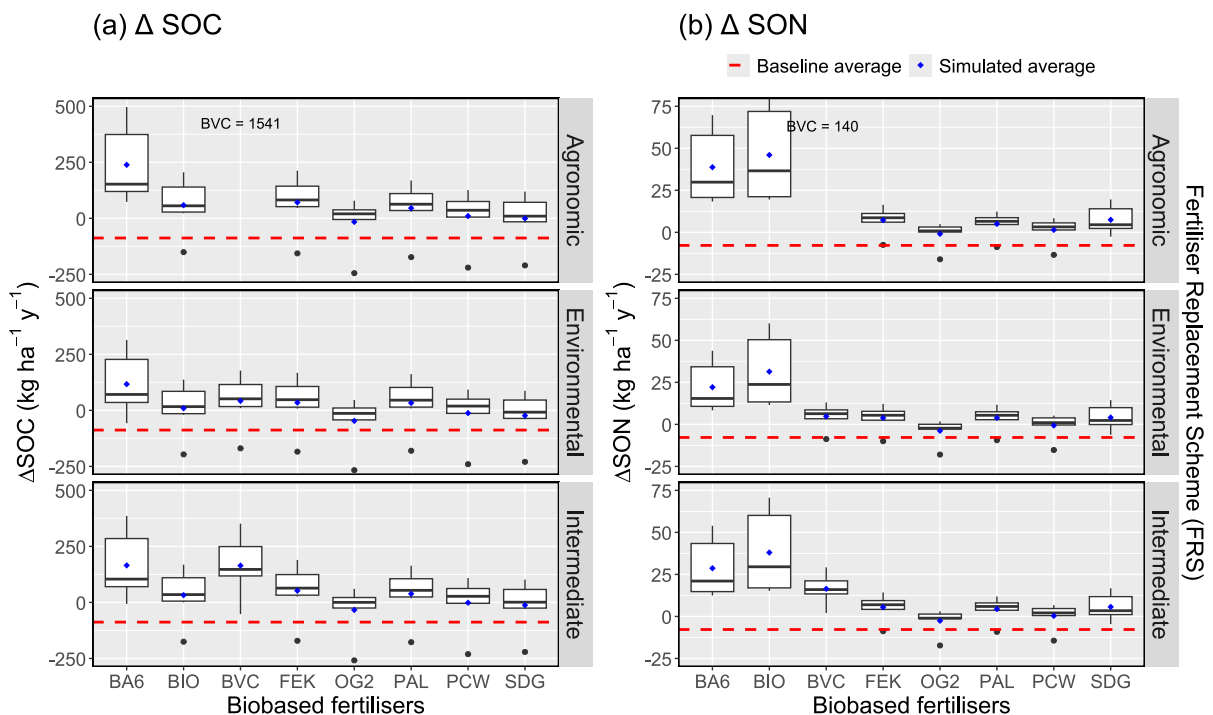


Fig. 4 Effect of different bio-based fertilisers (please refer to Table 2 for BBF descriptions) on soil organic C (a) and N (b) average stock changes over the 60-year simulation period in the different fertiliser replacement schemes (Agronomic, Environmental and Intermediate, see Materials & Methods for defi-

nition). The red dashed lines indicate average stock changes across cropping systems with baseline fertilisation (mineral N fertiliser). The blue point inside the boxplots represents the simulated average of all cropping systems. Note that BVC is out of scale (value given) for the Agronomic FRS

varied from $-4 \text{ kg N ha}^{-1} \text{ y}^{-1}$ under OG2 to $+31 \text{ kg N ha}^{-1} \text{ y}^{-1}$ under BIO in the Environmental FRS, and from $-3 \text{ kg N ha}^{-1} \text{ y}^{-1}$ under OG2 to $+38 \text{ kg N ha}^{-1} \text{ y}^{-1}$ under BIO in the Intermediate FRS. The results for the effects of BBFs on SOC and SON stocks of individual cropping systems are given in Fig. S5 and Fig. S6.

