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Specifying organic fertilizer composition in process-based models: overview of available data and sensitivity analysis with Biome-BGCMuSo

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Abstract

Organic fertilizers are widely used around the world, because they support the circular economy, sustainable agriculture, and improved soil quality, as well as carbon sequestration. State-of-the-art, process-based models can simulate the environmental impacts of organic fertilizer use and can address issues like the effect of fertilizer amount and type on crop production, soil fertility, soil organic matter accumulation, nitrate leaching, and greenhouse gas emission. However, the lack of information on the proper attribute settings for fertilizer inputs in the models hampers their application. In this study, the main goal was to support the setting of organic fertilizer attributes for process-based model applications. A comprehensive data collection was performed to gather organic fertilizer attributes that are relevant for the carbon and nitrogen cycle-related simulations. Based on the literature search, representative values are presented that can be instantly used in the models as generalized settings for several farmyard manure and slurry types. We also addressed the question of how fertilizer attribute-setting-related uncertainties propagate to the simulation outputs. We used the Biome-BGCMuSo biogeochemical model for that purpose with a maize monoculture simulation. The results indicate that manure type specific attribute setting is crucial for the nitrogen balance related model variables. For soil nitrous oxide efflux, improper composition settings can severely distort the simulation results. Sensitivity analysis suggested that dry matter content and organic nitrogen content are the two most important manure attributes that modellers must properly adjust. For slurry, the dry matter and ammonium content must be constrained for proper simulation results. The study supports crop and biogeochemical model setup with ready-to-use pragmatic information.

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Keywords: Biome-BGCMuSo, farmyard manure, slurry, parameterization, model uncertainty

Introduction

The field application of animal manure is currently experiencing a revival, as it can support the circular economy and sustainable agriculture, improve soil quality, and promote resource-use efficiency (Verma, G. *et al.* 2012; Wang, Y. *et al.* 2018; Chojnacka, K. *et al.* 2020). Manure application can stimulate soil microbial activity, soil organic mat-

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ter (SOM) stabilization, thus, increasing soil organic carbon (SOC) content, potentially mitigating global climate change (Yang, R. *et al.* 2016; Li, H. *et al.* 2017; Menšík, L. *et al.* 2019). Organic manure and slurry are widely used in many regions worldwide (FAO, 2018; FAOSTAT, 2021a). According to FAOSTAT (2021b), the global farmyard manure (FYM) use increased by 35 percent in the past 50 years. Today, around 7.5 Gt FYM is applied worldwide annually, amounting to approximately 800, 27, 13 and 35 Mt carbon, nitrogen, phosphorus and potassium input to soils, respectively (not mentioning additional important micronutrients).

Among other factors, manure composition greatly affects the nutrient release from organic fertilizers, thus, its effect on plant growth and SOM dynamics. The composition of animal manure varies greatly among source materials (Brown, C. 2013). The animal's diet, the use and type of bedding material, manure age, and the technology used for storage are the main factors that affect manure nutrient level (Chastain, J.P. and Camberato, J.J. 2003; Pettygrove, G.S. *et al.* 2009). These factors can vary substantially at local or at larger spatial scales. Some manure composition attributes can be found in incubation studies (e.g. Morvan, T. *et al.* 2006), agronomic reviews (e.g. Webb, J. *et al.* 2013), National Inventory Report (NIR) literature (e.g. Finzi, A. *et al.* 2015), and modelling studies (e.g. Levavasseur, F. *et al.* 2021). However, comprehensive summary of the manure composition attributes is not available from the scientific literature which is a major drawback if proper data is needed for practical applications such as modelling.

Crop models and generic biogeochemical models are widely used to quantify crop yield, net primary production, nutrient requirements, SOC content, and greenhouse gas (GHG) emissions of croplands (Rosenzweig, C. *et al.* 2013; Fodor, N. *et al.* 2014; Hidy, D. *et al.* 2021). These models are driven by environmental data (most of all meteorological data and soil properties), while quantification of management also plays a major role in the simulations (Potter, P. *et al.* 2010; Li, C. *et al.* 2012; Dobor, L. *et al.* 2016; Mohanty, S. *et al.* 2020). Since fertilization greatly affects crop growth and yield, also modulating GHG emission, manure decomposition and nutrient release have to be simulated well.

In biogeochemical models, a wide variety of methods are used to simulate the effects of manure application on plant- and soil-related processes. For example, the grazing module of LPJmL 5.0 uses specific equations to quantify N and C in animal feces and urine. Feces-derived C and N and urine-derived C are added into aboveground litter pools of the model, while urine-derived N is associated with the NH_4 pool (Heinke, J. *et al.* 2023). ORCHIDEE has dedicated modules for manure application (housing, yard, storage), considering important parameters like pH and timing of application, but the manure is not directly coupled with the biomass productivity (Beaudor, M. *et al.* 2023). The JULES model considers manure as a N input, and N cycling is included, but the model does not distinguish between manure and inorganic fertilizers (Wiltshire, A.J. *et al.* 2021; Mathison, C. *et al.* 2023). The AquaCrop model has no dedicated manure modules; it rather models soil fertility stress through user-calibrated coefficients and does not simulate nutrient balances or fertilizer effects directly (Gijsman, A.J. *et al.* 2002; Van Gaelen, H. *et al.* 2015). Manure-DNDC model handles manure with a microbe-mediated decomposition with linear and differential equations, urea hydrolysis, nitrification, denitrification, ammonia volatilization and fermentation modules with several sub-pools to calculate GHG and NH_3 emissions (Zhao, S. *et al.* 2025). Other models also handle manure and slurry applications like DSSAT and others (Zhao, S. *et al.* 2025). Obviously, for proper simulation of net biome production (NBP; see Chapin, F.S. *et al.* [2006] for definition of NBP) and GHG emission, the dry matter (DM), carbon and organic/mineral nitrogen content of manure must be prescribed accurately. This poses a challenge to the research community.

In this study, we present the results of a major data-collection initiative to develop generic manure composition parameters for a wide range of process-based models. Using the Biome-BGCMuSo biogeochemical-crop model (Hidy, D. *et al.* 2016, 2021) we demonstrate the effect of manure type attribute settings on the model results (note that in this study we distinguish between *model parameters* that are adjustable plant and soil characteristic, and *attributes* that are considered as known and have to be set by the user including management timing, amount and type of fertilizer and other human-induced activity; using this convention we call the properties of the manure and slurry as attributes or manure composition settings). Additionally, as the manure composition attributes are always associated with uncertainty, by performing sensitivity analysis, we highlight the manure composition attributes that have a determining role on the simulation for two sites in Hungary with contrasting soil composition parameters.

We aimed to answer the following questions: 1) What is the range of the most important animal manure composition parameters that are available in the literature and in other diverse information sources? 2) Based on the newly constructed, generic manure/slurry attribute setting, what is the effect of the manure/slurry composition settings on the biogeochemical model results? 3) Using the results of the sensitivity analysis, which manure attributes have to be quantified precisely to achieve adequate simulation results? Answering these research questions provides a pragmatic solution for setting the manure-related attributes.

The study fills a major scientific gap, as, to the best knowledge of the authors, no similar study exists that presents such a comprehensive dataset for animal manure composition-related attributes. The presented results provide solutions for the modeller community, independent from the Biome-BGCMuSo model. The results can be used to design targeted laboratory analysis to support modelling and proper estimation of the full GHG balance of the croplands to support country reporting.

Materials and methods

Organic fertilizer attributes

Crop models and process-based biogeochemical models need information (among others) on the C and N input of the simulated ecosystem in order to quantify plant production and the complete C and N cycle of the plant-soil system including SOC content. For the present study, we focus on the Biome-BGCMuSo model that has a large application history, thorough validation, and good documentation (Thornton, P.E. *et al.* 2002; Hidy, D. *et al.* 2012, 2016, 2021). The required parameters for the model's fertilizer input file are the following (Hidy, D. *et al.* 2021): date and depth of the fertilization, DM content of the fertilizer (%), nitrate (NO_3) fraction of DM (%), ammonium (NH_4) fraction of DM (%), organic nitrogen (ON) content of DM (%), organic carbon (OC) content of DM (%), labile (LAB) fraction of the organic carbon content (%) and cellulose (CEL) fraction of the organic carbon content (%). As the focus of this study is the composition of the organic fertilizers, application-related attributes, such as application date, depth, and amount, were not addressed here.

As it is suggested by Chambers, B. *et al.* (2001), to assess the fertilization value of livestock manure, the laboratory analyses should include the determination of DM, total N, P, K, and NH_4-N (crop available N). Additionally, for well-composted FYM, NO_3-N should be measured, and for poultry manure, uric acid-N should also be included. This list of prescribed attributes corresponds well with the list of organic fertilizer specific input data of the Biome-BGCMuSo model, which means that the model is suitable for studying the effect of organic fertilizer attribute setting on the simulated ecosystem. However, some of the above-mentioned attributes were (at least partially) excluded from the study due to two main reasons. First, at the moment, Biome-BGCMuSo does not have a routine for urea-related calculations. Second, only a very limited amount of data was found for the LAB and CEL fractions.

Our literature review, the keywords used, the selection of databases, and inclusion/exclusion criteria followed a predefined protocol *(Figure 1)*. According to previous works (ASAE, 2005; Pain, B. and Menzi, H. 2011), in this study, liquid manure and slurry are not handled separately, as their physical and chemical behaviours (i.e. how they flow and release nitrogen) are similar. Hits from Google Scholar, ScienceDirect and Web of Science were collected and completed with some additional references from the Land Application and Manure Storage and Handling database (ISU, 2025).

In our approach, animal-specific data contain all available data irrespective of the age and gender of the animals. For example, the cattle group contains data of dairy cattle and beef, as well; the pig group contains data of sow, nursery, feeder, and farrow. More detailed analysis of manure content based on the animal sub-groups would be relevant, but is out of scope of the present study. A summary of the compiled manure database can be found in *Table 1*.

We paid particular attention to ensure that data from different sources were comparable. Data relating to wet weight was converted to dry weight, and the units of measurement were standardized.

One-way ANOVA was used to test if there is a significant difference between the composition of the manure and slurry of different animals. This analysis was carried out in R programming language (R Core Team, 2021). Given that the data were compiled from multiple studies with varying methodologies and geographic regions, the assumptions of classical ANOVA may not be fully satisfied. Consequently, p-values were interpreted with caution. To account for the hierarchical structure of the data, the calculated mean and median values are presented as practical benchmarks for crop and/or environmental modelling rather than absolute inferential thresholds.

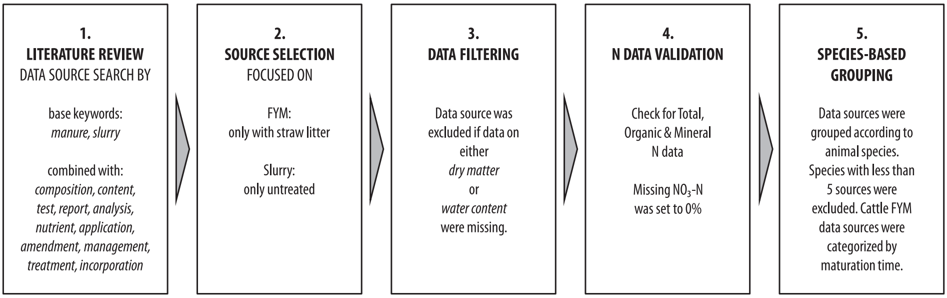

Fig. 1. Summarizing flow chart of the data source search. *Source:* Authors' own elaboration.

*Table 1. The number of FYM- and slurry-related data sources**

Period of publication	Total number of	FYM-related	Slurry-related	Country of origin
	data sources			
1961–1980	5	4	1	Hungary, Russia, USA
1981–2000	7	5	5	Italy, Moldova, UK
2001–2019	25	13	20	Austria, Canada, Chile, Denmark, Hungary, Ireland, Italy, Sweden, Switzerland, UK, USA

*As well as the period in which they were published, and the country from which the data originated.

Biome-BGCMuSo biogeochemical model

Biome-BGCMuSo model was used in this study to quantify the effect of manure type selection and attribute setting on the simulated plant production, GHG balance and soil related variables. Biome-BGCMuSo is a general-purpose biogeochemical model that simulates the storage and fluxes of carbon, nitrogen and water of terrestrial ecosystems (Hidy, D. *et al.* 2012, 2016). It can quantify the full GHG budget of the ecosystem including CO_2 and N_2O fluxes.

Biome-BGCMuSo was developed from the widely used Biome-BGC model (Running, S.W. and Hunt, E.R.J. 1993; Thornton, P.E. 1998; Thornton, P.E. *et al.* 2002; Churkina, G. *et al.* 2009). During the development, the original Biome-BGC was significantly extended and re-formulated in terms of soil processes, possible management options, disturbance effects on plant physiology, and many other processes not addressed in the original model. The major milestones of the model development were the construction of a 10-layer soil submodule with sophisticated soil water balance routine, the layer-by-layer representation of C and N dynamics within the soil, the implementation of detailed nitrification/denitrification routine including separate handling of soil NH_4-N and NO_3-N pools, the implementation of a submodel for soil N_2O and CH_4 emission, the improvement of handling of stomatal response due to soil water stress and increasing atmospheric CO_2 mixing ratio, the separation of soil related and plant related parameters in the input structure, the implementation of the option for phenophase dependent allocation patterns using a maximum of 7 phenophases (including option for varying specific leaf area), and the implementation of root growth dynamics including a nonlinear vertical root distribution function. New, detailed disturbance handler logic was also implemented that supports the simulation of major generic management events such as planting, fertilization, harvest, ploughing, forest thinning, grass mowing and grazing. The current version of Biome-BGCMuSo (v6.1; also some of the earlier versions, like v4.1) is capable of simulating cropland carbon and nitrogen balance with the estimation of the final crop yield. In cropland simulations, the timing, the amount, and the composition of the applied fertilizer are essential input information that is needed for the calculation of the total C and N balance of the ecosystem (Hidy, D. *et al.* 2021, 2022). The performance of Biome-BGCMuSo in simulating soil mineral N and soil N_2O efflux was validated by Hidy, D. *et al.* (2022) using experimental data collected in a fertilization experiment.

