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RESEARCH ARTICLE

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Policy measures effectively reduce soil nitrous oxide emissions with minor trade-offs in crop yield

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Abstract

Nitrous oxide (N_2O) emissions are closely linked to agricultural fertilisation. European and national policy incentives have been set to reduce greenhouse gas (GHG) emissions; however, only a few evaluations have been conducted. Avoiding such emissions is an important climate change mitigation measure, but it is still uncertain which management measures over a long-term, best out-balance crop yield and GHG balances in agricultural systems. We here used the process-based LandscapeDNDC model to simulate N_2O emissions and trade-offs in yield and soil nitrogen budget for four alternative arable cropping systems in three Austrian agricultural production zones belonging to different climatic regions. We evaluated statistical data on crop rotations and management practices, predominant soil types, and 10-year daily weather conditions for four cropping systems: (1) conventional farming receiving the maximum allowed nitrogen fertilisation rate (*Nmax*), (2) conventional farming receiving 15% less fertiliser, (3) conventional farming receiving 25% less fertiliser, and (4) organic farming. Our results showed that soil N_2O emissions could be best reduced in wet, high-yield regions. Reducing nitrogen fertilisation by 15% and 25% mitigated N_2O emissions by, on average, 22% and 39%, respectively, while the yield was reduced by 5% and 9%, respectively. In comparison, the same crops grown in the organic cropping system released 60% less N_2O, but yield declined on average by 23%. Corn, winter barley, and vegetables showed the highest N_2O reduction potential under reduced fertiliser input in conventional farming. In addition to N_2O emissions, reduced fertilisation substantially decreased other nitrogen losses into the water and atmosphere. Generally, the soils under all cropping systems maintained a positive mean nitrogen budget. Our results suggest a significant emission reduction potential in certain production zones which, however, were accompanied by yield reductions. Knowledge of the emission patterns from cropping systems under different environmental conditions is essential to set the appropriate measures. In addition, region-specific measures to reduce soil N_2O emissions have to be in line with farmers' interests in order to facilitate the successful implementation of targeted nitrogen management.

KEYWORDS

crop rotation, cropping systems, EJP Soil, fertilisation, LandscapeDNDC, N_2O emissions, nitrogen balance, policy-schemes

1 | INTRODUCTION

Nitrous oxide (N_2O) is a long-lived greenhouse gas (GHG) and the most important ozone-depleting substance in the stratosphere (Ravishankara et al., 2009). From 1850 to 2022, the atmospheric concentration of N_2O increased from 275.4 to 335.7 ppm, or 79% since 1945 (EEA, 2019; NOAA, 2023). Natural N_2O is a biochemical product of microbial denitrification and nitrification processes in soils and water and, to a minor extent, results from the combustion of biomass and fossil fuels (Thomson et al., 2012). Heterotrophic soil organisms reduce nitrogen (N) compounds like NO_3^- to NO_2^-, NO, N_2O and finally, under anaerobic conditions, to N_2, closing the N cycle (Del Grosso et al., 2020). Anthropogenic soil N_2O emissions from agricultural soils account for 43% of global N_2O emissions (Tian et al., 2020), and the excessive use of manure and synthetic N fertilisers is a major driver of N_2O emissions (Jia et al., 2019). The rate of soil N_2O emissions is primarily controlled by soil N availability, soil-specific temperature, soil moisture, oxygen, and organic carbon (C), depending on parameters such as climate, soil texture, land use, and management practices (Kaiser et al., 1998; Schindlbacher et al., 2004; Shcherbak et al., 2014). Driven by human activity, land use and land management practices contribute considerably to climate change.

Highlights

- A 15% reduction in N fertiliser reduced N_2O emissions by 22% and yield by 5%.
- N_2O emission reduction potential was the greatest in regions and crops with the highest emissions.
- In organic systems, >67% of N output was found in crop yields and little N was lost.

Therefore, the European Union is targeting climate change mitigation and implementing agri-environmental measures through new policy schemes or strategies such as the Biodiversity Strategy, Mission SOIL and Law on Soil Monitoring (Montanarella & Panagos, 2021). A target of the European Green Deal's Farm-to-Fork Strategy is a 20% reduction in N fertiliser and a 25% increase in land under organic farming by 2050 (EC, 2020). The Common Agricultural Policy (CAP) is an important instrument for implementing European policies at the national scale (EC, 2019). Since 1962, CAP has aimed to coordinate the European food supply and guarantee sustainable income for farmers. Since the 1990s, the CAP has also coupled direct payments to farmers with a minimal set of agri-environmental measures. Through the European Agricultural Fund for Rural Development (EAFRD), which comprises half of the CAP budget, member states have recently revised their programme and adjusted several policy schemes to fulfil the objectives of the European Green Deal (BML, 2023). As part of the EAFRD, Austria introduced an agri-environmental programme to enhance organic farming and, as part of the implementation of the Nitrate Directive (EC, 1991), incentives to reduce N fertilisation rates in 1992. These objectives remain central to the current Austrian EAFRD funds, effective from January 2023 (EC, 2022).

According to the GHG inventories, anthropogenic soil N_2O emissions in the European Union have decreased by 17% since the 1990s (EEA, 2022). Tian et al. (2020) proposed that the implementation of the Nitrate Directive was the main reason for this reduction. Furthermore, the European Union has successfully implemented agri-environmental and organic farming programmes in member states (EC, 2019). The calculations of N_2O emissions in the GHG inventory are based on agricultural activity data in the member states, using the guidelines of the Intergovernmental Panel on Climate Change (IPCC, 2006). The core element of this approach was an emission factor of 1% for the calculation of N_2O from the applied N fertiliser. In summary, from 100 kg N fertiliser applied per ha, it is assumed that 1 kg N is lost as N_2O-N. This method does not account for crop or site-specific parameters, for example, climate or soil and creates great uncertainty. Results from long-term field studies on N_2O emissions are rare; therefore, the calculation of emission factors rather relies on case studies, which are limited by the number of crops or drivers investigated. Case studies that focus on specific questions, policy decisions, and programmes must consider environmental synergies and comprehensive economic trade-off (Verspecht et al., 2012).

It is expected that organic farming practices reduce soil N_2O emissions, but this hypothesis has not been fully proven. For instance high content of easily available N and degradable C in green manure can also induce a high N_2O emission from the soil (Hansen et al., 2019). Further concerns regarding organic farming are, for example, its lower yields than chemical-based farming and an unsustainable depletion of nutrients in soils because of low fertilisation. Austria has the highest share of organic arable land worldwide: approximately 21% of the croplands are cultivated under organic standards (Bio Austria, 2022).

One reliable method for comparing cropping systems is to balance their N fluxes, which allows the detection of whether N depletion or accumulation has occurred in the soil (Jones et al., 2017). The N budget summarises all N inputs through fertilisation, atmospheric deposition, and biological fixation compared with all N exports through harvesting, leaching, and gaseous emissions within a defined area. Budgeting is especially important in organic farming because of the restricted availability of external fertilisers. The results of the N budget analysis indicate whether the soil N pool increased or decreased.