Residual effects of bio-based fertilisers

The BBFs showed variation in their residual effects after application, assessed by using the BBFs for the first six years (one rotation cycle for most scenarios) followed by the application of mineral N fertiliser for the remaining 54 years. In the Agronomic FRS, the residual positive effect of BBFs on DM yield was not long-lasting and mainly appeared for BVC and OG2

(Fig. 5a). These BBFs had the lowest NFRV and the highest total N application rates. The residual effect of BBFs on N leaching was observed for many years, with the highest effects seen with BVC, BA6, and BIO (Fig. 5c).

In contrast, with the Environmental FRS (NFRV=100%), the simulated DM yield from a one-time application of BVC, BIO, and PAL took longer to match the level under reference fertilisation (Fig. 5b). Additionally, BIO and BA6 in the Environmental FRS resulted in less N leaching compared to reference fertilisation, leading to a longer time for cumulative relative leaching to reach reference levels. BVC and OG2 had considerably higher leaching even under Environmental FRS, with cumulative relative leaching nearing 100% (baseline scale) soon after a one-time application (Fig. 5d).

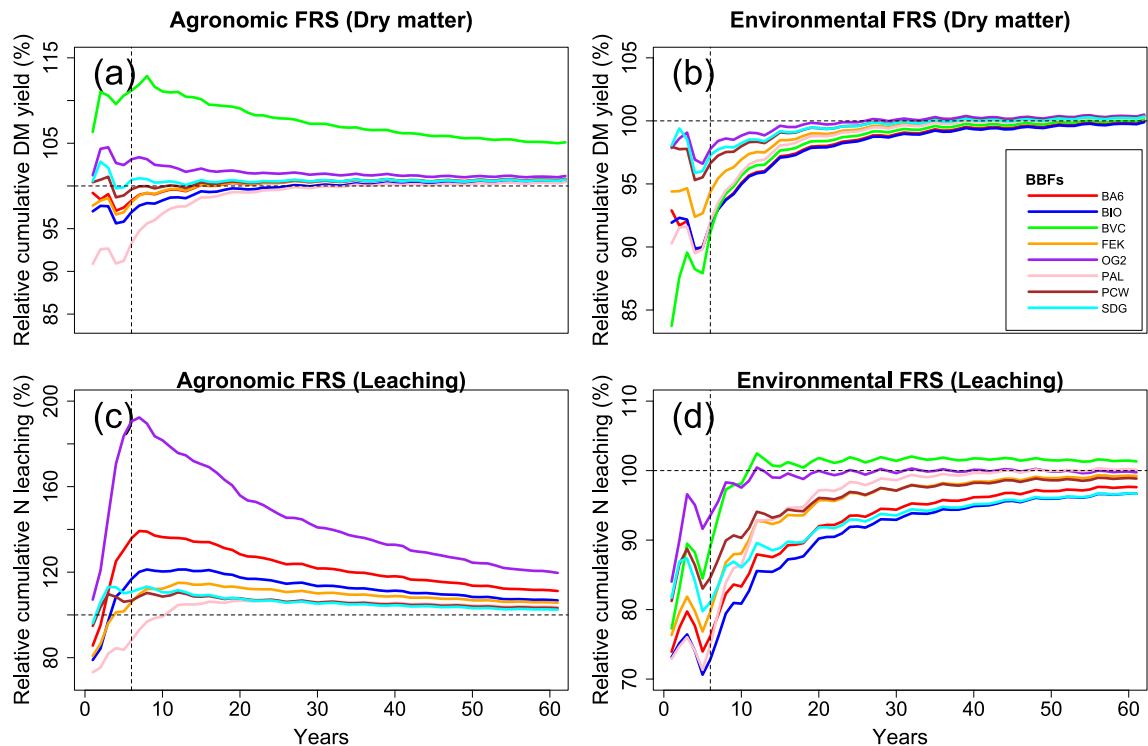


Fig. 5 Cumulative dry matter yield (a, b) and N leaching (c, d) resulting from eight bio-based fertilisers (for BBF descriptions, please refer to Table 2) over time expressed as a percentage relative to the baseline (mineral N fertiliser), with two fertiliser replacement schemes – Agronomic (a, c) and Environmental (b, d) (see Materials & Methods for definition). The BBFs were applied for the first six years, as indicated by the vertical dotted line, followed by the application of mineral N fertiliser only in all remaining years. The relative cumulative

values are calculated using the cumulative values with specific BBFs and mineral N fertiliser baseline. The legacy effect of 6 years of BBF application on dry matter yield and N leaching over the subsequent 54 years is depicted by how quickly or slowly the cumulative yields and leaching values approach the baseline (100%). Note that in Fig. (c) N leaching under BVC is out of scale, with values of 563% in year 1, 1777% in year 6, and 430% in year 60

