The model shows: In the long term, replacing mineral fertilisers with digestate from biogas plants can improve soil quality and reduce greenhouse gases

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- **Fermentation residues from biogas plants are a promising alternative to mineral fertilizers.**
- **Replacing mineral fertilizers can improve the greenhouse gas balance of agriculture.**
- **Soils benefit from humus formation and can act as CO_2 sinks.**

Background and Objectives

The growth of the world population requires an increase in agricultural production. However, this should be achieved by reducing the environmental impact of agricultural practices. The European Commission's Green Deal includes targets for more efficient use of nitrogen (N). This could be achieved by transporting manure and fermentation residues from livestock and biogas-rich regions to arable farming areas that mainly use mineral fertilizers. At the same time, this could also reduce gaseous N emissions. However, there are only a few studies that examine the long-term effects of reducing fertilizer use and replacing mineral fertilizers with organic fertilizers on humus stocks, nitrous oxide emissions (N_2O), the N cycle, and productivity. For this reason, long-term model simulations were carried out as part of the RESOURCE project to investigate this topic.

Approach

The project partner (Julius Kühn Institute) set up two field trials near Braunschweig in Sicke and Wipshausen. The variants mineral fertilization (MD) and fermentation residue application (GR) were tested in three intensity levels each – 100% (MD, GR), 80% (MD-20%, GR-20%), and 60% (MD-40%, GR-40%) of the nitrogen (N) demand value of the respective growing crop. These trials were used to further develop and evaluate the biogeochemical model DNDCv.CAN. The focus of the model development was on describing N turnover and flows in arable cropping systems. In particular, the agreement between measured and observed ammonia (NH_3) and N_2O emissions in the field trials was investigated. Permanent soil observation plots in Lower Saxony were used to confirm the suitability of the model for simulating changes in humus content depending on climate and soil conditions. Here, too, observed and modeled changes in humus stocks were compared. In order to predict how the substitution of mineral fertilizers with fermentation residues and different fertilization rates will affect yields, N_2O emissions, and changes in humus content in the medium to long term, scenarios from 2020 to 2060 were modeled with DNDCv.CAN. The assumed management of the scenarios was based on the variants tested in the field trials. Three climate scenarios from the German Weather Service were used to take future climate developments into account. These three scenarios describe different levels of temperature increase, from low (RCP2.5) to moderate (RCP 4.5) to high (RCP 8.5).
The model results were used to quantify the balance of land use-related greenhouse gas emissions in addition to production and N use efficiency. This is derived from carbon dioxide (CO_2) emissions and direct and indirect N_2O emissions. CO_2 emissions are mainly caused by changes in the humus stock.

Results

Similar to the measurement data, the modeling also revealed no significant differences in above-ground biomass and yield between the different fertilization variants. The various fertilization strategies had relatively little impact on changes in above-ground biomass and yield over time. This applies to the simulated locations and climate scenarios. The simulations showed that substituting mineral fertilizers with fermentation residues has a positive effect on the long-term development of humus stocks. Especially for the variants with higher N inputs (100% and 80% of the N requirement), there were significant increases in humus stocks in the topsoil compared to the variant with mineral fertilization covering the N requirement (Fig. 1). The GR-40% variant shows no significant increases in humus reserves compared to the MD variant (100% mineral fertilization): due to the reduced N supply, the additional carbon input via the fermentation residues is compensated by lower biomass growth. Reduced mineral fertilizer applications (MD-20%, MD-40%) reduce humus reserves in most cases, as the reduction in N supply affects plant growth and thus the input of crop residues. Soil properties have a very pronounced

effect on humus increase when digestate is applied, while the effect of climate scenarios is less pronounced.
In all three simulated fertilization levels, yields and N use efficiency change only slightly over time. This result is also evident in the fermentation residue variants GR and GR-20%. It was to be expected that an increase in humus reserves would increase mineralization and release more plant-available nitrogen. Here, it can be seen that plant growth in the variants with 100% and 80% N demand coverage is hardly limited by N, which is also confirmed by the experimental results.

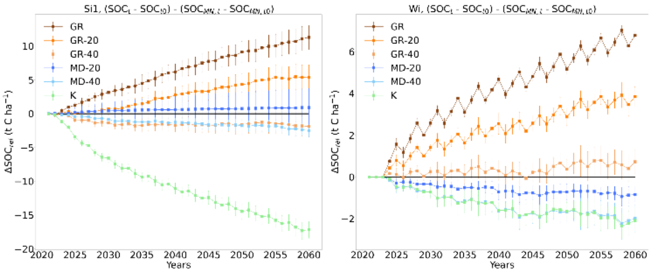

Figure 1: Modeling of temporal changes in soil organic matter for different mineral fertilization variants (MD) at the Sickte (left) and Wipshausen (right) field experiment sites; the vertical bars show the variations caused by the different climate scenarios of the climate models and the variability of the replicates used in the field trials (source: Tendler et al., 2025).

The modeled N_2O emissions were strongly influenced by the locations. Compared to loamy soils (Sickte), the simulated N_2O emissions on sandy soils (Wipshausen) are significantly lower. On sandy soils, both climatic conditions and the various fertilization variants have little influence on N_2O emissions, whereas this effect is very pronounced on loamy soils. This behavior is plausible because, due to low water content and pore structure, N_2O formation through denitrification as a result of anaerobic conditions in the soil is much less likely to occur on sandy soils. The modeled N_2O emissions increase over time in all management variants, but most strongly in those that show an increase in humus stocks.

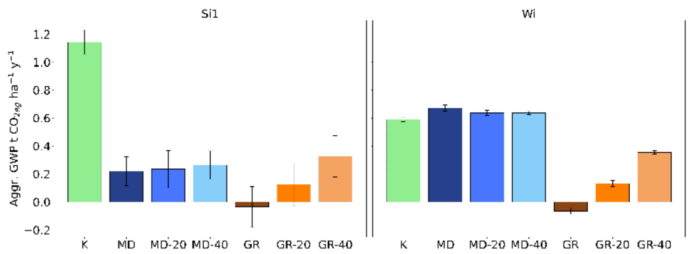

Figure 2: Modeled cumulative greenhouse gas emissions at the Sickte (left) and Wipshausen (right) sites; the standard deviations show how accurately the results of the various climate models can be predicted (source: own data).

Conclusions

Based on field experiments, model simulations were carried out using the improved biogeochemical model DNDCv.CAN. The results suggest that, in the medium term, replacing mineral fertilizers with fermentation residues can store enough CO_2 in the soil to compensate for direct and indirect N_2O emissions. This can turn soils into a temporary CO_2 sink. This depends on soil conditions and management history. Overall, mineral fertilizer substitution proved to be beneficial in the medium term (0–40 years) for the balance of land use-related greenhouse gas emissions (Fig. 2).
However, it is important to note that the use of digestate as the only N fertilizer generally leads to lower protein content in the crop. For this reason, a combination of organic and mineral fertilizers would be preferable. This has also proven to be beneficial for the balance of land use-related greenhouse gas emissions in the simulations.

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References:

Tendler et al., 2025. Gärreststrategien zur Optimierung von Nährstoffeffizienz, Wasser- und Klimaschutz im Pflanzenanbau.

Further information

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Publications

Grosz et al., 2024. Modeling N2O, NH3 fluxes, and Nmin concentrations in agricultural soils treated with biogas digestate using a modified DNDC model, EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24-16666

Grosz et al., 2025. Modeling of the long-term effects of reduced inputs of organic and inorganic fertilizers on SOC and N-balance of agricultural soils, EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-3552.

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