The environmental effects of socioeconomic decisions at the regional level (Schroeck et al., 2019) can be assessed using process-based biophysical soil models. These models are increasingly used to perform regional inventories, including scenario analyses of the effects of climate and land use (Molina-Herrera et al., 2016). Furthermore, Del Grosso et al. (2010) reduced the uncertainty in N_2O estimates by more than half by applying a process-based model in their assessments. In this context, we applied the LandscapeDNDC model (Haas et al., 2013; Kraus et al., 2016; Molina-Herrera et al., 2017, 2016) and used a Bayesian Model for model calibration, as Santabarbara (2019) suggested. We included an uncertainty analysis, which is important in communicating the modelling results to stakeholders. The main objective of this study was to evaluate the long-term effects of Austrian agri-environmental policy measures on soil N_2O emissions in three agricultural production zones belonging to different climatic regions. Additionally, it aimed to assess potential trade-offs in terms of yield and soil nitrogen budget for all regional cropping systems representing the alternative policy measures.

This is the first study to determine the effect of agri-environmental measures on N_2O emissions and any trade-offs in yields or soil N budgets at a regional scale. The three main hypotheses are as follows: (i) Reducing the application of N fertiliser mitigates N_2O emissions. (ii) As fertilisation intensity decreases, crop yields will decrease at the same rate as N_2O emissions. (iii) In the long term, cropping systems with reduced fertilisation deplete the soil N stock, and, hence, soil fertility.

2 | MATERIALS AND METHODS

2.1 | Regions, sites, crops, and cropping systems

An evaluation of the selected agri-environmental measures was conducted via simulations of three intensively managed regions in Austria Grieskirchen (high-yield region), Oststeirisches Huegelland (high-yield region), and Marchfeld (mid-yield region) for the 10 years from 2005 to 2014. Grieskirchen has an area of 162,000 ha, mainly arable land (82%), of which, 93% is managed under conventional farming practices and 7% under organic farming. Oststeirisches Huegelland, 136,000 ha (84% arable land), holds 5% of the cultivated land under organic standards. Marchfeld (57,000 ha), almost all arable land (98%), has a large share cultivated under organic standards (19%). The three regions belong to different climatic production zones in Central Europe (Brückler et al., 2018). From 2005 to 2014, the mean annual temperature was similar (10–11°C), whereas the mean annual precipitation differed significantly from 1026 mm in *moist* Grieskirchen, 783 mm in *occasionally dry* Oststeirisches Huegelland, and 591 mm and 537 mm (two weather stations) in *dry* Marchfeld.

The predominant soil types representing between 73% and 88% of the agricultural land in the regions. The simulated soil sites (Table 1) were selected from the digital soil map database by comparing the median and mean values of C content, texture, and pH from all horizons within the group of soil types (complete soil profile in Appendix 1). For calculation of the regional N budgets, the representative soil types of Marchfeld were assigned to two different weather stations; the central, western 'Gaenserndorf' (50% soil type 9, 40% soil type 11 and 100% soil type 10 and 12) and eastern 'Gross-Enzersdorf' (50% soil type 9, 60% soil type 11). Important parameters of the topsoil horizons and ranges of parameters for the three soil types (Nr. 5, 6 and 11ab) selected for the uncertainty analysis are listed in Table 1.

Region-specific conventional and organic crop rotations (CRs) were built from statistically recorded activity data from 2005 to 2017 (Table 2). In this study, we consider the term 'organic cropping system' following the principles of the regulation EU 2018/848 (2018). As suggested by regional experts, we divided the share of winter cereals into the crop groups 'winter wheat' and 'winter

TABLE 1 Description of topsoil (0–20 cm) parameters for the simulated soil types in Grieskirchen, Oststeirisches Huegelland and Marchfeld and the range from minimum (min) to maximum (max) of all sampled sites of the soil types used for the uncertainty analysis.

			pH ($CaCl_2$)	Sand (%)	Clay (%)	C_{org} (%)	pH ($CaCl_2$)			Sand (%)			Clay (%)			C_{org} (%)		
Site nr	**Soil type**	**Of arable soil (%)**	**Site**	**Site**	**Site**	**Site**	**Min**	**-**	**Max**	**Min**	**-**	**Max**	**Min**	**-**	**Max**	**Min**	**-**	**Max**
Grieskirchen																		
1	LOSA	13	6.8	48	12	1.3												
2	LOSI	6	6.7	13	33	1.3												
3	LOSI	18	5.7	15	18	1.8												
4	SASI	16	6	25	14	1.3												
5	SILT	35	6.5	7	12	1.6	5.4	-	6.9	3	-	23	9	-	21	1	-	2.4
Oststeirisches Huegelland																		
6	LOSA	27	6.9	57	11	1.6	4.7	-	7	32	-	69	5	-	14	0.6	-	3.9
7	LOSI	25	5.6	16	16	2.1												
8	SALO	21	5.2	35	18	1.8												
Marchfeld																		
9ab	LOSA	20	7.5	46	9	1.1												
10a	LOSA	7	6.1	56	14	0.8												
11ab	LOSI	32	7.5	24	18	1.9	3.7	-	8.1	3	-	42	6	-	33	0.1	-	15
12a	SALO	25	7	46	17	1.4												

Note: In Marchfeld, soil types are assigned to two different climate stations: a = 'Gaenserndorf', b = 'Gross-Enzersdorf'.
Abbreviations: LOSA, loamy sand; LOSI, loamy silt; SALO, sandy loam; SASI, sandy silt; SILT, silty soil.

TABLE 2 Amount of total mineral and organic N fertiliser applied per crop and year and proportion of crop in the crop rotation (CR) in the *Nmax* and the *organic* cropping systems from the regions Grieskirchen, Marchfeld and Oststeirisches Huegelland.

	Cropping system	Unit	Winter wheat	Winter barley	Corn	Spring barley	Soybean	Beet	Vegetable	Potato	Winter rapeseed	Pumpkin	Green manure[a]	Annual mean[b]
Grieskirchen														
Fertiliser	*Nmax*	(kg N ha^{-1})	170	155	180	130	0	-	-	-	180	-	-	157
	Organic		*130*	110	120	0	0	-	-	80	-	-	0	66
Proportion of CR	*Nmax*	(%)	32	18	31	6	6	-	-	-	6	-	-	
	Organic		26	21	11	11	10	-	-	6	-	-	14	
Oststeirisches Huegelland														
Fertiliser	*Nmax*	(kg N ha^{-1})	170	-	180	130	0	-	-	-	-	100	-	153
	Organic		95	80	95	0	0	-	-	-	-	70	0	55
Proportion of CR	*Nmax*	(%)	13	-	57	6	6	-	-	-	-	13	-	
	Organic		29	11	20	7	9	-	-	-	-	13	11	
Marchfeld														
Fertiliser	*Nmax*	(kg N ha^{-1})	145	130	155	80	0	155	170	-	-	-	-	136
	Organic		60	53	73	0	0	-	48	-	-	-	0	44
Proportion of CR	*Nmax*	(%)	33	14	10	10	5	14	14	-	-	-	-	
	Organic		32	16	11	5	10	-	16	-	-	-	10	

[a]Green manure crops in Grieskirchen and Oststeirisches Huegelland = grass-legume mix, in Marchfeld = Alfalfa.
[b]Over the years 2005–2014 of the crop rotations.