Effects of bio-based fertilisers on balanced application of phosphorus and potassium

To understand how replacement of mineral N fertilisers with BBFs affects the supply of other macro nutrients like P and K, the BBF N:P and N:K ratios (Table 2) were used to calculate P and K application rates in the Agronomic, Environmental and Intermediate FRS.

The average crop N fertiliser requirement across all the cropping systems (Table 1) was 203 kg available N ha⁻¹ y⁻¹. In the Environmental FRS, where total N in BBFs is applied equal to mineral fertiliser N in the baseline, this means that for all eight BBFs an average of 203 kg total N ha⁻¹ y⁻¹ is applied across the rotations (Table 4). With this N application rate, the P application rate will vary from 4 to 110 kg P ha⁻¹ y⁻¹ on average for the different BBFs. Correspondingly, the K application rate will vary from 0 to 862 kg K ha⁻¹ y⁻¹ on average for the different BBFs (Table 4), due to the highly different N:P and N:K ratios of the BBF. For comparison, typical arable crop P and K supply requirements for the crops in the six cropping systems will vary between 15 and 35 kg P ha⁻¹ y⁻¹ and 50–200 kg K ha⁻¹ y⁻¹ (Finck 1982).

On the other hand, if the BBF are applied according to the Agronomic FRS, both total N and total P and K application rates increase, especially for those BBF which have a lower NFRV, e.g. BVC, OG2 and

BA6. In particular BVC, with an estimated agronomic NFRV of only 12 and 9% for spring and winter crops, respectively, result in very high total N application rate (1932 kg N ha⁻¹ y⁻¹), and correspondingly high P and K application (947 kg P ha⁻¹ y⁻¹ and 652 kg K ha⁻¹ y⁻¹, respectively). However, the highly different N:P and N:K ratios of the different BBFs also lead to large P or K application rates for some of the other BBFs; i.e. 158 kg P ha⁻¹ y⁻¹ for BIO and 1020 kg K ha⁻¹ y⁻¹ for PCW in the Agronomic FRS.

Discussion

Data and model calibration for bio-based fertilisers

The performance of BBFs will depend on their physicochemical characteristics as well as their C and N mineralisation patterns upon application in the field, which can be studied experimentally but requires time and space. The approach used in this study is unique, as it utilises data from incubation experiments for C and N mineralisation of BBFs to calibrate the relevant model parameters for added organic matter turnover and use these in the model when substituting mineral N fertiliser in the baseline scenarios with BBFs. The calibration data from Agostini et al. (2024) also provided further dynamic insights into C and N turnover for diverse BBFs, highlighting significant variability

Table 4 Total annual application rate of N, P and K with the different bio-based fertilisers (BBF, please refer to Table 2 for detailed descriptions), depending on the mineral fertiliser replacement scheme (Agronomic or Environmental, see [Materials & Methods](#) for details) and the N:P and N:K ratios of

individual BBFs. Total N application in the two FRS depend on the estimated fertiliser replacement values (NFRV, Table 2) and are based on an average N application rate across all crops in the six baselines (Table 1) of 203 kg N ha⁻¹ y⁻¹

BBF	Parent material	Total N applied (kg N ha ⁻¹ y ⁻¹)		Total P applied (kg P ha ⁻¹ y ⁻¹)		Total K applied (kg K ha ⁻¹ y ⁻¹)	
		Agronomic	Environmental	Agronomic	Environmental	Agronomic	Environmental
	FRS:						
BA6	Plant based	319	203	71	45	86	55
BIO	Meat and bone meal	292	203	158	110	79	55
BVC	Food waste compost	1932	203	947	99	652	68
FEK	Chicken manure	258	203	85	67	157	124
OG2	Horn meal (pig bristl.)	325	203	7	4	0	0
PAL	Ferm. biochar/clay	230	203	41	36	283	249
PCW	Potato cell water	240	203	63	53	1020	862
SDG	Biogas digestate	255	203	37	30	68	54