The fertilization submodel of Biome-BGCMuSo

In Biome-BGCMuSo, inorganic or organic fertilization affects the litter and soil turnover processes and, thus, directly affects the C and N stocks and fluxes, including SOC accumulation and N mineralization. Inorganic fertilizers directly increase the soil NH_4-N and NO_3-N pools. Organic fertilizers are handled as organic matter input in an alternative way (besides, e.g. litterfall or fine root mortality). The simulation of soil organic and inorganic matter turnover is a complex process in Biome-BGCMuSo v6.1 (Hidy, D. *et al.* 2021). A new feature of this model version is the separation of carbon and nitrogen pools for each soil layer defined in the form of litter and soil organic matter (see *Figure 1*). Biome-BGCMuSo uses the concept proposed by Thomas, R.Q. *et al.* (2013) which assumes that plants have access only to a part of the given inorganic nitrogen pool, and the rest is bounded in the soil aggregates. The plant available NH_4-N and NO_3-N pools are assumed to be 10 and 100 percent of the actual pools, respectively (Gerber, S. *et al.* 2010, and Thomas, R.Q. *et al.* 2013), but the mobile proportion of NH_4 can be set by the modeller.

Application of fertilizers directly interacts with the nitrogen, and in the case of FYM, also with the carbon cycle-related calculations of the model (for details see Hidy, D. *et al.* 2022). Fertilizer input indirectly affects many additional processes due to the model logic that handles the carbon, nitrogen and water cycle jointly. The most important simulated, nitrogen-related processes are N-fixation (N flux from atmosphere to the root zone layers by microorganisms), N-deposition (N input from the atmosphere to the top soil layers by gravitation (dry) and precipitation (wet)), plant uptake (mineral N absorption from the soil layers in the root zone by plants), mineralization (release of plant-available nitrogen from SOM to inorganic nitrogen), immobilization (the consumption of mineralized nitrogen by microorganisms), nitrification (NO_3-production of nitrifying bacteria by biological oxidation of NH_4), denitrification (NO_3-reduction and conversion to nitrogen gas through microbial process), leaching (downward movement of water-soluble mineral nitrogen below the root zone), litterfall (transfer of plant material, including N, from plant reservoir to litter) and decomposition (transfer of litter carbon and nitrogen to soil pools and between soil pools) (see *Figure 1*). Input fluxes of soil organic matter pools are planting (carbon and nitrogen content of seeds), decomposition of litter pools and fertilizing (organic fertilizer). Output fluxes are mineralization and leaching from the lowermost soil layer. Input fluxes of soil inorganic nitrogen (NO_3-N and NH_4-N) pools are N-deposition, N-fixation, fertilizing (inorganic fertilizer), and mineralization. Output fluxes are leaching, immobilization (for NO_3 and NH_4), mineralization (for NO_3 and NH_4), denitrification (for NO_3), nitrification (for NH_4), and plant uptake.

Mass fluxes between different source (arrow head) and target (arrow tip) soil and litter pools are calculated based on the converging cascade scheme (Thornton, P.E. 1998; *Figure 2*). The C/N ratio of the source and target pools is the key factor in the direction of the processes, which determines whether mineralization or immobilization occurs: nitrogen leaves or enters the corresponding litter or SOM pools (Thornton, P.E. 1998).

In case of fertilization, the carbon and nitrogen content of the fertilizer is distributed across the litter pools of the soil layers that fall within the fertilizer depth (which is a model input) (see *Figure 2*).

Using the dry matter content percent, the water content of the fertilizer is also calculated which is added to the water content of affected soil layers (proportionally to thickness of the soil layer). The nitrate, ammonium and organic fractions of the fertilizer are added to the nitrate, ammonium and organic nitrogen and carbon content of litter pools of the model. The amount of C and N originated from the fertilizer is distributed across the different litter (LITTER1, LITTER2, LITTER3, LITTER4 – see *Figure 2*) pools based on the labile and cellulose content required to be set by the User. In this way, the organic part of the fertilizer enters the cascade scheme of the model presented in *Figure 2*. As organic matter increases, the amount of inorganic N also increases through mineralization, which reduces the N stress of the plant. Nutrients (organic C and N, inorganic N) are leached out in parallel with plant uptake and mineralization-immobilization, so the amount of precipitation can significantly influence the availability of nutrients from fertilizer.

Model calibration

The effect of organic fertilizer-related input data (or as we call it here, fertilizer attribute setting) on the model results was studied through maize monoculture simulations performed with the Biome-BGCMuSo model (v6.1). Biome-BGCMuSo maize parameterization was evaluated previously at multiple sites (among others at Klingenberg in Germany, Martonvásár and Kartal in Hungary, Mead and Bushland in the USA, Polkovice and Kresin in the Czech Republic; Hollós, R. *et al.* 2022; Kimball, B.A. *et al.* 2023, 2024; Nand, V. *et al.* 2025). Generally, Biome-BGC-MuSo performed well at the sites based on diverse observational data (LAI, ET, GPP, biomass, yield), and it was among the best models in the multimodel intercomparison study performed by Kimball, B.A. *et al.* (2023). The

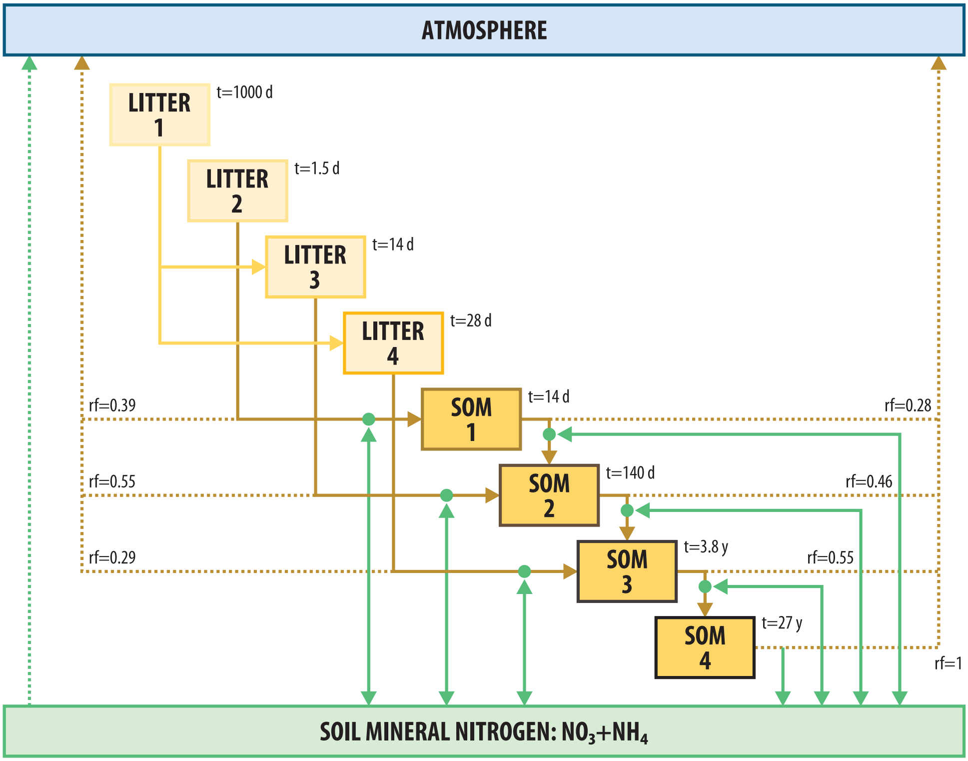

Fig. 2. The converging cascade model of litter and soil organic matter of Biome-BGCMuSo v6.1 model. rf is the respiration fraction of the different transformation fluxes; t is the residence time (reciprocal of the rate constants that is the turnover rate); brown solid arrows show mass fluxes of decomposing organic matter; brown dotted arrows show heterotrophic respiration (CO_2 emission) related to decomposition; solid green arrows show immobilization/mineralization fluxes. The subpools of litter and soil organic matter pools are defined based on their turnover are: coarse woody debris (LITTER1), labile litter (LITTER2), unshielded and shielded cellulose (LITTER3), lignin (LITTER4), labile SOM(1), medium decomposition rate SOM(2), slow decomposition rate SOM(3), passive/recalcitrant SOM(4). The subpools of inorganic (mineralized) nitrogen pool: NO_3 and NH_4. The dotted green arrow represents N loss via denitrification. *Source:* Authors' own elaboration.

maize parameterization that was used in the study is based on Hollós, R. *et al.* (2022, Supplement), where the parameterization was created using the Martonvásár long-term experiments (LTE), which is one target site for the present study.

In Biome-BGCMuSo v6.1, nitrogen cycle-related parameters can be adjusted in the soil file of the model (Hidy, D. *et al.* 2021). Observations were used to adjust the N cycle parameters based on data from one of the LTE with FYM treatments at Martonvásár (Hungary, 47.327° N, 18.789° E). Topsoil NH_4-N and NO_3-N content from 2017 was available for parameter adjustment. Additionally, dynamic chamber-based soil N_2O efflux observations were available from 2020. The N_2O efflux measurements with a gas incubation time of 10 minutes were performed by the Picarro G2508 cavity ring-down spectrometer (Christiansen, J.R. *et al.* 2015; Zhen, M. *et al.* 2021). Five soil parameters were adjusted during the optimization (denitrification rate per gC respiration of SOM, nitrification-related parameters, coefficient of N_2O emission for nitrification and

N_2/N_2O ratio multiplier for denitrification-related N gas flux; see corresponding equations in Del Grosso, S.J. *et al.* (2000), Parton, W.J. *et al.* (2001), and Thomas, R.Q. *et al.* (2013). Owing to the parameter adjustment, the model provided NH_4-N/NO_3-N content and N_2O emission that were consistent with the observations; however, the model somewhat overestimated the topsoil NH_4-N content.

Modelling strategy

Two sites in Hungary with contrasting soil characteristics were selected for model simulations. The Martonvásár experimental site, which is run by the Centre for Agricultural Research, HUN-REN, is located in the Mezőföld region of the Transdanubia macroregion on endocalcic chernozem soil. This region is characterised by intensive agricultural operations and commercial farms. In contrast, the Kiskunhalas site is located in the Danube-Tisza Interfluve plain, which is the second largest sandy region in the EU after the Landes of Gascony in France. This area is characterized mainly by small- to medium-sized farms, and the focus is on the importance of adaptive farming and land protection. The main climatic parameters and topsoil characteristics of these sites are presented in *Table 2*. The water management properties and organic matter content of the soils are important factors in crop production. In this respect, the two selected soil types differ significantly from each other. Soil selection is relevant because approximately 30 percent of Hungary's arable land is chernozem soils, which are characterised by a deep, humus-rich layer, excellent water and air management and a good nutrient supply. In contrast, around 8 percent of the cultivated land consists of light-textured sandy soils with low colloid content, unfavourable water management properties, and low water holding capacity (Tóth, E. *et al*. 2025).

For the presented modelling exercise, the Biome-BGCMuSo model was run from 1961 to 2018 with maize monoculture. The CarpatClim database was used to provide meteorological data for the simulations (Spinoni, J. *et al.* 2015). Soil-specific input data were retrieved from the DOSoReMi database (Pásztor, L. *et al.* 2020). The other settings followed the method from earlier Biome-BGC related studies (Barcza, Z. *et al.* 2010). Simulation results were analysed for the 2001–2010 years. Slurry or FYM were applied at 40 t ha^{-1} on a fresh weight basis in every 3rd year in the simulations. Organic fertilizer was added on 1st of October and was incorporated in 0.15 m depth. The fertilization composition attributes were set based on the results of the data collection. No irrigation was set in the simulations.

Selected model output variables were analysed at daily and annual time scale. Final crop yield and LAI were used to characterize plant production. LAI and yield were assessed in daily and annual time steps, respectively. Daily NEE and topsoil (0–30 cm) SOC were used to represent carbon cycle dynamics. Topsoil available NH_4-N and NO_3-N content, and daily N_2O soil efflux were studied to represent nitrogen cycle dynamics. N_2O flux was selected since it is a strong GHG with high relevance in terms of climate change.

*Table 2. Main climatic and topsoil characteristics of the two selected sites**

Parameters	Martonvásár	Kiskunhalas
Average temperature, °C	11.2	11.5
Average annual precipitation, mm	547	577
Soil bulk density, kg m^{-3}	1340	1390
Soil Organic Matter, %	3.05	0.78
Sand fraction, %	18	89
Clay fraction, %	17	4

* Climate data was derived from the CarpatClim database, while soil data was retrieved from the DOSoReMi database.