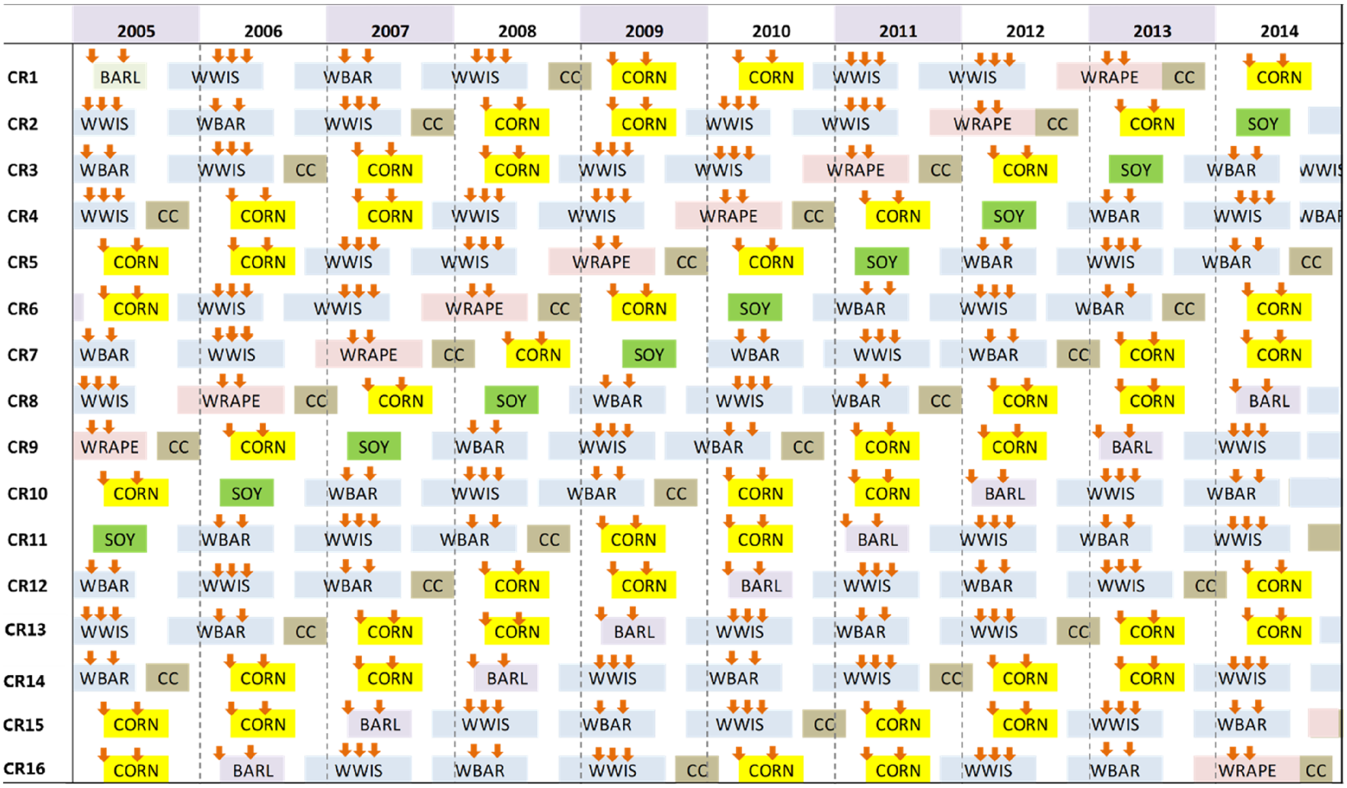

FIGURE 1 Conventional crop rotation (CR) setup in Grieskirchen for the period from 2005 to 2014. Orange arrows display time of fertiliser application in the model. BARL, summer barley; CC, catch crops (mustard); CORN, corn; SOY, soybeans; WBAR, winter barley; WRAPE, winter rape; WWIS, winter wheat.

barley' in the simulations, conducting slightly different management approaches (e.g., in Grieskirchen *Nmax*, *N-15%* and *N-25%*; winter wheat received the total sum N fertiliser in three shares of 50:30:20 percent winter barley in two shares of 55:45 percent). Regarding the *dry* Marchfeld region, the conventional and organic CRs were similar (e.g., share of winter cereals, corn, and vegetables). However, in Grieskirchen and Oststeirisches Huegelland, the CRs between the conventional and organic cropping systems differed significantly, especially the share of corn. In all organic CRs, the proportion of legumes was significantly higher than that in conventional CRs. As in Döring and Neuhoff (2021), we considered all CRs at all-times and simulated each crop of the CRs according to its share; in each run, the alternating CR was offset by 1 year, starting with the subsequent crop (rows in Figure 1). This approach ensures that the simulated crops represent regional farming practices at all times and, more importantly, prevents any bias caused by weather extremes or pre-crop effects on the results. For example, Figure 1 shows the conventional CR in Grieskirchen which consists of 16 crop sequences and, thereby, 16 × 10 years of offset runs (further CRs in Appendix 2).

While setting up the management files, the seasonal management steps (e.g., tillage and fertiliser application) for all crops were compared with the daily regional weather data. In cases of any climatic extremes (e.g., snow, frost, and on-going heavy rain events), measurements were adjusted within a timespan given by regional farm advisers (±1–14 days). General information on crop management was provided by the institutions in charge: the 'Austrian Ministry of Agriculture, Regions and Tourism' and the 'Austrian Agency for Health and Food Safety'. Furthermore, regional farm advisors provided additional information on specific management measures.

We simulated four different fertilisation regimes in each region: three conventional CRs and one organic CR in kg N ha^{-1}. The fertilisation regimes were defined as follows: *Nmax* is conventional management with the maximum regional level of fertilisation allowed according to regional experts and is in accordance with the Austrian decree to reduce nitrate (BMLFUW, 2016) for high- (Grieskirchen and Oststeirisches Huegelland) and mid- (Marchfeld) yield regions; *N-15%* and *N-25%* are two reduction scenarios for all conventionally grown crops, with 15% (*N-15%*) and 25% (*N-25%*) lower fertilisation rates than that of *Nmax*. In the simulations ammonium nitrate (NH_4NO_3) fertiliser was applied to the conventional CR. '*Organic*' refers to organic farming, and the total organic N fertilisation levels in this system were 40–60% of *Nmax* (annual mean in Table 2). Regarding the composition of organic fertilisers, in Grieskirchen and Oststeirisches Huegelland mainly farmyard manure (cows) and compost is applied, in Marchfeld, farmers usually combined compost and horse dung. In the simulations, the organic N fertiliser was defined as compost (C:N = 17.5) and slurry (C:N = 8), corresponding to the available organic fertilisers and applied to specific crops, as defined by activity data, regional experts, and the literature. Furthermore, in *dry* Marchfeld irrigation was simulated using the recommendations of regional experts in both conventional and organic CRs (40–60 mm for beet, vegetable and corn crops). In this region, the year 2012 was extra dry with −30% less precipitation than average. Over this season and in the following year the irrigation was intensified by one-third.