FRS=fertiliser replacement schemes based on either estimated 1st y NFRV of the BBFs (Agronomic) or a total N applied in BBF equivalent to the baseline mineral N fertiliser (Environmental).

among them. Some BBFs exhibit high degradability, releasing nearly 100% of BBF C within 84 days of aerobic incubation (PCW), while others release only about 10% of added C (BVC). Similarly, N mineralisation ranges from minimal release or even N immobilisation (BVC) to over 40% of total N mineralised (BA6, BIO, OG2), with some achieving rapid mineralisation already within 15–30 days. The range is similar to that found by Levavasseur et al. (2022) in their database containing N mineralisation data for more than 600 exogenous organic materials (animal manures, composts, digestates, sludges, etc.) and similar to other previous studies (Calderón et al. 2005; Morvan et al. (2006).

The model effectively captured most C and N mineralisation dynamics (Fig. 1), except for PCW (potato cell water). PCW, a by-product of industrial potato starch extraction, contains residual protein, amide-bound N, and suspended solids. During storage, organic solids degrade, resulting in a high pH and carbonate content. The significant C loss produced during incubation (Fig. 1B, PCW) may therefore not solely result from biological degradation, but also from off-gassing or carbonate dissolution and release as CO₂. This could explain the limited concurrent N mineralisation observed (Fig. 1A, PCW), with only about 35% of the applied total N mineralised over three months. Daisy's fit to these somewhat contradictory kinetics is a compromise due to its inability to model inorganic carbonate chemistry in this BBF. However, we did also test the implications of fitting to either the C or the N mineralisation data of PCW for the short-term (84-day) incubation, and the effects on crop yields or emissions in a yearly or multi-annual timescale were relatively minor.

While the BBF mineralization data from Agostini et al. (2024) are suitable for calibrating the model for short-term C and N turnover dynamics, their relatively brief duration (less than 3 months at 15 °C and optimal moisture) may only justify using them to calibrate the model for short-term and not the medium- to long-term BBF C and N dynamics. For this, we relied on earlier extensive calibrations of the Daisy model using organic amendments, including medium-term (one growing season, Mueller et al. 1998, 2003) and long-term field data (Jensen et al. 1997; Bruun et al. 2003). Previous studies have shown that the Daisy model, with these calibrations, can successfully evaluate scenarios and estimate emission factors for

added organic C and N (Yoshida et al. 2016; Bruun et al. 2016).

Agronomic impacts of replacing mineral with bio-based N fertilisers

When replacing mineral N fertilisers with alternative BBFs, farmers would prioritise optimising their agronomic yields and hence knowing an expected NFRV for the BBF in question is crucial. However, as the expected NFRV is typically less than 100% when considering only crop response in the application year, farmers will increase BBF total N application, exceeding total N application in mineral fertiliser in the baselines, to maintain crop yields. The results from this study indicate that in the Agronomic FRS, all BBFs resulted in similar or slightly higher DM and N yields (Fig. 2) compared to the baseline. Notably, OG2 and BVC showed 5–15% higher yields and 10–30% higher N harvests across six cropping systems. Müller et al. (2024) conducted a 2-year field trial across multiple European sites, including the same BBFs as in the current study, and found that the first year yield response of BVC was very low, with a NFRV only around 9–12%, and for OG2 around 50–75%, with application rates based on equivalent total N. It should be noted that for BVC in the Agronomic FRS this low NFRV estimate resulted in a somewhat excessive BVC compost application rate, around 130–140 t fresh matter ha⁻¹, as also indicated by the excessive P and K rates in Table 4 (942 kg P and 652 kg K ha⁻¹, respectively). This contradiction between the short-term (first growing season) experimental results and the long-term modelled impact on yields was likely due to both the higher total N application of these two BBFs in the Agronomic FRS, related to their estimated lower first-year NFRV (Table 2), and to their consequent significantly higher N mineralisation in subsequent years, as residual organic N from the BBF accumulates. Hendriks et al. (2022) also reported no significant difference in potato yield when comparing mineral fertiliser with a combination of manure and BBF, suggesting that the plant-available N from BBFs applied according to the Agronomic FRS likely remained comparable to or slightly higher than baseline fertilisation. Müller et al. (2024) also found a positive residual yield effect of most of the BBFs in the second year.