Model simulations were performed with the proposed organic fertilizer attribute values that are derived as the median of all collected data per attribute per manure type (*Table 3* and *4*). Model output data was filtered for the growing seasons only. The Wilcoxon rank sum test was performed to check whether the manure attribute setting (manure type selection) had a significant effect on the simulation results. The statistical test compared the medians of the daily data aggregated for the growing season (DOY: 120–243).

*Table 3. Minimum, maximum and median of the cattle, pig and poultry FYM composition values**

Farmyard manure (FYM) composition values		Cattle Fr	Cattle 3mo	Cattle 6mo	Pig	Poultry
DM, %	minimum	17.5	18.4	20.0	19.3	35.0
	maximum	28.0	31.4	39.0	36.0	65.2
	median	21.1	25.0	32.0	25.0	48.4
ON (DM %)	minimum	1.00	1.40	1.32	1.62	1.60
	maximum	2.33	3.28	2.95	3.28	4.20
	median	1.88	2.13	2.04	2.35	2.99
NH_4-N (DM %)	minimum	0.368	0.008	0.009	0.210	0.787
	maximum	0.620	0.652	0.350	1.661	1.800
	median	0.556	0.243	0.155	0.720	1.250
NO_3-N (DM %)	minimum	0	0.08	0.001	0	0
	maximum	0	0.08	0.063	0	0
	median	0	0.08	0.013**	0	0
OC (DM %)	minimum	38.20	31.20	26.00	28.00	21.32
	maximum	40.10	39.36	35.60	37.67	40.54
	median	39.15	36.40	28.50	37.13	36.60

*See more details in *Figure S1* (Supplementary section). **Although very small but non-zero values were also found in the literature, zero values were used and proposed for model parameterization according to Chadwick, D.R. *et al.* (2011).

*Table 4. Minimum, maximum and median of the cattle and pig slurry composition values**

Composition values		Cattle	Pig
DM, %	minimum	3.10	2.27
	maximum	14.80	7.95
	median	6.50	5.00
ON (DM %)	minimum	0.26	0.36
	maximum	4.50	5.54
	median	2.16	2.89
NH_4-N (DM %)	minimum	0.001	0.722
	maximum	3.973	10.310
	median	2.000	5.870
NO_3-N (DM %)	minimum	0	0
	maximum	0.005	0
	median	0	0
OC (DM %)	minimum	31.46	17.93
	maximum	46.30	33.10
	median	37.83	31.96

*See more details in *Figure S2* (Supplementary section). DM % abbreviation means that the parameters are expressed as percent of DM content.

Sensitivity analysis

A sensitivity analysis was performed to pinpoint the important fertilizer-related model input data. We used the so-called least squares linearization (LSL) method (Verbeeck, H. *et al.* 2006) for this purpose. The LSL method is a computationally efficient numerical approximation technique used to estimate variance-based Sobol sensitivity indices (Saltelli, A. *et al.* 2004). Rather than requiring an unfeasibly large number of full model runs, LSL approximates the model's response surface at the Monte Carlo sampling points using multidimensional planes.

The aim of the analysis is to highlight the importance of the fertilizer-related input data uncertainty in terms of output variability. The advantage of the technique against the one-at-a-time approaches is that the LSL method varies all input data simultaneously.

The analysis was carried out in two different ways. First, the attributes were changing within uniform ranges (±10% around the medians). Second, the attributes were allowed to change within the full range defined by the minimum and maximum of the selected manure input data based on the presented literature review (see Results). The first option shows the relative model sensitivity to the selected input data, while the second option shows an overall, effective sensitivity that includes the uncertainty of the input data, represented by the magnitude of the data ranges found in the literature.

In both cases, uniform distribution was assumed within the input attribute intervals because a preliminary analysis indicated that the distribution of the parameters is not Gaussian in many cases, but rather it is closer to a uniform distribution. Fertilization-related input data sensitivity was quantified by the variance observed in the model outputs. The relative sensitivity to every input data (manure parameter) for every investigated model output was scored. If the relative sensitivity was between 0–20, 20–40, 40–60, 60–80 or 80–100 percent, a score of 1, 2, 3, 4, or 5 was given, respectively. The final score, which is a metric of overall model sensitivity to a given manure parameter, was calculated by cumulating the given scores across the model outputs. The mean or the median of the relative sensitivity values could also be used, but these metrics are greatly affected by extreme relative sensitivity values and can suggest disproportionately high or low overall relative sensitivity. The higher the final score, the more important the input data in terms of model result uncertainty. We present the scores in color-coded figures suggested by Olesen, J.E. *et al.* (2011).

The sensitivity analysis was performed separately for all FYM and slurry types addressed in this study. For cattle FYM a categorization was used according to the stabilization time (Fr, 3mo and 6mo old), cf. the data collection method presented above (see subsection *Organic fertilizer attributes*). Note that sensitivity analysis was performed for manure composition attributes with sufficient data availability. For this reason, LAB and CEL fractions were excluded from the analysis, and their values were fixed based on the limited available data (see Results). For each fertilizer type, 10,000 simulations were performed.

Results

Organic fertilizer composition: DM content

Figure S1 (Supplementary section) shows the distribution of DM content values based on the collected data. *Table 3* shows the summary of the data collection, presenting the median, the minimum, and the maximum of all collected data for each manure type. The range of the medians is somewhat broader than that of the means *(Table S1)* (Supplementary section).

Comparison of the DM values per manure type is presented in *Table S1*. The mean DM content values of the five investigated manure groups are significantly different, except for the Fr vs. 3mo group. The ranges (defined by the difference between the maximum and the minimum) of the cattle and pig manure DM content data are similar but differ considerably from the poultry FYM characteristics (*Figure S1*, *Table S1*). The corresponding p-values of the ANOVA tests are presented in *Table S2* (Supplementary section).

Figure S2 (Supplementary section) shows the distribution of DM content values of the collected slurry data. *Table 4* shows the summary for slurry in terms of minimum, maximum, and median of all collected DM data for each slurry type. The average DM content of cattle slurry is significantly higher than that of the pig slurry, and their data ranges are also quite different *(Figure S2)* based on the published studies investigated *(Table S1).* The corresponding p-values of the ANOVA tests can be found in *Table S2.*

There is additional information in the animal-specific DM contents. According to age, piglets' slurry contained less DM than that of sows (2.27 vs 7.95% – Csaba, L. *et al.* 1978). According to breeding goal, DM content of laying hens manure was less than that of broilers (40.6 vs. 60.3% – Menzi, H. 2002; Webb, J. *et al.* 2010). More detailed analysis of the results is out of scope of the present study.

Organic fertilizer parameters: Nitrogen

Figure S1 shows the distribution of nitrogen-related parameters based on the data collection. The median and mean ON values of cattle FYM (see *Table 3*), and also *Table S3* (Supplementary section) show an increasing tendency because of the maturation process (Levi-Minzi, R. *et al.* 1986). The resulting differences are significant between the fresh and the older FYMs *(Table S2).* ON content is significantly higher in pig FYM, though only in comparison with the Fr cattle manure. Poultry FYM has the highest ON content, significantly higher than any of the other types *(Table S3).* Pig slurry ON is significantly higher than cattle slurry ON, although their data ranges are similar *(Figure S2).*

Considering inorganic N forms, FYM NH_4-N means *(Table S4)* (Supplementary section) differ significantly for any pair of manure groups except for the Fr cattle and pig manure type comparison *(Table S2)*, though even those are significantly different at $p = 0.1$ level. In general, slurry tends to have much higher NH_4-N than manure, which is especially true for pig slurry.

Regarding NO_3-N, there are only scarce data (in fact, only one data source) for Fr and 3mo cattle manures (see *Table 3*), and also *Table S5* (Supplementary section), as NO_3-N is not present in fresh manure unless active mixing is present in the animal house (Chadwick, D.R. *et al.* 2011). The only zero value found in this data source was used as an input parameter for modelling (see *Table 3*). In contrast, the well-composted 6mo cattle FYM has significant NO_3 content. Note that *Table 3* indicates lower maximum for 6mo cattle FYM NO_3-N than for Fr and 3mo but this is compensated by the high number of zero values found in the literature.

Hardly any data has been published for pig and poultry manure as practically no NO_3-N is present in these FYM types *(Table S5).* Scarce NO_3-N data was found for slurries *(Table S5).*

Organic fertilizer parameters: Carbon

Synthesis of the collected OC data is presented in *Figure S1* and *Table 3*. According to *Table S6* (Supplementary section) OC data are less available than nutrient content data for manures. According to the statistical analysis presented in *Table S2*, all manure types show significant differences regarding cattle FYM OC. Owing to the low number and the scatter of poultry data, its mean value does not show a significant difference in comparison with other manure types, though, for example, the difference between the means of the Fr and 3mo cattle FYM types is actually smaller than that of the Fr cattle and poultry FYM types.

The average cellulose and lignin data used in this study are calculated from the limited number of references (Chadwick, D.R. *et al.* 2000; Li, Y. *et al.* 2013; Li, K. *et al.* 2015; Rehman, K.U. *et al.* 2017; Li, R. *et al.* 2019; Shen, J. *et al.* 2019). The average cellulose and lignin content for cattle FYM is 44.6 and 29.3 percent, for pig FYM 46.8 and 15.4 percent, for poultry FYM 46.5 and 21.3 percent, for cattle slurry 40.9 and 22.1 percent, and for pig slurry 43.1 and 19.2 percent, respectively. Labile fraction was calculated as a residual based on the above numbers for each organic fertilizer type separately.

Simulations with the proposed parameterization using median values

Figure 3 shows the simulated time series of LAI, final crop yield, NEE, SOC, soil N_2O flux, topsoil NO_3-N and NH_4-N concentration for the 10 simulated years for Martonvásár, based on the proposed FYM parameterizations (see *Table 3*) for 5 different manure

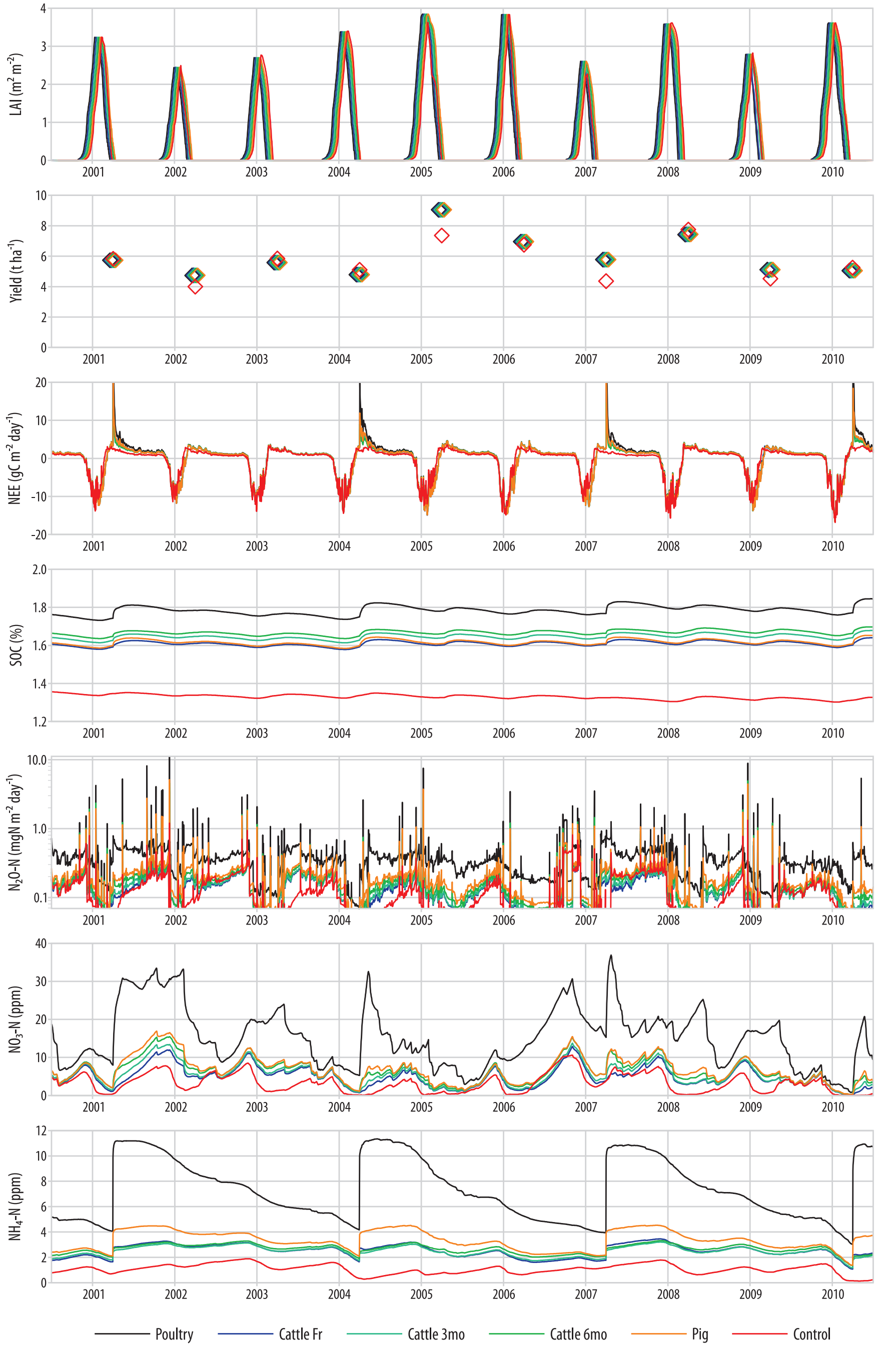

Fig. 3. Biome-BGCMuSo simulation results for Martonvásár using the median parameter values (proposed parameterization; see *Table 2*) for the different FYM types. For N_2O efflux logarithmic scale is used for clarity. Note that in some cases, the lines/symbols overlap. Black, blue, light blue, light green, yellow and red lines represent poultry, cattle Fr, cattle 3mo, cattle 6mo, pig FYM and control treatments, respectively. NO_3-N and NH_4-N refer to the simulated topsoil N content. *Source:* Authors' own elaboration.

types and for the non-fertilized control. The Kiskunhalas simulations show a similar pattern *(Figure S3)* (Supplementary section).