2.2 | Modelling tool

All simulations were conducted on a daily time step from 2005 to 2014 in a non-spatial manner, using the process-based model LandscapeDNDC (version 1.9.3). LandscapeDNDC is a framework for dynamic ecosystem modelling that, simulates fluxes of energy, water, carbon and nitrogen between the hydro- and atmosphere, and plant growth (Haas et al., 2013; Kraus et al., 2016) and builds on the soil bio-geochemical model DNDC (C. S. Li, 2000; C. Li et al., 1992). The model comprised sub-modules of cropland ecosystems and vegetation growth, as Kim et al. (2014, 2015) and Molina-Herrera et al. (2016) have described. In accordance with the 'Homogeneous Spatial Soil Mapping Units' (HSSMUs) described by Schroeck et al. (2019) the input variables include the profile data of soil bulk density, texture, and pH-value, and the Corg and N content in the soil horizon down to the parent layer or ground water obtained from the Austrian digital soil map (BFW, 2017). Regional daily temperature, precipitation, wind speed and radiation data were obtained from the Central Institution for Meteorology and Geodynamics (ZAMG). For the regional mean N deposition, we down-scaled N deposition data from the European Monitoring and Evaluation Program (EMEP; Simpson et al., 2012) to a 1 × 1 km raster and used the average regional value as an input for the simulations, comparable to a method in Dirnböck et al. (2017). The model was comprehensively validated using different agricultural and grassland sites across Europe, including the pedoclimatic zones of our test regions, and observational data such as soil micrometeorology, water cycling, plant growth, N_2O and NO emissions, NO_3 leaching and, specifically in our regions, yields in Molina-Herrera et al. (2017, 2016), Kasper et al. (2019), and Schroeck et al. (2019).

2.3 | Calculation of N_2O emissions, yields and N budgets

The N_2O emissions (mean, median, minimum, and maximum) in kg ha^{-1} year^{-1} were calculated over all CRs, the selected soil sites and climate stations per cropping system and region.

Since LandscapeDNDC displayed the yield results as kg C ha^{-1} year^{-1} of exported biomass (e.g., grains) the following conversion has been made:

$$\text{kg yield DM ha}^{-1} = \left(\text{kg C ha}^{-1}\ \text{year}^{-1}\right)/0.45.$$

We assessed the regional soil N budget for each year (2005–2014) and all CRs by calculating all inputs and exports of N per hectare (ha) as follows:

$$\text{Soil N budget} = \Sigma\,\text{N input} - \Sigma\,\text{N losses}$$

where

$$\Sigma\,\text{N input} = \text{N}_{\text{deposition}} + \text{N}_{\text{fixation}} + \text{N}_{\text{fertiliser(organic or mineral)}}$$

and

$$\begin{aligned}\Sigma\,\text{N losses} = {} & \text{N}_{\text{harvested biomass}} \\ & + \text{gaseous N losses}(\text{N}_2;\text{N}_2\text{O},\text{NO};\text{NH}_3) \\ & + \text{leaching N losses}\left(\text{NO}_3^-;\text{NH}_4^+\right).\end{aligned}$$

The LandscapeDNDC model considers the N in residues left aboveground at the field, and that this organic N consequently returns to soil layers depending on the depth of tilling. N in roots and residues enter pools of more or less easily degradable N following crop-specific default values. N in seeds is not specified in the calculation due to its minor importance. Finally, the budgets for each site and management scenario were weighted by the regional share of each soil type (Table 1) to gain mean regional N budgets.

2.4 | Uncertainty quantification and statistics

The verification of simulated emissions was obtained by performing an uncertainty analysis. By this means the modelling uncertainties for simulated N_2O soil emissions of the *Nmax* scenario at sites representing the three major soil types in the study areas can be elaborated and explained. Based on a previous study by Santabarbara (2019) deriving joint parameter distributions by applying Bayesian model calibration techniques similar to those deployed by X. Li et al. (2015) and Myrgiotis et al. (2018) in three steps. First, a *global sensitivity analysis* was performed on all 188 process parameters of the biogeochemical module in LandscapeDNDC. The Global Sensitivity Analysis (Gelman et al., 2004) allows the establishment of a hierarchy of parameters that influence a given output (N_2O emissions) in order to identify the most sensitive parameters. The method was implemented as follows: (i) comparing maximum and minimum results, (ii) comparing the interquartile range of the simulation results and (iii) analysing the variation of the Euclidian distance between simulation results and field observations to identify and rank the most sensitive model parameters influencing soil N_2O emissions. All parameters showing an effect above the 75 quartile were selected. These parameters are as follows: the decomposition rates and parameters controlling the temperature and moisture dependency for soil organic material decomposition; partitioning of decomposed organic matter into CO_2 and dissolved C; microbial death and growth rates; microbial N (NO_3) uptake; interaction between nitrifiers and denitrifiers; auto- and heterotrophic nitrification; moisture, temperature and pH control of NO and N_2O production via nitrification; separation of the anaerobic and aerobic soil environment; gas and matter diffusion of chemical species between anaerobic and aerobic soil environment, various pH control of the denitrification enzymatic reactions reducing $NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$ as well as rate and temperature control of chemo-denitrification. In the second step, the *uncertainty analysis* performed a Bayesian Model calibration constructing a Markov-Chain-Monte-Carlo simulation to sample a joint model parameter and input data distribution based on observation data of N_2O emissions (Myrgiotis et al., 2018; Santabarbara, 2019). The uncertainty analysis compacts the uniform prior parameter distributions yielding posterior joint parameter distributions determined by the observation data on N_2O emissions and the used likelihood function. In the third step, the *uncertainty quantification* was obtained by propagating the joint parameter distributions through the model. This propagation was realised by sampling 500 representations of the posterior distributions and deploying 500 site simulations including the respective input data and parameter perturbations (referring to ranges described in Table 1). The uncertainty quantification revealed statistical model results (distributions for any result quantity) instead of single result values and statistical analysis of these result distributions finally quantified the modelling uncertainty. The interquartile range Q25 to Q75, determining the model result interval with high confidence, generally defines the uncertainty range of the model output, whereas the interval Q10 to Q90 represented the widest variability interval neglecting outliers (Myrgiotis et al., 2018). For more details on the methodology and the uncertainty quantification see Myrgiotis et al. (2018), Santabarbara (2019) or van Oijen (2017).

The Shapiro–Wilk test showed that neither daily nor annual simulated N_2O emissions were normally distributed. The Fligner-Killeen median test indicated that most parameters did not exhibit homogeneity of variances. Therefore, we applied non-parametric tests for all further analyses. The Kruskal-Wallis-test followed by a pairwise Wilcoxon rank sum test detected any significant differences between soil types, cropping systems and regions. Mood's median test followed by a pairwise median test compared the results for the N_2O emissions from the different management practices. The relationships between all variables were explored by Spearman correlation (r_s) analysis. The statistical evaluations were performed, and graphs were created with R 3.4.4 and Python 3.8.5.