In the Environmental FRS, where total N application with BBFs was not allowed to exceed total N application in mineral fertiliser in the baselines, average DM yield and N harvest over the 60 years simulated generally declined relative to the baseline (Fig. 2, centre panel), albeit only a little, with most declines less than 10%. However, it should be noted that the initial yield decline is much greater; especially for BVC it is more than 15% in the first year, due to its low N mineralisation rate (Fig. 1A). The average effect over the 60-year simulation still suggests a negative effect, though only around 5% for DM yield of BVC (Fig. 2b), indicating that increasing residual N mineralisation over time can only partly compensate for N losses from poor synchronisation of N mineralisation and crop demand. Poor synchronisation of N release seems to play an even larger role for e.g. BA6 and BIO, where reductions averaged over 60-years in dry matter yield (7–8%) and harvested N (12–15%) are larger than for BVC (Fig. 2). Other studies have found that evaluating BBF products based on total plant-available N (assuming NFRV of $\text{BBF} = \text{proportion of mineral N}$) yields similar performance as the mineral fertiliser reference (Gunnarsson et al. 2010; Huygens et al. 2020; Sigurnjak et al. 2019; Luo et al. 2022; Prado et al. 2023a, b).

The variation in DM yield and harvested N is very high for BVC, but also relatively high for BIO. For BVC the main reason is the low estimated fertiliser replacement value (9–12%, Table 2), which implies crop performance and response to BVC more prone to local soil, climate and crop conditions. For BIO the higher variation is likely derived from its characteristics (Table 2; Fig. 1); a very low C:N ratio, rapid N mineralisation, and relative high potential ammonia volatilisation, similarly making BIO more prone to scenario conditions.

Environmental impacts of replacing mineral with bio-based N fertilisers

It is known that BBF application may lead to higher N losses, attributed to the asynchrony between mineral-N release and crop demand, as well as increased potential for NH_3 and denitrification N losses due to higher ammonium content, easily degradable carbon content, and pH (Schröder et al. 2013; Svoboda et al. 2013; Nkoa 2014; Surey et al. 2020). In this study, N losses were generally higher across all BBFs in the

Agronomic FRS compared to the baseline (Fig. 3), especially for BVC due to its very high total N application. Additionally, digestate (SDG) also resulted in higher gaseous losses (Fig. 3a, primarily due to higher NH_3 volatilisation (in Table 2 the highest of all BBFs)). The N leaching losses were generally two to three times higher from animal by-products (BA6, BIO, and OG2) but also from the BVC than the baseline in the Agronomic FRS (Fig. 3b), mainly because their relative lower fertiliser replace value in the Agronomic FRS (Table 2), implying rather excessive total N application rates. This also produces the largest variation in N leaching across all scenarios, due to the variations in soil, climate and crops.

Overall, the simulated leaching N losses from the different BBFs were consistent across cropping systems (Fig. S4), whereas the gaseous N losses varied more across cropping systems. Gaseous N losses were consistently higher from the MDW and MDE systems growing silage maize only (Fig. S3), mainly due to larger off-season risks of N loss through denitrification, due to heavier soils, higher precipitation and warmer winter temperatures. In the Environmental FRS, the leaching and gaseous N losses were generally much lower, while in the Intermediate FRS, they fell in between but were closer to the Environmental FRS, clearly indicating the non-linearity of especially environmental responses. These results indicated that the higher total N input in the Agronomic FRS was the key cause of the higher N losses. Prado et al. (2023a) also found a higher risk of N and P leaching with BBFs due to nutrient ratio imbalances and the need to adjust application rates not only to the NFRV of the BBF but also to the nutrient ratios.