The figures show that manure application affects all simulated quantities to some extent relative to the control. The LAI for the non-fertilized simulation differs from the fertilized LAI dynamics in some (but not all) years. LAI, final crop yield, and NEE time series are very similar for all manure types. In contrast, SOC and soil nitrogen-related variables show considerable dependency on manure type selection. Similar conclusions can be drawn from slurry-related simulations (*Figure S4* and *S5*) (Supplementary section).

The Wilcoxon rank sum test was performed separately for the two study sites, for the two manure types (FYM and slurry), and for the selected output variables individually. We discuss the existence or lack of significant differences in the following subsections for the major output variable groups. Manure type dependent simulations were compared against each other, plus we compared the organic fertilizer driven simulations with the control as well, and searched for significant differences between the time series.

LAI and yield

In the case of LAI, the control simulation significantly differed from the fertilized simulations ($p < 0.001$) for both sites and for both organic fertilizer types (FYM and slurry). Fertilizer type selection caused non-significant differences between the LAI simulations, both for FYM and slurry, which is well demonstrated by the overlap of the LAI curves representing the fertilized simulations in *Figure 3*.

Mean crop yield for the control simulations was 5.7 t ha^{-1} at Martonvásár and 4.4 t ha^{-1} at Kiskunhalas. For the five FYM simulations, the yield was 6 t ha^{-1} for Martonvásár, and 5.4 t ha^{-1} for Kiskunhalas, in accordance with the fact that the soil at Kiskunhalas is less fertile. Slurry driven yields were slightly lower at both sites than that of the FYM driven yields (not shown). In spite of the increase of the final yield, there was no significant difference between the control simulation time series and any of the organic fertilizer driven simulations. The exception is the five FYM simulations at Kiskunhalas where the control simulation was different from all of the FYM related simulations, but the differences were significant only at the $p = 0.1$ level. No significant differences were found between the yield simulations made with the different organic fertilizer types for both the Martonvásár and the Kiskunhalas site.

NEE and SOC

Simulation results indicated that NEE is not affected significantly by the FYM/slurry type selection either at Martonvásár or at Kiskunhalas. One exception is the pig slurry-related simulation that differs from the control at Kiskunhalas, but the difference is significant only at $p = 0.1$ level. The control simulation did not differ significantly from the organic fertilizer-driven ones, considering all possible combinations at both sites.

In contrast, SOC was found to be affected by the choice of the organic fertilizer type (and the associated parameterization) at both sites (see *Figure 3*). All differences (control vs. FYM, control vs. slurry, and also FYM vs. another FYM, slurry vs. the other slurry) were significant ($p = 0.001$).

Nitrogen balance

Considering NH_4-N and NO_3-N content in the topsoil and soil N_2O efflux, almost all simulation results differed significantly, at both sites and for both organic fertilizer types ($p = 0.001$). For NO_3, 6mo cattle and pig FYM-related simulations did not differ significantly at Martonvásár. For NH_4-N and N_2O-N emission, Fr and 3mo cattle FYM driven simulations did not differ significantly at both sites; however, in the case of N_2O flux, they differed significantly at $p = 0.1$ for the Kiskunhalas site.

Given the importance of soil N_2O efflux in the global warming context, the related simulation results were further analysed. The long-term mean daily N_2O flux is 1.2-3.4 times larger in the fertilized simulations at Martonvásár, and 1.9-9.5 times larger at Kiskunhalas relative to the control (the high end was obtained with poultry FYM).

Results of the sensitivity analysis

The presentation of the results of the LSL-based sensitivity analysis follows the same logic as in previous subsection (*Simulations with the proposed parameterization using median values*). Namely, the output variables are grouped, and the importance of the organic fertilizer parameters is discussed for the target sites together. The results are expressed as a contribution to the overall variability of the selected output variable (in %), and scores are associated with the sensitivity values for a more generalized view. In the following subsections, output variable specific assessment of the effective sensitivity was in focus (relative model sensitivity is also presented but not discussed in detail).

Yield and LAI

Tables S7–S10 (Supplementary section) show the detailed results of the sensitivity analysis for the simulated LAI and final yield for both demonstration sites and for all fertilizer types. OC has an insignificant effect on the plant growth-related output variance for most of the manure types. The same holds for NH_4-N, but only for FYM types. For the investigated slurry types, especially when the full range of the input parameter variance was taken into account, NH_4-N may account for up to 58.2 percent of the variance of the growth-related outputs. ON is an important parameter in the case of cattle FYMs, especially on the chernozem soil. For slurry types, ON has a very low share in determining the output variance. DM is the most determinative FYM parameter in terms of output uncertainty only for the sandy soil. For the chernozem soil, ON was found to be the main source of output uncertainty except for poultry FYM. The comparison of the results for pig and poultry FYMs *(Table S7)* shows that the model is sensitive to the DM parameter when considering LAI and yield results, but the effective sensitivity is very different for the two FYM types. It is likely because the mean and standard deviation of DM of poultry FYM are almost two and three times larger than those of pig FYM, respectively.

If the contributions are averaged for both sites and for both output variables, DM content is found to be the most relevant for FYMs (with 49.1% overall contribution), followed by ON (35.4%) and NH_4-N (10.3%). For slurries, NH_4-N is the main source of output variability (45.8%), followed by DM (36.9%) and ON (17.3%).

NEE and SOC

According to *Tables S7–S10* NH_4-N has an insignificant effect on the carbon balance-related output variance in the case of FYM types. For slurries, NH_4-N has a more significant contribution to the output variability, but only in the case of NEE. SOC seems to be insensitive to the manure NH_4 content. ON has an insignificant effect on the output variance with only one exception. For fresh cattle FYM, only for the chernozem soil and only for the NEE output ON accounts for almost 95 percent of the variability. With the exception of poultry FYM, manure OC is not responsible for the large variability in carbon-related outputs. For poultry FYM, the wide range of the literature-based OC values looks to be the main reason for its importance, causing large variability when considering NEE and SOC outputs. Regarding SOC the DM content has a prominent role which is reasonable given that soil C input is determined by the DM content of the manure. Regarding NEE, for slurries and for fresh cattle FYM, this determinative role is not so pronounced. The contribution of DM to output variability varies between 1.4 and 21.2 percent. The sandy soil is an extreme exception here, showing 93.4 percent contribution.

If the contributions are averaged for both sites and for all output variables, DM content is found to be the most relevant for FYMs (with 67.9% overall contribution), which is followed by OC (21.1%) and ON (10.0%). For slurries DM and NH_4-N content is equally important (with 41.4 and 41.2% overall contribution) followed by ON (15.7%).

Nitrogen balance

Tables S7–S10 show the detailed results of the sensitivity analysis for the simulated soil N_2O emission, and topsoil NO_3 and NH_4 contents for both demonstration sites and for all fertilizer types. The uncertainty of the OC input parameter has practically zero effect on the nitrogen balance-related outputs, irrespective of the fertilizer type and the soil type. It is consistent with the fact that OC ranges are relatively smaller than those of the ON and NH_4-N ranges. DM is the second most important input parameter determining the variance of the outputs, showing the minimum and maximum relative contribution for 3mo cattle FYM and poultry FYM, respectively. For slurries, pig and poultry FYMs ON has a relatively low contribution to the output variability, while for cattle FYMs the contribution is large, varying between 32 and 74 percent. Practically the opposite can be stated for NH_4-N as it is marginally determinative in case of cattle FYMs but very important for slurries and pig FYM. In terms of the soil types, no sharp differences were found in the contribution characteristics.

If the contributions are averaged for the two sites and for the three output variables, ON content is found to be the most relevant for FYMs (41.8% overall contribution), which is followed by DM (35.5%) and NH_4-N (22.6%). For slurries, NH_4-N content contributes the most to the output variance (45.2%) followed by DM (41.1%) and ON (13.7%).

Overall scores

In *Table 5*, the relative contribution of the investigated input attributes to the variance of the selected outputs is presented, averaged for the fertilizer types and for the two sites. Here, we discuss relative and effective sensitivity together. Both for FYM and slurry, DM content is the parameter the model is most sensitive to (*Table 5*; SCORE2). If we consider the effective sensitivity, when the literature-based uncertainty of the input parameters is taken into account, FYM DM is still the most determinative. However, for slurry, NH_4-N content seems to be the most important input (see *Table 5*) due to the one order of magnitude larger range of NH_4-N values found in the literature (*Figure S2*). The effective sensitivity to the nitrogen-related inputs is usually larger than the corresponding model sensitivity caused by the fact that the minimum values for these input parameters are close to zero for many manure types. Consequently, effective sensitivity to DM and OC is usually smaller than the corresponding model sensitivity.

Discussion

Organic fertilizer composition

Animal manure is traditionally considered to be a mixture of faeces and urine. It contains DM, such as several nutrients, plant residues, indigestible food, and other wastes. DM is comprised of ash and organic matter. During composting, ash content remains the same, while organic matter is decreasing due to decomposition and stabilization processes. DM loss could be up to 40 percent of the initial content (Eghball, B. *et al.* 1997; Tiquia, S.M. *et al.* 2002). At the same time, water content also decreases until the end of the composting, thus, the DM content of the mature manure could be higher than that of the fresh one (Tiquia, S.M. *et al.* 1998). Results of the comprehensive data collection presented in this study indicate that during the maturation process, the DM content increases, which is consistent with the expectations (see *Table 3*).

Nitrogen is present in manures in different forms. Our results indicated that glob-

*Table 5. Relative contribution of the investigated input parameters (in columns) to the variance of the selected outputs (in rows) and the SCORE for each input showing their overall importance in terms of output uncertainty**

FYM full range				
Parameter	DM	NH_4-N	ON	OC
LAI	45.7	10.8	38.8	4.7
YIELD	52.5	9.6	32.1	5.9
NEE	58.9	1.6	16.5	23.1
SOC	77.0	0.4	3.5	19.1
N_2O	34.6	24.1	41.2	0.2
SNO_3	35.7	12.2	51.9	0.1
SNH_4	36.2	31.6	32.2	0.0
SCORE1	*19*	*9*	*14*	*8*

FYM ±10% range				
Parameter	DM	NH_4-N	ON	OC
LAI	62.0	2.9	20.3	14.9
YIELD	62.7	2.9	19.3	15.1
NEE	41.8	0.5	5.8	51.9
SOC	55.9	0.1	1.0	43.0
N_2O	57.8	8.4	32.9	0.9
SNO_3	54.5	4.1	40.5	0.9
SNH_4	63.6	11.0	25.3	0.3
SCORE2	*24*	*7*	*12*	*11*

Slurry full range				
Parameter	DM	NH_4-N	ON	OC
LAI	35.3	47.4	17.3	0.0
YIELD	38.5	44.2	17.2	0.2
NEE	16.4	59.6	22.7	1.3
SOC	66.4	22.8	8.7	2.2
N_2O	40.8	46.7	12.6	0.0
SNO_3	44.3	36.8	19.0	0.0
SNH_4	38.4	52.3	9.4	0.0
SCORE1	*17*	*19*	*8*	*7*

Slurry ±10% range				
Parameter	DM	NH_4-N	ON	OC
LAI	61.7	25.4	12.1	1.0
YIELD	51.7	24.5	10.4	13.5
NEE	30.7	25.7	12.1	31.4
SOC	72.1	7.2	5.6	15.1
N_2O	59.5	29.5	10.7	0.3
SNO_3	63.1	23.7	13.2	0.1
SNH_4	60.3	31.7	7.6	0.3
SCORE2	*24*	*13*	*7*	*8*

*DM, NH_4-N, ON and OC denote the DM, NH_4, organic nitrogen and organic carbon content of the fertilizer, respectively. LAI, YIELD, NEE, SOC, N_2O, SNO_3 and SNH_4 denote the simulated leaf area index, final yield, net ecosystem exchange, SOC content, soil N_2O emission, and topsoil NO_3 and NH_4 content, respectively.

ally, the most abundant mineral N pool in manures is NH_4. NO_3 content is very low and can be considered to be virtually zero for all studied organic fertilizer types (see *Tables* 3 and 4). Our results might support simple estimations for practical considerations. If missing, total N can be estimated from the presented DM content, and NH_4-N can be approximated from total N content.