3 | RESULTS AND DISCUSSION

3.1 | Uncertainty analysis

An uncertainty analysis verified the simulations by quantifying the variability of the model output owing to the variability of the data input. In this study, the variation in the simulated N_2O emissions originated from interaction among local climate, agricultural management, and soil properties; the parameterisation of soil biogeochemical processes and input data accuracy were represented in the uncertainty analysis by the 500 simulation results based on the sampled sets of parameters from the database (Table 1). This analysis was conducted for the predominant soil type in each region for the *Nmax* cropping system, which performed with the widest range of annual N_2O emissions in the simulations and was generally transferable to sites with similar conditions. As shown in Figure 2a, for *moist* Grieskirchen, the *Nmax* baseline simulations for all sites fit well within the kernel of the resulting density distribution of the N_2O emissions.

The uncertainty analysis showed the N_2O distributions and the likelihood of N_2O emissions in a probabilistic manner. The three relatively narrow uncertainty ranges are summarised in Figure 2b. For all sites, the average annual N_2O emissions from the *Nmax* simulations (red circles) remained within the averaged interquartile range. The comparison of the *Nmax* simulation and the simulation with the default parameterisation revealed that the model results were close to the medians

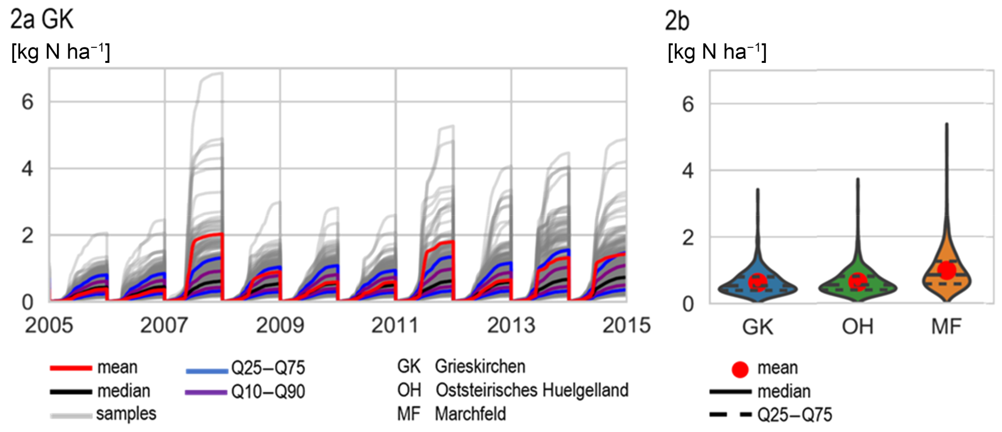

FIGURE 2 (a) Illustration of the temporal dynamics of cumulative sums of soil N_2O emissions for Grieskirchen (GK); red line: mean of *Nmax*-baseline simulation, grey lines: realisation of the 500 parameter samples, black line: median, blue lines: quantile ranges Q25–Q75, purple lines: quantiles Q10–Q90 of the 500 simulation results. (b) Overall result distribution of annual N_2O emissions for Grieskirchen (GK), Oststeirisches Huegelland (OH) and Marchfeld (MF) from the uncertainty analysis. In the violin plots the dotted lines show the interquantile (Q25 and Q75) of the N_2O emission results. The solid black line between them is the median. The red circle is the mean of *Nmax*-baseline simulation.

of the result distributions. The quantification of the uncertainty ranges for all three regions produced similar interquartile ranges of the median of the result distribution for Grieskirchen (−29.0% to 49.6%) and Oststeirisches Huegelland (−28.8% to 47.8%) and was greatest for Marchfeld (−34.7% to 51.9%), with a wide range in N_2O emissions and a low density of data near the median (i.e., the narrower 'violin'). The calculated ranges are in good agreement with those of other uncertainty quantification studies, such as those of Lehuger et al. (2009), X. Li et al. (2015), Myrgiotis et al. (2018), Van Oijen (2017) and Van Oijen et al. (2011, 2005). Per the average across the three regions, the overall uncertainty ranged from −30.8% to +50.8% of any annual N_2O emission. This represents a much more narrow and robust uncertainty range compared to the default IPCC emission factor uncertainty range of −66% to +200% (0.003–0.03 kg N_2O-N kg N^{-1}; IPCC, 2006). The variation in the uncertainty intervals was very small (lower bound: 5.9% and upper bound 4.1% of the estimated annual emissions) which provides evidence for the trustworthiness and robustness of the applied method.

3.2 | N_2O emissions under reduced fertiliser input

Figure 3 summarises the annual soil N_2O emissions for all regions and cropping systems. The simulations showed that across all sites, scenarios, and CRs the annual N_2O emissions ranged from 0.1 to 12.5 kg N_2O-N ha^{-1} $year^{-1}$, and the reduction in N fertiliser application substantially affected N_2O fluxes. The overall mean annual N_2O emissions ranged from 0.59 kg N_2O-N ha^{-1} $year^{-1}$ in the *organic* scenarios to 1.24 kg N_2O-N ha^{-1} $year^{-1}$ in *Nmax* and differed significantly within the regions in the order *Nmax* > *N-15%* > *N-25%* > *organic* (lowercase letters 'abc' in Figure 3; $p < 0.001$). Spearman correlations supported these findings and described the annual N_2O emissions by the amount of applied N (synthetic or organic) fertiliser ($R_s = 0.46$), soil N content ($R_s = 0.45$), biological N fixation ($R_s = -0.35$), and water content (%) in the topsoil ($R_s = 0.30$; all $n = 11{,}060$ years and $p < 0.001$). These correlations imply that the simulated N_2O emissions are greater in the years with excessive plant available N and sufficient or higher water supply and lower in years with higher biological N fixation which support the focus on an adapted N management in mitigating N_2O emissions.

In addition to the choice of cropping system, significant regional differences existed for the *Nmax* and *N-15%* scenarios in the order of Grieskirchen > Marchfeld > Oststeirisches Huegelland (uppercase letters 'ABC' in Figure 3; $p < 0.5$). Interestingly, the results in Figure 3 highlight that the *moist* Grieskirchen region with the largest N_2O emissions has the highest potential to reduce N_2O emissions through moderate management measures. The median N_2O emissions of *N-15%* and *N-25%* scenarios were by respectively −36% and −56%, significantly lower than that of *Nmax*. However, under less intensive N fertilisation scenarios (e.g., *organic*) there was no significant difference between the regional annual N_2O emissions in *dry* Marchfeld (median 0.42 kg N_2O-N ha^{-1} $year^{-1}$) and *wet* Grieskirchen (median 0.45 kg N_2O-