Wester-Larsen et al. (2022) found that a number of the BBFs included in this study had the potential for high NH_3 volatilisation losses. Martin et al. (2023) also found high NH_3 loss potential for urine-based BBFs (up to 34%), but also a high NFRV of these (> 70%). In this study, only a few of the BBFs showed NH_3 volatilisation to be the major part of gaseous N loss (BIO 58%, SDG 72%), while for the remaining BBFs the main gaseous loss of N simulated was by nitrification or denitrification to $\text{N}_2\text{O}/\text{N}_2$, with only between 1% (PCW) and 24% (FEK) being emitted as NH_3 volatilisation (data not shown, only as total gaseous N loss in Fig. 3a and S3). Egene et al. (2022) found that cumulative N_2O emissions from BBF treatments were either comparable or lower than

when mineral fertilisers were applied, and Martin et al. (2023) made similar findings. However, organic BBFs tend to stimulate microbial activity, increasing O_2 consumption and CO_2 emission, mostly in the first days after application. Such rapid turnover may create conditions (hot spots and hot moments) conducive to N_2O formation and loss, contributing to climate change (Butterbach-Bahl et al. 2013; Schwager et al. 2016). However, currently, the Daisy N turnover model is not conceptually built for reliable prediction of dynamic N_2O emissions, so we cannot interpret these effects from the simulated results. Work is currently ongoing to enable Daisy to simulate N_2O emission dynamics more correctly (see <https://daisy.ku.dk/>).

Long-term potential effects of BBFs for soil C sequestration and N supply capacity

The BBFs affect SOC and SON stocks positively due to the higher addition of organic material. In this study, all BBFs led to positive long-term changes in SOC and SON relative to the baseline in all FRS (Fig. 4). Especially BVC (compost) resulted in 'out of scale' impacts on SOC and SON in the Agronomic FRS, mainly due to the low NFRV and consequently very high application rates (130–140 t fresh matter ha^{-1}). From a practical point such a compost application rate is excessive, as composts would rarely be used as a sole first year N source; however here it was maintained in the Agronomic FRS for consistency. Conversely, in the Environmental FRS, all BBFs behaved more similarly, including the BVC (here applied around 12–14 t fresh matter ha^{-1}). Moretti et al. (2020) also found that compost application initially led to yield reduction but produced better N fertiliser value in the medium term with repeated application, along with significant increases in labile organic soil fractions. Wester-Larsen et al (2024) found that the same compost (BVC) improved soil quality most (particularly total C, water-holding capacity and CEC). Thomas et al. (2019) found that digestates, compost, and farmyard manure improved grain yield and soil organic matter relative to mineral fertilisation only, with higher increases in SOC and SON associated with higher nutrient concentrations in grain, mitigating 'biomass dilution' of secondary and micronutrients found with mineral fertilisation only. This BBF-induced C and N retention in the soil

is beneficial not only for N supply capacity but also for securing plant protein content.

Enhancing soil long-term N supply capacity will also risk increasing N leaching. However, using ^{15}N -labelled cattle slurry, Frick et al. (2022) found that most nitrate leaching originated from the mineralisation of soil organic N, with relatively little from the recently applied slurry N. In the current study, some BBFs initially contributed significantly more to off-season N leaching (in particular BVC, but also OG2, BA6 and BIO) in the Agronomic FRS. For BVC this is mainly due to excessive total N input, while for the other it is mainly from poor synchrony between N mineralisation and crop demand, with residual N leaching persisting over subsequent rotations (Fig. 5c). However, in the Environmental FRS, leaching consistently remained below the baseline over all-years (Fig. 5d), again illustrating the non-linear response of the cropping system. In the Environmental FRS, all BBFs resulted in less initial leaching than in the mineral reference baseline, particularly BA6, BIO, and PAL, but in the long-term it levels out towards the baseline (Fig. 5d). These effects are due to the amount of total N application, quality of the BBFs and linked to asynchrony between crop demand and release of organically bound N (de Boer 2017; Kandel et al. 2020).

Balancing inputs of all nutrients with application of bio-based fertilisers

The primary focus of the current study was N, but it is crucial to acknowledge that BBFs also contain P, K and other essential nutrients. All the organic matter-rich BBFs in this study, except one (OG2), contain both N, P, and K. However, when applied solely as a source of N, the fertiliser ratios of N:P and N:K (Table 2) result in unbalanced P and K applications, as illustrated in Table 4. Achieving more balanced fertilisation relative to crop demand may require adjusting BBF application rates and supplementing with mineral N (and P or K) or combining with a suitable complementary BBF to optimise the N:P:K ratio according to crop needs and to adhere with nutrient application restrictions. Alternatively, the P and K supply strategy could be optimised at the crop rotational level rather than aiming to fulfil individual seasonal crop P and K needs. Nevertheless, some BBFs may be challenging to use as the sole fertiliser; for

instance, BIO and PCW would require supplementary N to compensate for their high P or K content, respectively.