As OC is not considered as a nutrient, its measurement is not included in a typical routine laboratory analysis of manures. Consequently, there is much less information available on carbon content than on nitrogen content. It should be mentioned that carbon is present in proteins, fatty acids, lipids, carbohydrates, cellulose, and lignin, but the detailed investigation of the fractions of these components is beyond the scope of the study. The maturity process is responsible for the significant decrease of OC that can be observed in the presented cattle FYM data (Levi-Minzi, R. *et al.* 1986). The total C content can be estimated from the organic matter content (Navarro, A.F. *et al.* 1993; Hao, X. *et al.* 2004; Larney, F.J. *et al.* 2004). According to the literature, the mean OM/TC ratio for pig slurries is 1.83 (Hao, X. *et al.* 2004), and in the case of organic wastes, including livestock manure, it is 1.94 (1.71–2.19) (Navarro, A.F. *et al.* 1993). For beef FYM it is 1.917 (1.51–2.60) according to Larney, F.J. *et al.* (2004).

Fractions of hemicelluloses, cellulose and lignin in organic carbon are important parameters of the carbon cycle and required during the Biome-BGCMuSo model simulations. The manure carbon fractions depend on the type of animal and its feeding, but some useful ranges are available in the literature, providing an overview (FAO, 1987). Besides, our mean values provide guidance for practical applications.

Proposed parameterization for manure composition

Application of the proposed, median-based organic fertilizer attribute setting is a relevant next step considering the practical use of our results. Biome-BGCMuSo provided insight into the effect of the end-users' input data choice on the simulated variables of interest. The results indicated that for LAI and final crop yield, organic fertilizer type selection and its related input data setting are not relevant. In contrast, manure type selection (in terms of the proposed parameterization of FYM and slurry) has a major role in SOC dynamics simulation. This finding is relevant if the long-term SOC dynamics are the focus of the study. The results highlighted that nitrogen balance-related simulation results are substantially affected by the selected manure attribute setting. This indicates that setting the proper input values is essential in the N_2O efflux estimations in any kind of organic fertilizer management.

Previous multi-model intercomparison studies found that model calibration might result in biased internal model parameter estimation (Martre, P. *et al.* 2015) with acceptable relevant output variables (like final yield or NPP). Our study is a major step forward in the sense that it also focuses on the internal model parameters (NH_4-N and NO_3-N in the topsoil) that are useful if the model is supposed to be parameterized properly.

Sensitivity analysis

Sensitivity analysis might support the selection of relevant input values, leaving the other attributes at their default value. This kind of logic simplifies the simulation procedure if the results have a general message. The study used the Biome-BGCMuSo biogeochemical model, which was first parameterized at one of the target sites (Martonvásár) with data from treatments including FYM application. As all biogeochemical models are associated with parameter and input data uncertainty, possible interactions can be present. One limitation of the study is the static parameterization of the soil module that affects the organic fertilizer utilization. Nevertheless, as we kept the decomposition and nitrification/denitrification, etc. parameters constant, and also as the model provided feasible results during the optimization, the results indicate the effect of the manure application. Interactions between calibration uncertainty and fertilizer attribute uncertainty are inevitable, which means that further studies might be needed to address this issue.

The presented results highlighted the determinant role of DM and ON in the FYM-related simulations when production-related output variables were considered. Sensitivity to DM and ON settings is consistent with our knowledge about the long-term, slow mineralization of organic manure after field application (Archontoulis, S.V. *et al.* 2014; Wang, Y. *et al.* 2018). For some organic fertilizer types (e.g. pig slurry), the proper setting of NH_4 content is also crucial for reliable simulations.

The results indicate that soil type and selection of simulation output variable strongly determine the set of most important organic fertilizer attribute settings. The fertilizer type can also have a strong effect on the rank of input data sensitivity, so no general pattern can be highlighted.

Due to the lack of obvious and simplified findings, our recommendation is that the modellers should perform a preliminary analysis for their model, for the selected manure type, which can be easily done following the presented method. The results of the modelling exercise are expected to support the selection of the input values (organic fertilizer attributes) that require accurate adjustment. If a given attribute has a major influence on the overall variability of a selected output variable, then the end-user is supposed to focus on the proper setting of the attribute, based on locally available data, information from experts, or based on targeted laboratory analysis.

Scope of validity of the results

The results are restricted to two sites representing two different soil types and similar climatic conditions, and to the Biome-BGCMuSo biogeochemical model. Within the European Union, 3.6 percent of soils are classified as sandy soils (arenosols), whereas only 2 percent are classified as chernozems (Tóth, G. *et al.* 2008). These soil types are uncommon in western European regions but are characteristic of Central Europe. (FAO, 2022). According to Tóth, G. *et al.* (2020), Hungary is situated in the Carpathian Basin and belongs to the southern subcontinental pedoclimatic zone. Therefore, our findings regarding C and N cycling and GHG emissions on arenosols and chernozems can only be extended to similar regions in Europe, which occupy an estimated total area of 12 million hectares. Nevertheless, as the model can be considered as a typical, process-based model, and as the results are consistent with our general knowledge about the functioning of the plant-soil system, the findings might be generalized to other sites and models as well.

The current version of Biome-BGCMuSo does not have the capacity to simulate the effect of dry matter (e.g., crop residue) on infiltration. Since both simulated soils have a high infiltration capacity, no runoff was observed in the simulation results. Therefore, considering the positive effect of accumulated surface biomass on infiltration would not significantly alter the results.

Conclusions

Manure storage and management is a major emission source of GHGs, mostly in the form of CH_4 and N_2O (Amon, B. *et al.* 2006; Kupper, T. *et al.* 2020). There is a large literature focusing on the quantification of GHG emission of manure and slurry storage, but relatively few studies address the GHG emission-related consequences of field application of organic fertilizers (e.g. Sommer, S.G. and Olesen, J.E. 1991).

In this study, we focused on the synthesis and direct application of available organic fertilizer composition data that supports the usage of crop models simulating the effects of FYM and slurry application. The results can support improved estimation of crop production and GHG balance of agro-ecosystems based on process-oriented models.

We addressed the question of whether generic manure-related input data settings per manure type are expected to affect the simulation results significantly. The results suggest that the manure type choice matters mostly for the internal model parameters (e.g. topsoil NO_3 content, SOC), thus, no single generic FYM or slurry input data set can be constructed. We also highlighted that N_2O emission is largely affected by the manure type selection, which is relevant in the estimation of the GHG balance of croplands. Mitigation-related model simulations have to be careful in the manure attribute setting in order to avoid biased estimations.

The results of the sensitivity analysis highlighted that site conditions, manure type, and selection of simulated output variables jointly affect the most important organic fertilizer attribute that needs to be constrained for a proper modelling exercise. In any case, careful estimation of the most relevant fertilizer attributes is always recommended (most of all DM and ON for FYM; DM and NH_4-N for slurry). Given the large variability of some of the organic fertilizer composition values, this task might be challenging.

Probably the most important added value of the study is the comprehensive, quantitative summary of available data on the manure-related C and N attributes. The presented results are unique to the knowledge of the authors, since no similar synthesis study is available in the literature that is easily accessible and that can be directly used by the modelling community for adjusting the organic fertilizer-related inputs. In other biogeochemical models or crop models, different input requirements can be present. For that purpose, some additional calculations can be done (e.g. if organic N content is expected to be provided relative to total manure weight), but this can be easily accomplished using the presented tables. The complete dataset is available from the lead author upon request.

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Supplementary section

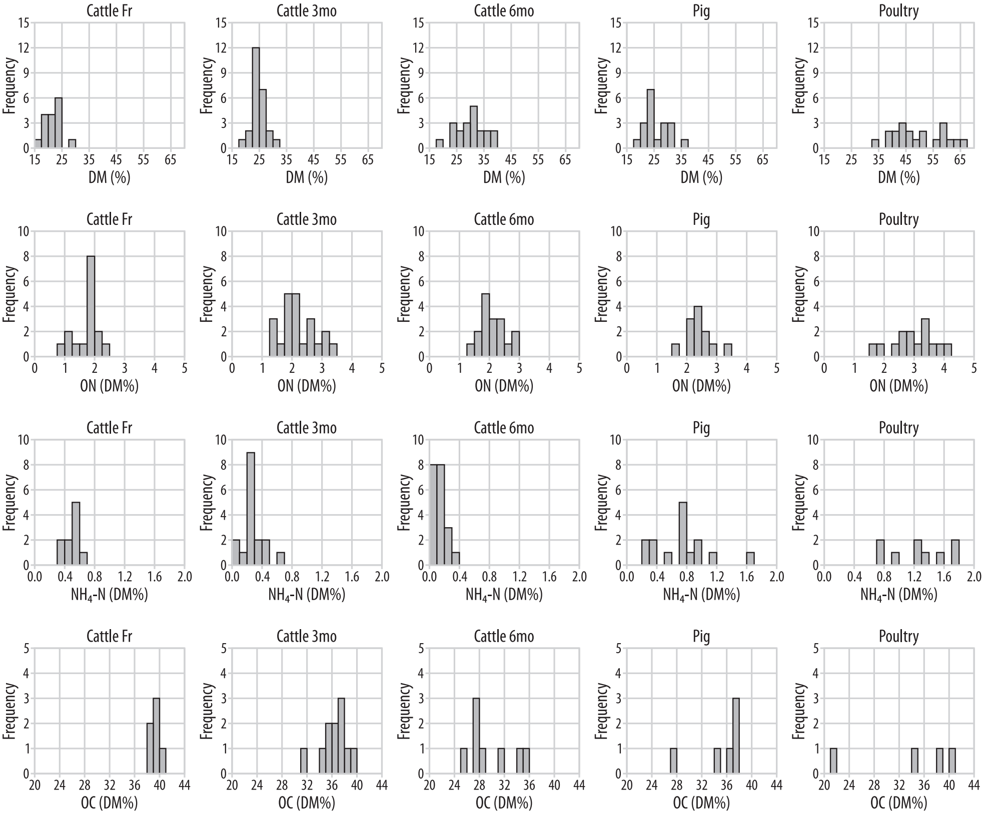

Fig. S1. Results of data collection presented as histograms for the different FYM types. DM denotes DM content; ON, NH_4-N and OC denote the organic nitrogen, NH_4-N and organic carbon content of DM, respectively. *Source:* Authors' own elaboration.

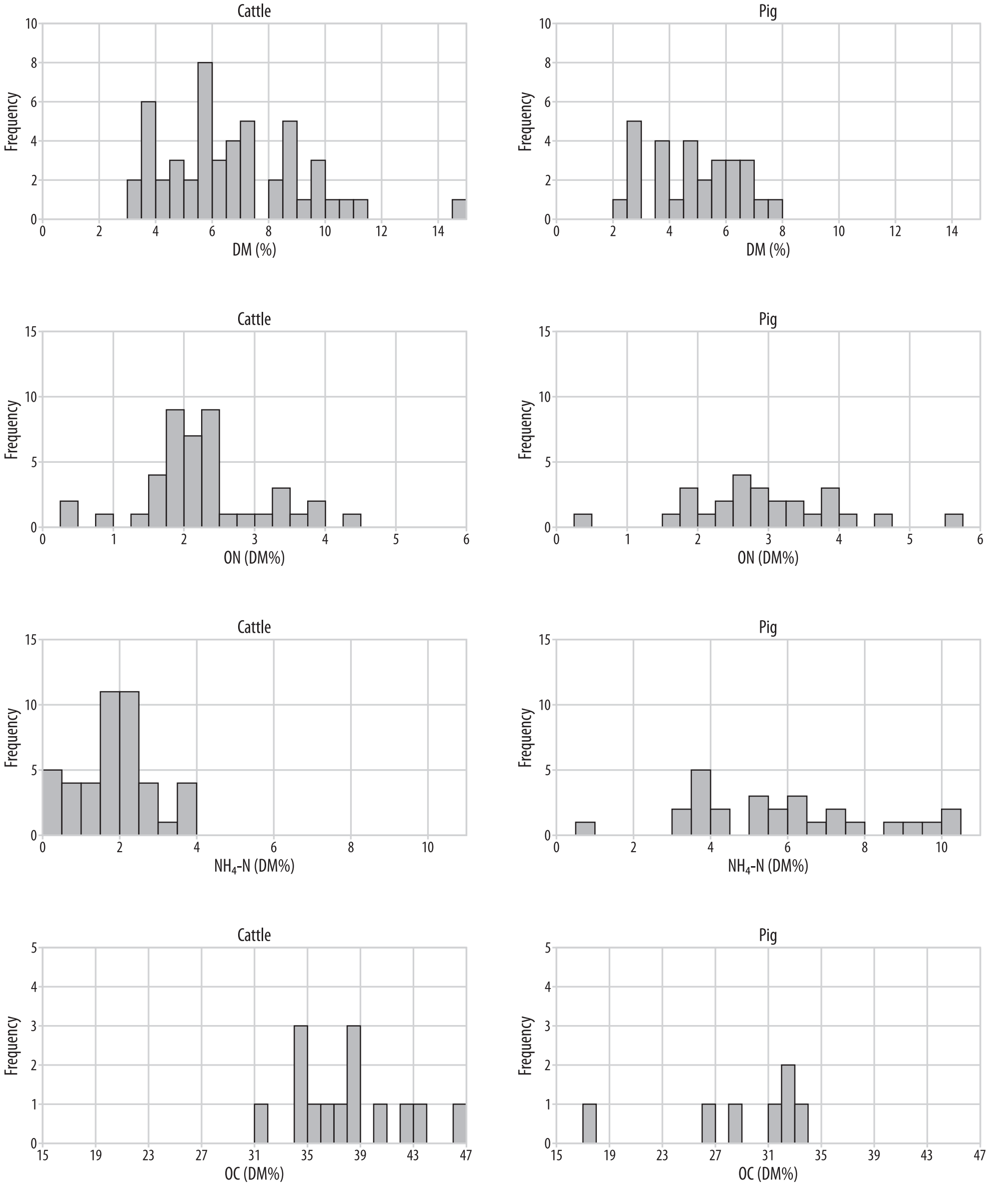

Fig. S2. Results of the data collection for slurry related organic fertilizer parameters. The abbreviations are the same as in *Fig. S1. Source:* Authors' own elaboration.