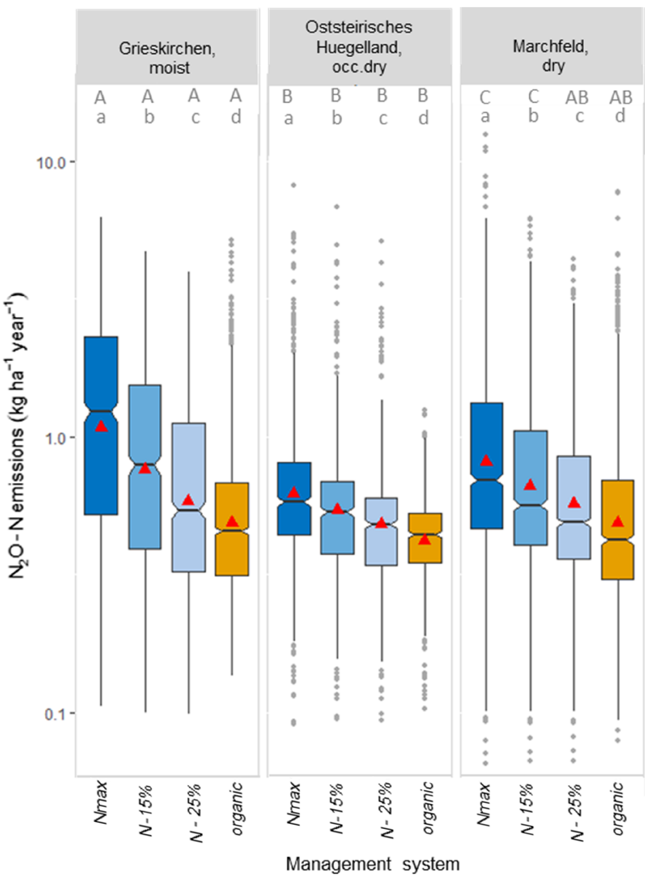

FIGURE 3 Regional annual N_2O-N emissions (kg ha^{-1}) from the *Nmax*, *N-15%*, *N-25%* and *organic* cropping systems in Grieskirchen, Oststeirisches Huegelland and Marchfeld. Back notch shows median, red triangle mean and the grey dots the outliers. NB! *y* axis in logarithmic scale. Uppercase letters (ABC) show the significant differences between regions ($p > 0.05$) and lowercase letters (abc) describe the significances of differences of N_2O emissions between cropping systems within a region ($p > 0.001$).

N ha^{-1} $year^{-1}$). Even though the fertilisation rate in Grieskirchen *organic* was 30% greater. This non-linear correlation between N_2O emissions and N fertiliser application rates has been demonstrated, for example, in Shcherbak et al. (2014) and suggests, that whereas at low N fertilisation rates, the N_2O emissions are low, the excessive N under more intensive cropping systems is prone to be lost to the environment. This, and the beforementioned higher mitigation effect of *N-15%* and *N-25%* on N_2O emissions in regions with high N turnover, supports results-oriented incentives, which is particularly important in the new CAP.

The outliers in Figure 3 are the individual years with very high peak N_2O emissions (under both *Nmax* and *organic* systems), especially in the *dry* region of Marchfeld and in *occasionally dry* Oststeirisches Huegelland. The simulated peak emissions in Marchfeld occurred especially in years after a prolonged drought, frequently in years under the cultivation of irrigated crops (i.e., vegetables and beets) and occasionally in winter barley. The highest peak emissions in Oststeirisches Huegelland occurred in 2014 under *Nmax* during the cultivation of corn and pumpkin. In this region, 2014 was the third consecutive year with 25% higher precipitation than the average (2005–2014). Weather extremes that cause drought or extremely wet soils modify microbial decomposition activity. Droughts reduce the growth and decomposition of aboveground and belowground biomass, and applied N accumulates in the topsoil. As soon as the soil conditions recover, the accumulated organic and mineral N compounds are readily reduced to N_2O.

3.3 | Crop-specific N_2O emissions and trade-off in yields

The overview in Table 3 reveals a wide range of mean annual N_2O emissions from 0.25 (soybean) to 2.43 (vegetable) kg ha^{-1} $year^{-1}$ under *Nmax* management. Overall, reducing the amount of applied N fertiliser for example, by 15%, resulted in a mean decline of 26.2% in N_2O emissions, and mean yields were reduced by 5.4%. Such strong responses of N_2O emissions to reduced N fertilisation can be explained by the high impact of fertilisation rates on microbial denitrifying processes and N_2O emissions compared with that of plant growth and yield (Fuss et al., 2011; Kim et al., 2015; Van Groenigen et al., 2010). These results verify a low trade-off and provide a strong argument for implementing agri-environmental policy incentives across Europe.

Farmers' participation in the EAFRD programmes is voluntary and unfortunately not attractive for high-yielding regions. However, funds for 'implementing catch-crops' in the CR and 'renunciation of yield-increasing inputs' are popular throughout the whole farming community. The latter, for example, limits N fertilisation to 170 kg N ha^{-1} $year^{-1}$ and prohibits area-wide application of pesticides (AMA, 2023; BML, 2022). Such restrictions are inexpensive and have minor impact on yield success. Economic aspects are vital to farmers before implementing new or different practices, even if those that are scientifically sound and promoted by authorities. Kanter et al. (2020) stated that cost and labour-efficient measures, such as those aforementioned, are the most likely to be implemented. Even so, it has to be stressed that these most popular measures are the least effective in mitigating N_2O emissions.

As expected, certain crops emitted high N_2O emissions per kg ha^{-1} $year^{-1}$, especially vegetables, corn, and winter barley. Although these crops received the highest N fertilisation rates, the emissions at *Nmax* were significantly

TABLE 3 Mean N_2O emissions (kg ha^{-1} $year^{-1}$) and mean DM yield (Mg DM ha^{-1} $year^{-1}$) of main crop under *Nmax* and the relative mean difference related N_2O emissions and yield of *N-15%*, *N-25%* and *organic* management compared to *Nmax* for the whole study period 2005–2014, all regions.

	N_2O emissions				Yield			
	Mean				Mean			
	N_2O-N kg ha^{-1}	% Difference to mean *Nmax*			Mg DM ha^{-1} $year^{-1}$	% Difference to mean *Nmax*		
Main crops	***Nmax***	***N-15%***	***N-25%***	***Organic***	***Nmax***	***N-15%***	***N-25%***	***Organic***
Spring barley	1.11	−18.4	−37.1	**−70.9**	4.6	−3.37	−6.88	**−43.27**
Beet	1.06	−13.2	−32.6		19.1	−7.60	−14.17	
Corn	1.51	−23.8	**−43.3**	**−59.7**	9.7	−4.79	**−10.20**	**−36.58**
Pumpkin	1.07	−16.2	−28.1	**−40.3**	0.5	−0.05	−0.12	**−19.60**
Vegetable	2.43	−31.9	**−52.9**	**−67.6**	3.8	−4.81	**−9.73**	**−18.47**
Winter rapeseeds	0.41	−13.7	−34.3		4.5	−10.54	**−18.52**	
Soybean	0.25	−6.5	−13.3	**+75.6**	2.4	−0.29	−0.55	**+0.67**
Winter barley	1.48	−24.1	**−46.2**	**−57.4**	6.9	−6.31	**−12.19**	**−49.31**
Winter wheat	0.93	−17.2	−33.0	−21.7	5.2	−4.61	−9.05	−36.50
Mean		−26.2	−41.2	−51.5		−5.4	−10.7	−23.3

Note: Only crops grown in *Nmax* are considered. Bold numbers = difference of N_2O emissions >40%.

higher for corn despite this crop receiving only 10 kg N ha^{-1} more than winter wheat (Table 2). Here, different management operations in combination with seasonal conditions trigger an increase in N_2O emissions; winter wheat is already growing when the temperature rises and N fertiliser is applied; by contrast, corn is sown in late May, leaving the fertilised soil bare for several weeks before young plants increase N uptake (Maier et al., 2022).