It is also important to recognise that practical logistics and geographical distribution may pose barriers to implementing more N:P:K-optimised bio-based fertilisation strategies, particularly for bulky BBFs. For example, Akram et al. (2019) found that recycling all excreta (human and livestock) in Sweden at the national level could meet up to 75% of crop N and 81% of P needs, but would exceed crop K needs by >50%. Addressing large regional differences and imbalances in nutrient surplus and crop needs would require reallocation geographically to avoid over- or under-fertilisation, which could incur significant transport costs, often exceeding the total NPK fertiliser value of transported excreta. Similar challenges exist at the European level, where significant imbalances in P surplus and demand occur across member states (van Dijk et al. 2016), mainly due to regions with highly concentrated livestock production. Nonetheless, considering BBFs as multi-nutrient fertilisers will be crucial for implementing balanced nutrient management strategies to optimise crop productivity while mitigating environmental risks. Future research should prioritise assessing all nutrient contents in BBFs and their agronomic and environmental impacts, including crop yields and nutrient losses, as well as addressing logistical challenges.

Conclusions

Based on the modelling of agronomic and environmental performance for eight BBFs using different schemes of N fertiliser replacement in selected European cropping systems we conclude:

- The BBFs showed clear potential to replace mineral N fertiliser and maintain or even increase yields in the long-term when applied according to the estimated BBF first-year agronomic N fertiliser replacement value (NFRV < 100%). However, in this case, BBFs also tended to increase environmental N emissions, especially BBFs with low NFRV (hence applied at higher total N input rates).
- When BBFs were applied according to an environmentally more cautious scheme, with total N

application rates in BBFs equal to mineral fertiliser N in baseline, N emissions were maintained relatively similar, while average crop yields were in the long-term reduced by up to 10%, relative to the baseline (more in the first years after shifting to BBF).

- When BBFs were applied according to the intermediate scheme, crop yields could be maintained similar to the baseline, while N losses to the environment in most cases only increased marginally, except for two of the BBFs, compost (BVC) and digestate (SDG).
- To best protect the environment, BBFs should be used to replace mineral fertilisers in a manner where BBF total N application does not exceed the recommended mineral N fertiliser rate. For some of the BBFs this will mean a yield loss in initial years (up to 15%), but in the long-term when the residual N effect of BBFs accumulate, yield reductions are small (1–8%, 60 year average).
- BBFs rich in organic N (and C) showed the potential to enhance soil quality by improving soil organic C and N stocks, regardless of the fertiliser replacement scheme, thus enhancing soil N supply capacity in the long term.
- BBFs like digestate (here SDG) are prone to gaseous N loss in all schemes, especially due to ammonia volatilisation; soil incorporation should therefore be recommended. Compost BBFs (here BVC) have low immediate fertiliser value, but a high residual N effect, so in the long-run can maintain yields with repeated applications; however, also with a considerable risk of increased gaseous and leaching N losses. An intermediate group of BBFs with high organic-N content (here BA6, BIO, OG2) and relatively low C:N ratio shows risk of N leaching if applied at higher BBF total-N than recommended mineral fertiliser N rate.
- N-rich BBFs also contain other nutrients (P and K), which should be considered for a balanced application aligned with crop production and environmental protection needs.

Acknowledgements This study was funded by the European Union's Horizon 2020 research and innovation programme under the LEX4BIO (Grant agreement No. 818309) project. This output reflects only the author's views, and the European Union cannot be held responsible for any use that may be made of the information contained herein. The funding source had

no involvement in the study, apart from providing financial support.

Author contributions Muhammed Adil Rashid: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Writing – original draft; Writing – review & editing Lærke Wester-Larsen: Conceptualization; Data curation; Methodology; Writing – review & editing Lucilla Agostini: Data curation; Writing – review & editing Lars Stoumann Jensen: Conceptualization; Funding acquisition; Methodology; Project administration; Resources; Supervision; Writing – review & editing.

Data availability Data and Daisy setup files will be made available at reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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