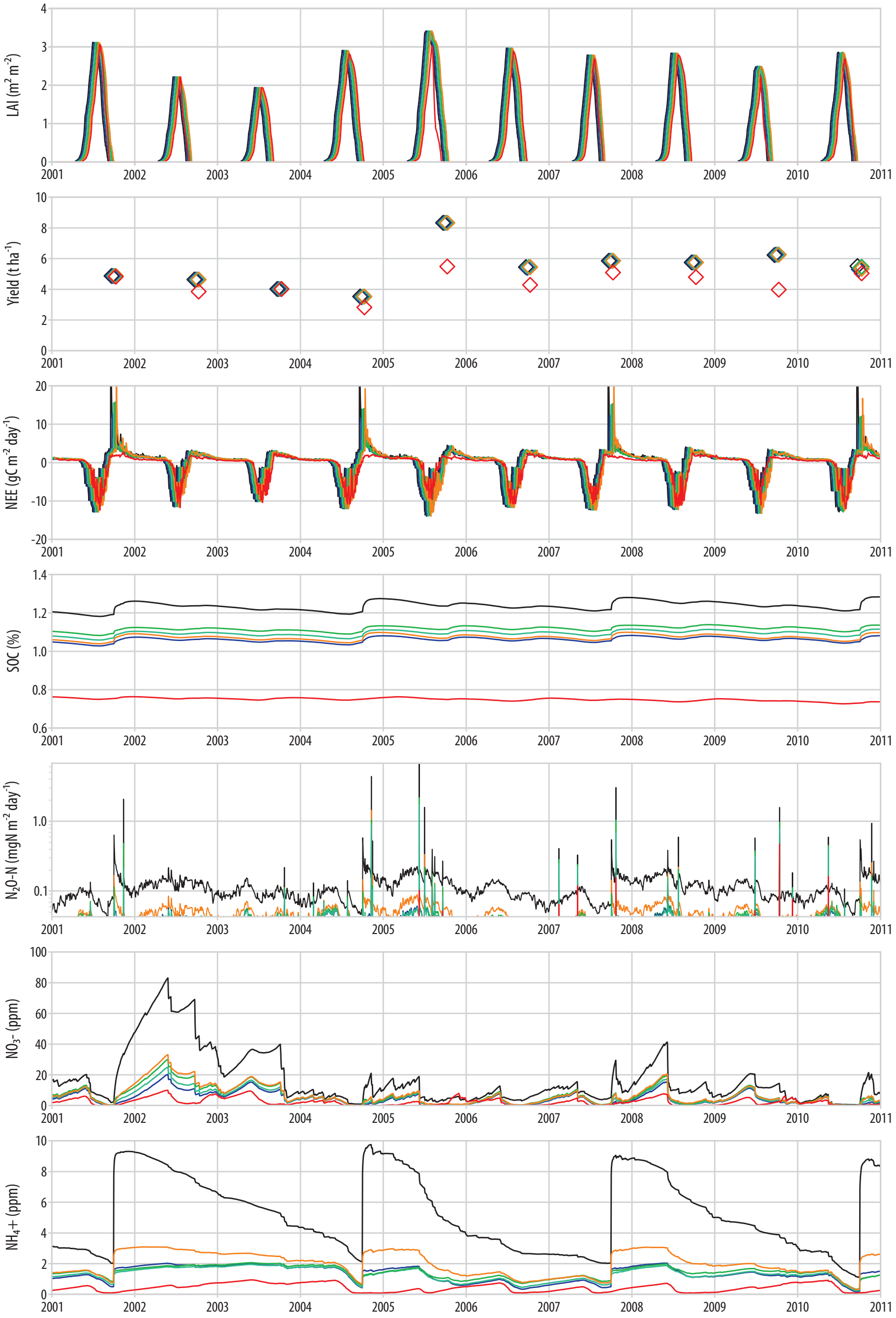

Fig. S3. Biome-BGCMuSo simulation results for Kishunhalas (sandy soil) using the median (proposed) parameterization for the different FYM types. For N_2O efflux logarithmic scale is used for clarity. Note that in some cases the lines/symbols overlap. The different colors represent simulation results driven by different FYM types. Black line represents poultry, blue line represents cattle Fr, light blue represents cattle 3mo, light green represents cattle 6mo, yellow represents pig, red represents control treatment. *Source:* Authors' own elaboration.

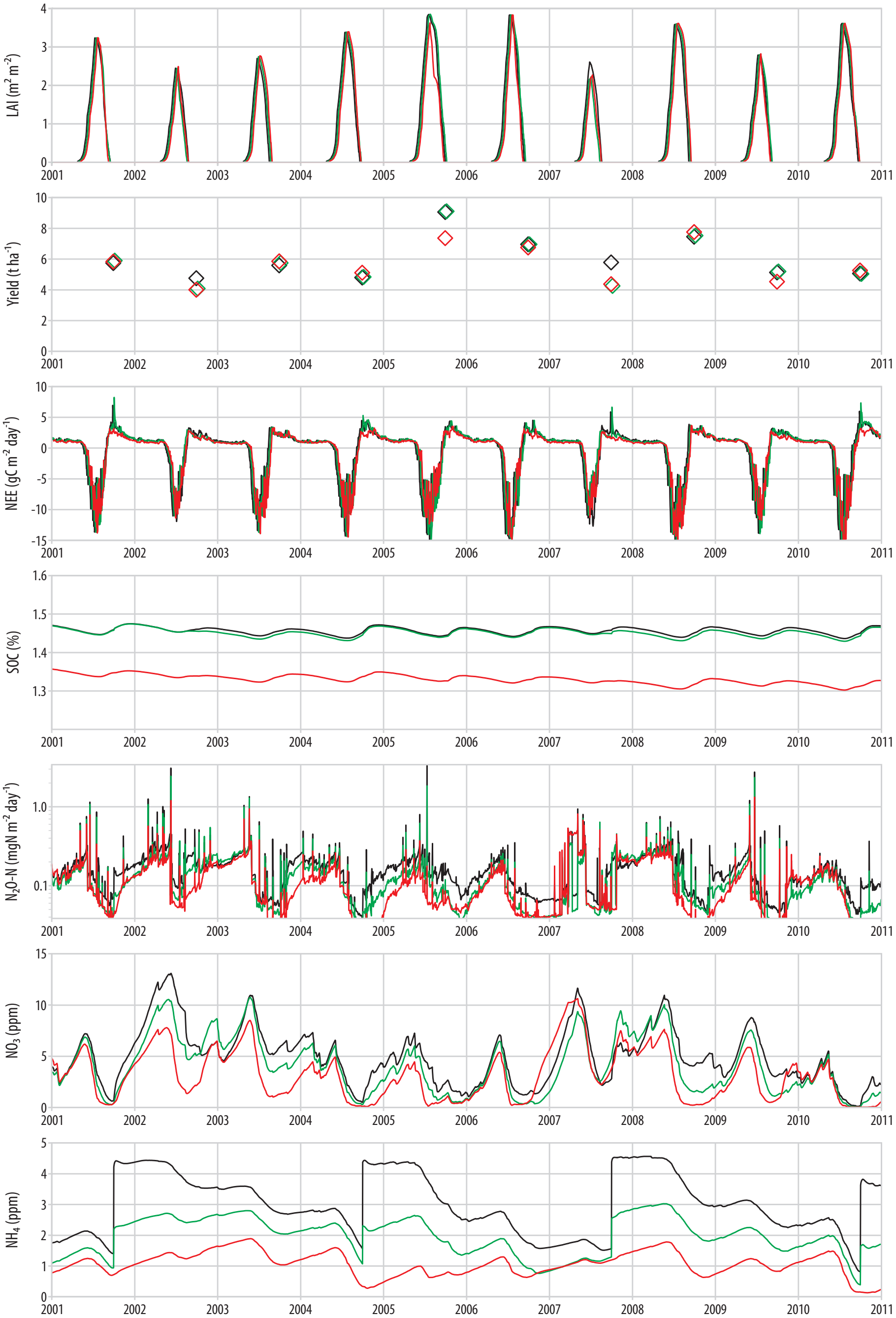

Fig. S4. Biome-BGCMuSo simulation results for Martonvásár (chernozem soil) using the median (proposed) parameterization for the different slurry types. For N_2O efflux logarithmic scale is used for clarity. Note that in some cases the lines/symbols overlap. The different colors represent simulation results driven by different slurry types. Black line represents pig, light green represents cattle, red represents control treatment. *Source:* Authors' own elaboration.

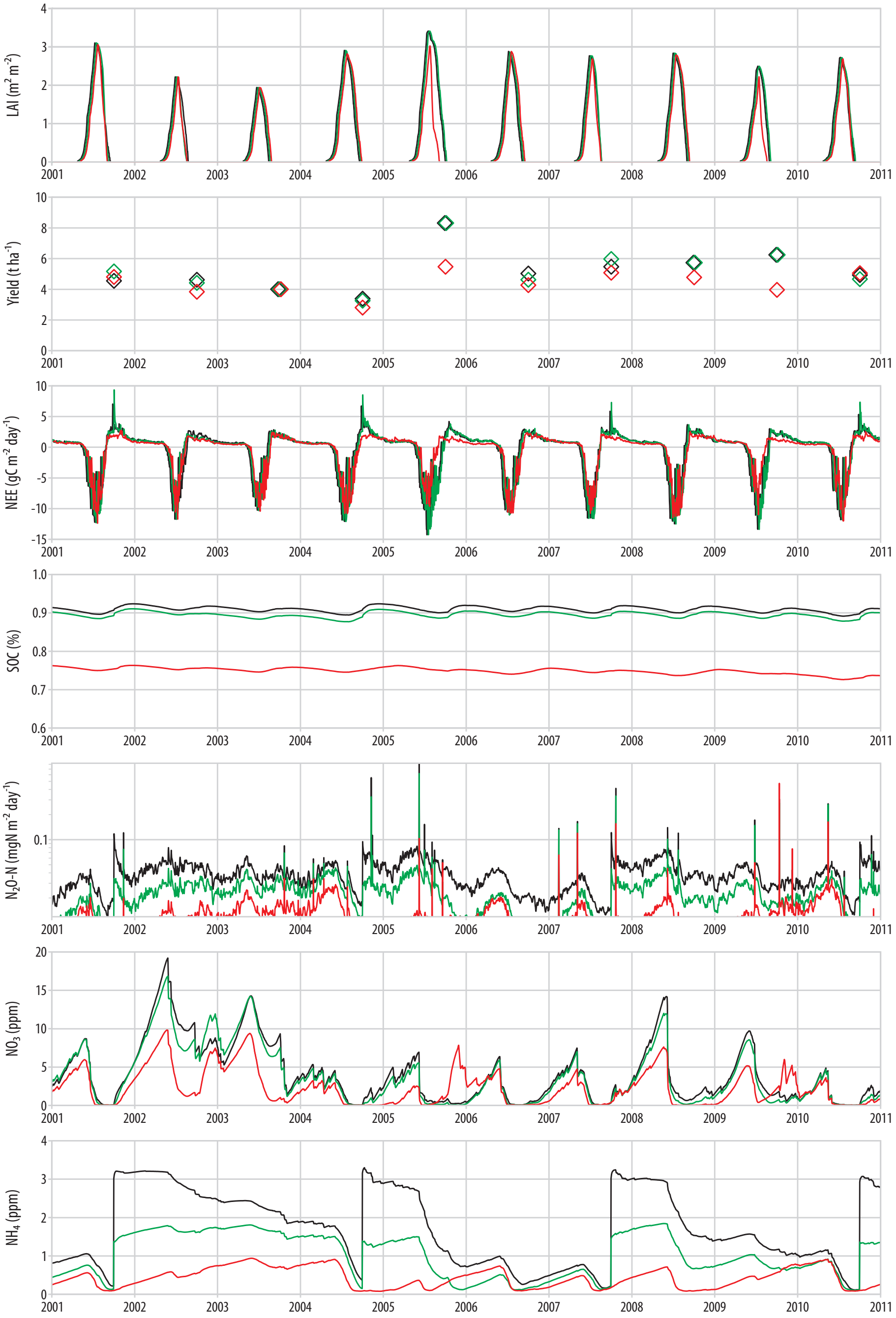

Fig. S5. Biome-BGCMuSo simulation results for Kiskunhalas (sandy soil) using the median (proposed) parameterization for the different slurry types. For N_2O efflux logarithmic scale is used for clarity. Note that in some cases the lines/symbols overlap. The different colors represent simulation results driven by different slurry types. Black line represents pig, light green represents cattle, red represents control treatment. *Source:* Authors' own elaboration.