However, the introduction of any of the environmentally friendly management options examined here is generally accompanied by a certain yield reduction. This yield gap is particularly important for internationally relevant crops. Therefore, corn and winter cereals, which are among the leading global staple crops and grown abundantly in all three simulated regions, should be a focus. A 15% reduction in fertiliser application for both crops (corn and winter wheat) had a strong beneficial effect on N_2O, and soils released 23.8% and 17.2% less N_2O respectively. This decrease is notable because the yield trade-off for both crops was less than 5%. Similar to the regional N_2O mitigation results, these results show that crops with the highest N_2O emissions have the greatest mitigation potential. Therefore, we suggest implementing crop-specific agri-environmental incentives.

Not only for the staple crops but for all crops, a substantial decrease in N_2O emissions could be achieved by introducing environmentally friendly management operations. Overall, the greatest reduction (>50%) in simulated N_2O emissions was observed under organic farming of corn, vegetables, spring and winter barley. However, this does not account for cultivation of soybean which is cultivated frequently in organic CRs. Despite that this N-fixing plant receiving no fertiliser in any of the cropping systems, the accumulated N pool potentially releases N_2O because the N-enriched residues are tilled during the preparation of subsequent crops. Nevertheless, the annual N_2O emissions from soybeans were minor (Table 3).

As already mentioned, turning away from conventional farming with extensive N application (*Nmax*) to less intensive farming systems is interlinked with a certain yield gap. In this study, the yield reduction was greatest in the *organic* cropping system (23%), whereby the yield gap between *organic* production and *Nmax* was the largest for cereals and corn (>36%). These results are even larger than those reported by Maeder et al. (2002; European long-term measurements), de Ponti et al. (2012; global review) and Seufert et al. (2012; global meta analysis). One underlying reason for these contrasting yield gaps is that winter cereals are often bred for high performance at high fertilisation levels. Hence, they respond more strongly to fertiliser reductions than soybeans or vegetables. Furthermore, in organic cropping systems, cultivars with other production targets besides yields (e.g., higher resistance to pests and pathogens) are preferred, making these systems more resilient.

Since organically grown vegetables in Marchfeld received 70% less fertiliser (Table 2) than those in *Nmax*, a greater yield loss was expected. However, we calculated a comparably small yield gap between organically and conventionally grown vegetables and soybeans which supports the results of Seufert et al. (2012).

Positive results were also obtained by comparing *organic* pumpkins with those of *Nmax*, with <20% less yield and >40% lower N_2O emissions.

Since in Europe the share of organic farming is intended to increase by 25% by 2030, shifting from mineral N application to *organic* cropping systems not only reduces emissions at a rather low yield loss but also positively affects the physiology of the crops, for example, the content of vitamin C, antioxidants, and carotenoids, improving onion bulb quality (Petrovic & Pokluda, 2020). Moreover, reducing the agri-environmental impact of food production requires reforming agricultural measures that have many constraints as discussed above. On top of this, there exists another approach towards closing the yield gap: by shifting crop production from feed for livestock towards food for human consumption (Foley et al., 2011).

3.4 | N budgets

In Figure 4, N budgets over the 10 years are visualised, indicating the importance of the different inputs and outputs and the impact of fertiliser reduction on the N balance of cropping systems. Most importantly, the N balances (black numbers in Figure 4) were positive and reached up to +14 kg N ha^{-1} year^{-1}, and decreased as fertiliser decreased. Only under *organic* management in Marchfeld was a mean N deficit of −3 kg N ha^{-1} year^{-1} calculated. An explanation for this deficit is that in this region, devoid of animal production, organic farms are completely reliant on a small share of legumes in the CR. How can this problem be resolved? Owing to the risk of plant diseases, the share of legumes is limited to 25%–30% of the CR (Jeangros & Courvosieier, 2019; Kolbe, 2008; Yang et al., 2021). A reasonable solution is to use cultivars that provide more efficient N fixation at higher fixation rates than those currently used (Danso & Eskew, 1984; Hossain et al., 2017). However, on the favourable side, *organic* management in Marchfeld showed the best N-use efficiency: 67% of the N output was found in crop yields and little N was lost.

The overall positive N budgets of the modelled regions indicate that, in the long term, organic soil N stocks and organic matter stocks are increasing. This trend supports the findings of AGES (2015), which showed that the C_{org} content increased by 0.3% between the 1990s and the 2010s throughout Austria. This was attributed to the current soil management supported by the EAFRD policy measures advancing the use of cover crops, green manure and organic fertilisers.

The contribution of different N forms to inputs and outputs (Figure 4) demonstrates that N_2O emissions constitute a small fraction of the outputs (dark blue, less than 1%), and most of the N is fully denitrified to N_2 (up to 18% of outputs). Other N losses occur as NH_3, which is up to 18% of the output in *dry* regions with high pH soils. Furthermore, N can be lost via NO_3-leaching, which reached 47% of the outputs in the *occasionally dry* region of Oststeirisches Huegelland. The latter phenomenon explains the paradox of comparably low N_2O emissions in this region despite high fertilisation rates. This region is particularly prone to N leaching, attributed to prevalence of corn cultivation (Maier et al., 2022) and possibly patchy rainfall and shallow soil profiles (Z. Li et al., 2021).

Similarly, the distribution of N forms revealed notable information about N-inputs (Figure 4). Striking is the importance of N-deposition (Figure 4, red) which constitutes up to 20 kg ha^{-1} year^{-1} in the neighbouring industrial urbanised areas of Marchfeld. Notably, the large contribution of up to 33% biological N-fixation to the total N-inputs in organic farms in the same area is an inexpensive, sustainable method of N-supply (Barbieri et al., 2023; de Bruijn, 2015). By contrast, N fertiliser was almost 90% of the N inputs under conventional farming in Grieskirchen.

The comparison of management options (Figure 4) demonstrated that with reduced fertiliser inputs, all N-outputs substantially decreased. Except for N_2O emission reduction, this decrease was most evident for NO_3-leaching, reduced by −39% with *N-25%* fertiliser in Oststeirisches Huegelland and by −47% with organic farming. Thus, the environmental benefit of N-fertiliser reduction is evident for GHG reduction as well as ground water protection. These environmental benefits can be achieved at different spatial scales. For instance, Schroeck et al. (2019) calculated the societal benefit of regional management diversification by reducing fertiliser use on sites of high emission, so-called 'hot spots'. In their study, regional N_2O emissions were reduced by 14% and yield by 5%. We considered the regional N budget, and we found that any agri-environmental measure implemented to reduce excessive N not only reduced the N_2O emissions significantly but also decreased the N fluxes of other N compounds to the environment. Kanter et al. (2020) stated that any measure implemented to effectively reduce N_2O emissions could contribute to regional environmental benefits that would outweigh the cost of N pollution from agriculture. Even on a global scale, the total societal benefits of N mitigation tend to exceed the costs of agri-environmental measures by approximately 15 times (Gu et al., 2023).