Table S1. Dry matter content of manure, %

Animal	Manure	Number of data	Mean and SD	References
Cattle	FYM Fr	16	22.0 ± 3.13	Stefanovits, P. 1964; Szpravocsnik, 1964; Levi-Minzi, R. *et al.* 1986; Chambers, B.J. *et al.* 1999; Misselbrook, T.H. *et al.* 2005b; DEFRA, 2010; Chadwick, D.R. *et al.* 2011; Richner, W. *et al.* 2017.
Cattle	FYM 3mo	25	25.2 ± 2.62	Stefanovits, P. 1964; Szpravocsnik, 1964; Levi-Minzi, R. *et al.* 1986; Chambers, B.J. *et al.* 1999; Chadwick, D.R. *et al.* 2000a, 2000b, 2011; Misselbrook, T.H. *et al.* 2005a; Properties of manure, 2005; DEFRA, 2010; Brown, C. 2013.
Cattle	FYM 6mo	20	30.1 ± 5.1	Stefanovits, P. 1964; Szpravocsnik, 1964; McGinn, S.M. and Sommer, S.G. 2007; Pettygrove, G.S. *et al.* 2009; Árendás, T. 2019.
Pig	FYM	20	26.3 ± 3.83	Benne, E.J. *et al.* 1961; Szpravocsnik, 1964; Chambers, B.J. *et al.* 1999; Chadwick, D.R. *et al.* 2000a, 2000b, 2011; Misselbrook, T.H. *et al.* 2005b; DEFRA, 2010; Hartman, M. 2010; Rajendran, K. *et al.* 2012; Brown, C. 2013; Richner, W. *et al.* 2017.
Poultry	FYM	20	50.0 ± 9.37	Benne, E.J. *et al.* 1961; Sesztakov, K.A. 1961; Curkan, M.A. 1985; Chadwick, D.R. *et al.* 2000b, 2011; Menzi, H. 2002; Rao, J.R. *et al.* 2007; DEFRA, 2010; Hartman, M. 2010; Brown, C. 2013; Richner, W. *et al.* 2017.
Cattle	slurry	50	6.81 ± 2.46	Csaba, L. *et al.* 1978; Thompson, R.B. *et al.* 1990; Chambers, B.J. *et al.* 1999; Chadwick, D.R. *et al.* 2000a, 2000b, 2011; Smith, K.A. *et al.* 2000; Menzi, H. 2002; Thompson, R.B. and Meisinger, J.J. 2002; Bol, R. *et al.* 2003; Chastain, J.P. and Camberato, J.J. 2003; Misselbrook, T.H. *et al.* 2005a, 2005b; Properties of manure, 2005; Amon, B. *et al.* 2006; Fangueiro, D. *et al.* 2008; Bhandral, R. *et al.* 2009; DEFRA, 2010; Brown, C. 2013; Cavalli, D. *et al.* 2016; Nguyen, Q.V. *et al.* 2017; Richner, W. *et al.* 2017; Alfaro, M. *et al.* 2018.
Pig	slurry	28	4.92 ± 1.60	Csaba, L. *et al.* 1978; Chambers, B.J. *et al.* 1999; Chadwick, D.R. *et al.* 2000a, 2000b, 2011; Menzi, H. 2002; Misselbrook, T.H. *et al.* 2005b; Properties of manure, 2005; Bertora, C. *et al.* 2008; DEFRA, 2010; Brown, C. 2013; Richner, W. *et al.* 2017.

Table S2. P-values of ANOVA test for cattle Fr, 3mo and 6mo, pig and poultry FYM and for cattle and pig slurry comparison

FYM	DM	ON	NH_4-N	OC
Cattle Fr – 3mo	0.001036**	0.01148*	0.000116***	0.01444*
Cattle Fr – 6mo	$< 10^{-5}$ ***	0.02338*	$< 10^{-5}$ ***	$< 10^{-5}$ ***
Cattle 3mo – 6mo	$< 10^{-5}$ ***	0.5992	0.001132 **	0.000227***
Cattle Fr – Pig	0.00131**	0.00054***	0.08379	0.03399*
Cattle 3mo – Pig	0.2847	0.3736	$< 10^{-5}$ ***	0.455
Cattle 6mo – Pig	0.00599**	0.1299	$< 10^{-5}$ ***	0.02268*
Cattle Fr – Poultry	$< 10^{-5}$ ***	$< 10^{-5}$ ***	$< 10^{-5}$ ***	0.155
Cattle 3mo – Poultry	$< 10^{-5}$ ***	0.00073***	$< 10^{-5}$ ***	0.3366
Cattle 6mo – Poultry	$< 10^{-5}$ ***	0.00024***	$< 10^{-5}$ ***	0.3209
Pig – Poultry	$< 10^{-5}$ ***	0.01382 *	0.002492 **	0.6985
SLURRY				
Cattle – Pig	0.0004722***	0.003736**	$< 10^{-5}$ ***	0.0004148***

***, **, and *: Denote significant differences at 0.001, 0.01, and 0.05 confidence level, respectively.

Table S3. ON content of manure, DM %

Animal	Manure	Number of data	Mean and SD	References
Cattle	FYM Fr	16	1.8 ± 0.38	Stefanovits, P. 1964; Szpravocsnik, 1964; Levi-Minzi, R. *et al.* 1986; Chambers, B.J. *et al.* 1999; Misselbrook, T.H. *et al.* 2005b; DEFRA, 2010; Chadwick, D.R. *et al.* 2011; Richner, W. *et al.* 2017.
Cattle	FYM 3mo	22	2.2 ± 0.56	Stefanovits, P. 1964; Szpravocsnik, 1964; Levi-Minzi, R. *et al.* 1986; Chambers, B.J. *et al.* 1999; Chadwick, D.R. *et al.* 2000b; 2011; Misselbrook, T.H. *et al.* 2005a.
Cattle	FYM 6mo	17	2.1 ± 0.44	Stefanovits, P. 1964; Szpravocsnik, 1964; McGinn, S.M. and Sommer, S.G. 2007; Pettygrove, G.S. *et al.* 2009; Árendás, T. 2019.
Pig	FYM	12	2.37 ± 0.42	Chambers, B.J. *et al.* 1999; Chadwick, D.R. *et al.* 2000b, 2011; DEFRA, 2010; Richner, W. *et al.* 2017.
Poultry	FYM	14	2.99 ± 0.72	Curkan, M.A. 1985; Chadwick, D.R. *et al.* 2000b, 2011; Menzi, H. 2002; Rao, J.R. *et al.* 2007; Richner, W. *et al.* 2017.
Cattle	slurry	43	2.27 ± 0.85	Thompson, R.B. *et al.* 1990; Chambers, B.J. *et al.* 1999; Chadwick, D.R. *et al.* 2000a, 2000b; 2011; Smith, K.A. *et al.* 2000; Menzi, H. 2002; Thompson, R.B. and Meisinger, J.J. 2002; Chastain, J.P. and Camberato, J.J. 2003; Misselbrook, T.H. *et al.* 2005a, 2005b; Properties of manure, 2005; Amon, B. *et al.* 2006; Fangueiro, D. *et al.* 2008; Bhandral, R. *et al.* 2009; DEFRA, 2010; Brown, C. 2013; Cavalli, D. *et al.* 2016; Nguyen, Q.V. *et al.* 2017; Richner, W. *et al.* 2017; Alfaro, M. *et al.* 2018.
Pig	slurry	26	2.96 ± 1.05	Csaba, L. *et al.* 1978; Chambers, B.J. *et al.* 1999; Chadwick, D.R. *et al.* 2000b, 2011; Menzi, H. 2002; Misselbrook, T.H. *et al.* 2005b; Properties of manure, 2005; Bertora, C. *et al.* 2008; DEFRA, 2010; Brown, C. 2013; Richner, W. *et al.* 2017.

Table S4. NH_4-N content of manure, DM %

Animal	Manure	Number of data	Mean and SD	References
Cattle	FYM Fr	10	0.53 ± 0.09	Stefanovits, P. 1964; Szpravocsnik, 1964; Levi-Minzi, R. *et al.* 1986; Chambers, B.J. *et al.* 1999; Misselbrook, T.H. *et al.* 2005b; DEFRA, 2010; Chadwick, D.R. *et al.* 2011; Richner, W. *et al.* 2017.
Cattle	FYM 3mo	17	0.28 ± 0.15	Stefanovits, P. 1964; Szpravocsnik, 1964; Chambers, B.J. *et al.* 1999; Chadwick, D.R. *et al.* 2000a, 2000b, 2011; Misselbrook, T.H. *et al.* 2005a.
Cattle	FYM 6mo	20	0.132 ± 0.10	Stefanovits, P. 1964; Szpravocsnik, 1964; McGinn, S.M. and Sommer, S.G. 2007; Pettygrove, G.S. *et al.* 2009; Árendás, T. 2019.
Pig	FYM	15	0.742 ± 0.37	Szpravocsnik, 1964; Chambers, B.J. *et al.* 1999; Chadwick, D.R. *et al.* 2000a, 2000b, 2011; Misselbrook, T.H. *et al.* 2005b; Richner, W. *et al.* 2017.
Poultry	FYM	9	1.279 ± 0.38	Chadwick, D.R. *et al.* 2000b, 2011; DEFRA, 2010; Richner, W. *et al.* 2017.
Cattle	slurry	44	1.896 ± 1.00	Thompson, R.B. *et al.* 1990; Chambers, B.J. *et al.* 1999; Chadwick, D.R. *et al.* 2000b, 2011; Smith, K.A. *et al.* 2000; Thompson, R.B. and Meisinger, J.J. 2002; Chastain, J.P. and Camberato, J.J. 2003; Misselbrook, T.H. *et al.* 2005a, 2005b; Properties of manure, 2005; Amon, B. *et al.* 2006; Fangueiro, D. *et al.* 2008; Bhandral, R. *et al.* 2009; DEFRA, 2010; Brown, C. 2013; Cavalli, D. *et al.* 2016; Nguyen, Q.V. *et al.* 2017; Richner, W. *et al.* 2017; Alfaro, M. *et al.* 2018.
Pig	slurry	27	5.864 ± 2.41	Csaba, L. *et al.* 1978; Chambers, B.J. *et al.* 1999; Chadwick, D.R. *et al.* 2000a, 2000b, 2011; Misselbrook, T.H. *et al.* 2005b; Properties of manure, 2005; Bertora, C. *et al.* 2008; DEFRA, 2010; Brown, C. 2013; Richner, W. *et al.* 2017.

Table S5. NO_3-N content of manure, DM %

Animal	Manure	Number of data	Mean and SD	References
Cattle	FYM Fr	1	0	Chadwick, D.R. *et al.* 2011.
Cattle	FYM 3mo	1	0.08	Chadwick, D.R. *et al.* 2000.
Cattle	FYM 6mo	16	0.017 ± 0.02	McGinn, S.M. and Sommer, S.G. 2007; Pettygrove, G.S. *et al.* 2009; Árendás, T. 2019.
Pig	FYM	2	0	Chadwick, D.R. *et al.* 2000a negligible; Chadwick, D.R. *et al.* 2011.
Poultry	FYM	1	0	Chadwick, D.R. *et al.* 2011.
Cattle	slurry	5	0.002 ± 0.003	Chadwick, D.R. *et al.* 2000a negligible; Fangueiro, D. *et al.* 2008; Chadwick, D.R. *et al.* 2011; Alfaro, M. *et al.* 2018.
Pig	slurry	3	0	Chadwick, D.R. *et al.* 2000a negligible; Chadwick, D.R. *et al.* 2011.

Table S6. OC content of manure, DM %

Animal	Manure	Number of data	Mean and SD	References
Cattle	FYM Fr	6	39.13 ± 0.65	Levi-Minzi, R. *et al.* 1986.
Cattle	FYM 3mo	11	36.45 ± 2.30	Levi-Minzi, R. *et al.* 1986; Chadwick, D.R. *et al.* 2000a, 2000b, 2011.
Cattle	FYM 6mo	8	30.20 ± 3.57	Pettygrove, G.S. *et al.* 2009; Árendás, T. 2019.
Pig	FYM	6	35.33 ± 3.74	Chadwick, D.R. *et al.* 2000a, 2000b, 2011.
Poultry	FYM	4	33.77 ± 8.60	Chadwick, D.R. *et al.* 2000b, 2011.
Cattle	slurry	14	38.02 ± 4.25	Chadwick, D.R. *et al.* 2000a, 2000b, 2011; Bol, R. *et al.* 2003; Amon, B. *et al.* 2006; Rodhe, L. *et al.* 2006; Fangueiro, D. *et al.* 2008; Cavalli, D. *et al.* 2016.
Pig	slurry	7	28.88 ± 5.35	Chadwick, D.R. *et al.* 2000a, 2000b, 2011; Bertora, C. *et al.* 2008.

*Table S7. Relative contribution of the investigated FYM input parameters (in columns) to the variance of the selected outputs (in rows) and the SCORE for each input showing their importance in terms of output uncertainty. Simulation results for chernozem soil at Martonvásár**

Parameter	DM	NH_4-N	ON	OC		Parameter	DM	NH_4-N	ON	OC
LAI	17.2	3.6	79.2	0.0	Fresh Cattle FYM	LAI	42.1	5.1	47.1	5.7
YIELD	13.5	3.0	83.4	0.0		YIELD	48.1	10.8	39.3	1.9
NEE	1.4	3.5	94.4	0.7		NEE	2.1	4.7	43.0	50.3
SOC	87.7	0.6	11.2	0.5		SOC	62.4	0.3	2.2	35.0
N_2O	28.0	4.6	67.4	0.0		N_2O	54.0	7.7	36.5	1.8
SNO_3	29.6	3.3	67.1	0.0		SNO_3	57.5	5.2	36.6	0.7
SNH_4	32.4	7.7	59.9	0.0		SNH_4	62.1	11.2	26.3	0.4
SCORE1	*14*	*7*	*26*	*7*		*SCORE2*	*21*	*7*	*15*	*10*
Parameter	DM	NH_4-N	ON	OC	3mo Cattle FYM	Parameter	DM	NH_4-N	ON	OC
LAI	17.7	16.9	65.0	0.4		LAI	36.7	1.0	56.7	5.7
YIELD	17.9	22.7	59.2	0.2		YIELD	22.0	0.2	68.0	9.8
NEE	32.7	9.2	38.5	19.6		NEE	16.7	0.2	14.3	68.9
SOC	83.5	0.8	3.3	12.3		SOC	60.6	0.1	2.2	37.1
N_2O	24.4	18.8	56.6	0.2		N_2O	47.9	2.0	48.1	2.0
SNO_3	27.2	13.4	59.3	0.1		SNO_3	49.7	1.3	48.0	1.0
SNH_4	27.7	40.7	31.6	0.0		SNH_4	63.1	4.6	32.3	0.0
SCORE1	*15*	*10*	*18*	*7*		*SCORE2*	*19*	*7*	*17*	*11*
Parameter	DM	NH_4-N	ON	OC	6mo Cattle FYM	Parameter	DM	NH_4-N	ON	OC
LAI	27.6	7.0	64.5	0.9		LAI	70.7	2.6	23.1	3.6
YIELD	31.7	7.9	59.8	0.6		YIELD	87.3	0.5	7.2	5.0
NEE	41.8	2.7	26.8	28.7		NEE	52.1	0.0	0.1	47.9
SOC	83.2	0.2	2.0	14.5		SOC	54.6	0.0	0.3	45.1
N_2O	33.0	6.4	60.0	0.7		N_2O	44.3	0.8	52.1	2.9
SNO_3	34.3	3.8	61.4	0.5		SNO_3	44.4	0.5	52.8	2.3
SNH_4	42.9	18.5	38.5	0.0		SNH_4	63.7	2.5	33.7	0.1
SCORE1	*19*	*7*	*20*	*8*		*SCORE2*	*25*	*7*	*13*	*11*
Parameter	DM	NH_4-N	ON	OC	Pig FYM	Parameter	DM	NH_4-N	ON	OC
LAI	19.5	39.9	39.8	0.7		LAI	96.0	0.0	0.0	4.0
YIELD	2.6	52.8	43.9	0.7		YIELD	95.9	0.0	0.0	4.1
NEE	80.0	0.1	0.1	19.9		NEE	50.1	0.0	0.0	49.9
SOC	81.6	0.0	0.0	18.4		SOC	49.9	0.0	0.0	50.1
N_2O	33.8	49.1	17.1	0.1		N_2O	60.6	9.4	29.4	0.6
SNO_3	39.4	43.5	17.2	0.0		SNO_3	65.7	7.5	26.7	0.0
SNH_4	30.8	62.7	6.5	0.0		SNH_4	69.4	15.6	14.8	0.2
SCORE1	*18*	*17*	*10*	*7*		*SCORE2*	*28*	*7*	*9*	*11*
Parameter	DM	NH_4-N	ON	OC	Poultry FYM	Parameter	DM	NH_4-N	ON	OC
LAI	98.5	0.0	0.0	1.5		LAI	96.9	0.0	0.2	2.8
YIELD	98.3	0.0	0.0	1.7		YIELD	97.1	0.0	0.1	2.8
NEE	48.8	0.0	0.0	51.2		NEE	48.9	0.0	0.0	51.1
SOC	49.0	0.0	0.0	51.0		SOC	49.1	0.0	0.0	50.9
N_2O	43.3	22.9	32.7	1.1		N_2O	59.5	17.8	21.6	1.1
SNO_3	47.6	19.9	32.2	0.2		SNO_3	64.1	15.1	20.6	0.1
SNH_4	52.3	32.6	15.0	0.1		SNH_4	67.5	23.4	8.9	0.2
SCORE1	*25*	*9*	*9*	*11*		*SCORE2*	*27*	*8*	*9*	*11*

*Left charts: full range; right charts: median±10% range.

*Table S8. Relative contribution of the investigated slurry input parameters (in columns) to the variance of the selected outputs (in rows) and the SCORE for each input showing their importance in terms of output uncertainty. Simulation results for chernozem soil at Martonvásár**

Parameter	DM	NH_4-N	ON	OC		Parameter	DM	NH_4-N	ON	OC
LAI	34.7	37.7	27.5	0.1	Cattle Slurry	LAI	65.4	16.1	17.4	1.1
YIELD	37.7	35.1	27.1	0.1		YIELD	57.0	25.7	15.0	2.3
NEE	8.0	52.1	37.3	2.6		NEE	36.1	18.5	22.4	23.0
SOC	79.7	10.3	7.7	2.2		SOC	74.8	8.1	7.0	10.0
N_2O	44.4	36.3	19.3	0.0		N_2O	56.8	25.4	17.6	0.2
SNO_3	47.2	32.3	20.5	0.0		SNO_3	63.1	18.9	17.9	0.1
SNH_4	41.3	46.1	12.6	0.0		SNH_4	62.5	27.0	10.3	0.2
SCORE1	*18*	*15*	*11*	*7*		*SCORE2*	*24*	*10*	*8*	*8*
Parameter	DM	NH_4-N	ON	OC		Parameter	DM	NH_4-N	ON	OC
LAI	31.8	55.6	12.6	0.0	Pig Slurry	LAI	48.2	39.6	12.2	0.1
YIELD	30.8	55.7	13.5	0.0		YIELD	51.6	39.1	9.3	0.0
NEE	20.6	64.8	13.5	1.1		NEE	5.1	25.7	8.0	61.2
SOC	59.2	30.8	6.9	3.1		SOC	68.3	5.1	1.1	25.5
N_2O	40.1	52.6	7.4	0.0		N_2O	60.5	34.5	4.9	0.1
SNO_3	40.8	51.1	8.1	0.0		SNO_3	62.0	33.0	5.0	0.0
SNH_4	36.3	59.4	4.3	0.0		SNH_4	59.5	37.5	3.0	0.0
SCORE1	*17*	*21*	*7*	*7*		*SCORE2*	*22*	*13*	*7*	*11*

*Left charts: full range; right charts: median±10% range.

*Table S9. Relative contribution of the investigated FYM input parameters (in columns) to the variance of the selected outputs (in rows) and the SCORE for each input showing their importance in terms of output uncertainty. Simulation results for sandy soil at Kiskunhalas**

Parameter	DM	NH_4-N	ON	OC		Parameter	DM	NH_4-N	ON	OC
LAI	47.7	3.7	48.6	0.0	Fresh Cattle FYM	LAI	66.0	1.8	8.2	24.0
YIELD	90.7	0.1	8.3	0.9		YIELD	67.4	0.1	4.2	28.4
NEE	93.4	0.3	4.7	1.6		NEE	46.9	0.0	0.1	53.0
SOC	87.1	0.6	11.8	0.5		SOC	60.3	0.2	1.3	38.2
N_2O	29.1	5.8	65.1	0.0		N_2O	58.4	8.7	32.1	0.9
SNO_3	24.8	1.6	73.6	0.0		SNO_3	50.3	2.5	45.8	1.4
SNH_4	27.9	6.9	65.2	0.0		SNH_4	56.9	10.2	31.5	1.5
SCORE1	*24*	*7*	*18*	*7*		*SCORE2*	*24*	*7*	*11*	*12*
Parameter	DM	NH_4-N	ON	OC	3mo Cattle FYM	Parameter	DM	NH_4-N	ON	OC
LAI	48.8	14.5	35.9	0.7		LAI	68.0	0.1	8.7	23.1
YIELD	70.0	0.3	25.0	4.7		YIELD	68.7	0.1	11.2	20.0
NEE	81.9	0.1	0.3	17.8		NEE	51.5	0.0	0.0	48.5
SOC	83.7	0.9	3.8	11.6		SOC	60.7	0.0	2.9	36.4
N_2O	28.6	33.9	37.5	0.0		N_2O	59.3	3.1	37.5	0.0
SNO_3	27.0	5.0	67.9	0.1		SNO_3	45.8	0.4	52.4	1.5
SNH_4	26.6	39.2	34.2	0.0		SNH_4	59.6	4.1	36.2	0.1
SCORE1	*23*	*9*	*14*	*7*		*SCORE2*	*24*	*7*	*11*	*12*
Parameter	DM	NH_4-N	ON	OC	6mo Cattle FYM	Parameter	DM	NH_4-N	ON	OC
LAI	55.6	6.2	37.8	0.3		LAI	69.2	0.0	14.8	16.1
YIELD	70.3	0.0	22.9	6.8		YIELD	68.1	0.0	14.7	17.2
NEE	80.0	0.0	0.0	19.9		NEE	51.1	0.0	0.0	48.8
SOC	83.3	0.2	2.4	14.1		SOC	57.1	0.0	1.0	41.9
N_2O	43.1	14.5	42.5	0.0		N_2O	61.0	2.0	37.0	0.1
SNO_3	34.8	1.3	63.5	0.3		SNO_3	43.3	0.2	54.8	1.7
SNH_4	41.2	18.1	40.7	0.0		SNH_4	60.8	2.5	36.7	0.0
SCORE1	*25*	*7*	*16*	*7*		*SCORE2*	*25*	*7*	*11*	*11*
Parameter	DM	NH_4-N	ON	OC	Pig FYM	Parameter	DM	NH_4-N	ON	OC
LAI	73.9	13.9	6.0	6.2		LAI	66.4	0.7	2.7	30.1
YIELD	80.7	6.7	5.5	7.1		YIELD	65.9	0.7	3.8	29.6
NEE	80.1	0.1	0.0	19.8		NEE	49.6	0.0	0.0	50.4
SOC	82.4	0.3	0.1	17.2		SOC	55.1	0.1	0.2	44.6
N_2O	32.4	57.3	10.3	0.0		N_2O	66.9	12.6	20.6	0.0
SNO_3	46.4	22.8	30.7	0.0		SNO_3	60.6	3.0	36.4	0.0
SNH_4	30.7	60.3	9.0	0.0		SNH_4	66.6	14.3	19.1	0.0
SCORE1	*26*	*13*	*8*	*7*		*SCORE2*	*26*	*7*	*9*	*13*
Parameter	DM	NH_4-N	ON	OC	Poultry FYM	Parameter	DM	NH_4-N	ON	OC
LAI	50.7	2.6	10.7	36.0		LAI	8.3	17.2	41.1	33.4
YIELD	48.8	2.5	12.9	35.8		YIELD	6.3	16.7	44.5	32.5
NEE	48.5	0.0	0.0	51.5		NEE	49.4	0.0	0.0	50.6
SOC	48.7	0.0	0.0	51.3		SOC	49.5	0.0	0.0	50.5
N_2O	50.1	27.3	22.6	0.0		N_2O	66.3	19.8	13.9	0.0
SNO_3	46.1	7.6	46.3	0.0		SNO_3	63.6	5.7	30.7	0.0
SNH_4	49.9	29.0	21.1	0.0		SNH_4	65.8	21.2	13.0	0.0
SCORE1	*21*	*9*	*11*	*13*		*SCORE2*	*20*	*8*	*12*	*13*

*Left charts: full range; right charts: median±10% range.

*Table S10. Relative contribution of the investigated slurry input parameters (in columns) to the variance of the selected outputs (in rows) and the SCORE for each input showing their importance in terms of output uncertainty. Simulation results for sandy soil at Kiskunhalas**

Parameter	DM	NH_4-N	ON	OC		Parameter	DM	NH_4-N	ON	OC
LAI	42.6	37.9	19.5	0.0	Cattle Slurry	LAI	66.1	17.5	14.9	1.6
YIELD	47.2	33.0	19.6	0.2		YIELD	68.4	15.0	14.5	2.2
NEE	15.7	54.6	28.6	1.1		NEE	74.1	13.2	12.0	0.6
SOC	74.8	12.7	10.9	1.7		SOC	73.9	8.3	12.2	5.7
N_2O	41.2	42.0	16.8	0.0		N_2O	60.4	22.9	15.8	0.9
SNO_3	45.9	21.6	32.4	0.0		SNO_3	63.0	14.9	21.6	0.4
SNH_4	39.3	45.8	14.9	0.0		SNH_4	59.7	25.9	13.4	1.0
SCORE1	*19*	*16*	*9*	*7*		*SCORE2*	*27*	*9*	*8*	*7*
Parameter	DM	NH_4-N	ON	OC	Pig Slurry	Parameter	DM	NH_4-N	ON	OC
LAI	32.1	58.2	9.6	0.0		LAI	67.0	28.2	3.7	1.1
YIELD	38.1	53.1	8.6	0.3		YIELD	29.6	18.0	2.9	49.5
NEE	21.2	67.0	11.3	0.5		NEE	7.6	45.5	6.0	40.9
SOC	52.0	37.3	9.1	1.6		SOC	71.2	7.3	2.2	19.3
N_2O	37.3	55.9	6.9	0.0		N_2O	60.2	35.1	4.6	0.1
SNO_3	43.1	42.0	14.9	0.0		SNO_3	64.1	27.8	8.1	0.0
SNH_4	36.5	57.8	5.7	0.0		SNH_4	59.6	36.4	3.8	0.1
SCORE1	*16*	*21*	*7*	*7*		*SCORE2*	*22*	*13*	*7*	*11*

*Left charts: full range; right charts: median±10% range.

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