The length of the bars demonstrates that with reduced fertiliser application, the N cycle becomes closer, with fewer outputs and inputs. Accordingly, we had a maximum of inputs and outputs of 311 kg N ha^{-1} year^{-1} in the intensively managed farms (*Nmax*) of Grieskirchen, and the smallest inputs and outputs occur in the organic farms of Oststeirisches Huegelland, 166 kg N ha^{-1} year^{-1}.

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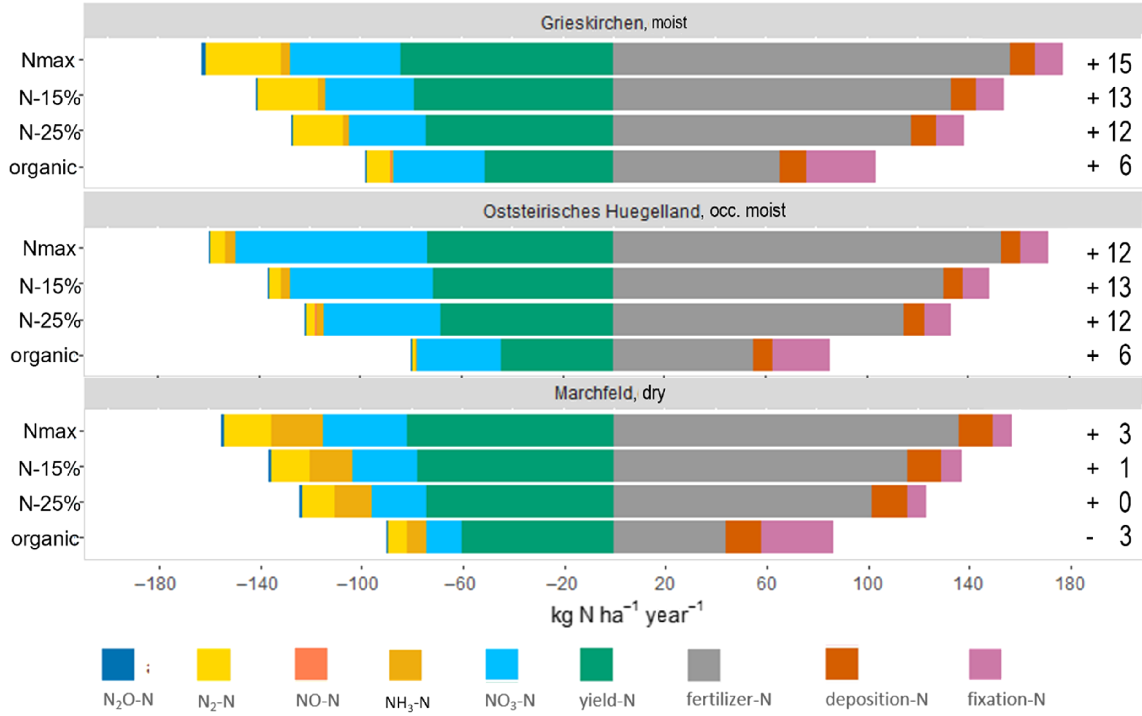

FIGURE 4 Mean N-input, N-export and the N balances across all CRs and years for the study period 2005–2014 displayed as kg N ha^{-1} (black numbers at the right of the bars).

Closed N-cycles are more favourable for the environment because they avoid the transport of reactive N compounds into water and air (Küstermann et al., 2010). Oststeirisches Huegelland, as an example, shows that simultaneously, plant productivity can be sustained, farming can be profitable and soil fertility and N-status can be generally well maintained.

The optimistic outcome of this exercise on N-budgets is that contrary to our initial concerns—shared with many farmers—about an imminent depletion of N-stocks with N-fertiliser reduction, we showed that fertiliser reduction by *N-25%* does not deplete soils in the long term (160 years simulated).

4 | CONCLUSION

A reduction in applied N fertiliser and an expansion of land under organic management are central objectives of the European Green Deal; thus, this evaluation study is highly topical, and the results set a benchmark of interest outside Austria. Our modelling results provide detailed long-term insights into the N dynamics under representative region-wide management, soil, and climate conditions. The results revealed that implementing agri-environmental measures had a positive effect on N utilisation by reducing N_2O emissions. Notably, the response of mean N_2O emissions in the cropping systems was much larger than that of the reduction of applied N for all crops. A large reduction in N fertiliser (*N-25%* and *organic* system) had a significant climate mitigation effect. However, substantial crop-specific trade-offs in yield under organic cultivation must be considered. A sustainable soil N budget in cropping systems relies on maintenance but not exceedance of soil N levels. Our findings will help policymakers and stakeholders identify relevant management options to reduce N losses to the environment while maintaining high levels of crop production. For future evaluations of the CAP and the introduction of targeted regional climate mitigation measures by EAFRD funds, a Tier 3 approach involving soil models, such as LandscapeDNDC, is highly recommended. These climate mitigation options, identified by model simulations, must be both effective and attractive to farmers in order to be implemented successfully. The results of this study have already supported stakeholders and decision-makers in Austria in developing further mitigation measures to promote environmentally friendly farming.

AUTHOR CONTRIBUTIONS

Cecilie Birgitte Foldal: Conceptualization; funding acquisition; project administration; methodology; formal analysis; data curation; visualization; writing – original draft. **Martina Kittinger:** Formal analysis; writing – review and editing; investigation; methodology. **Edwin Haas:** Methodology; validation; visualization; writing – review and editing; software. **Sophie Zechmeister-Boltenstern:**

Conceptualization; supervision; funding acquisition; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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APPENDIX 1

Soil pH value and content of sand, clay, and organic soil carbon (Corg) in all layers, complementary to Table 1.

Site nr	Soil type	Soil depth (cm)	pH ($cacl_2$)	Sand (%)	Clay (%)	C_{org} (%)
Grieskirchen						
1	LOSA	0–25	6.8	48	12	1.3
		25–65	6.9	41	16	0.3
		65–200	6.9	36	21	0.3
2	LOSI	0–25	6.7	13	33	1.3
		25–40	6.2	7	23	0.3
		40–70	6.1	5	25	0.2
3	LOSI	0–25	5.7	15	18	1.8
		25–35	5.2	10	30	0.4
		35–70	5.4	9	35	0.1
4	SASI	0–20	6.0	25	14	1.3
		20–45	6.4	24	23	0.3
		45–200	6.6	36	25	0.2
5	SILT	0–20	6.5	7	12	1.6
		20–55	6.2	5	21	0.4
		55–80	6.0	5	23	0.3
		80–200	6.0	6	27	0.2
Oststeirisches Huegelland						
6	LOSA	0–20	6.9	57	11	1.6
		20–60	5.9	47	14	0.3
		60–200	5.8	84	3	0.1
7	LOSI	0–25	5.6	16	16	2.1
		25–60	4.4	20	22	0.6
		60–80	4.4	65	12	0.3
8	SALO	0–20	5.2	35	18	1.8
		20–70	4.9	31	25	0.2
		70–140	5.0	30	18	0.0
Marchfeld						
9ab	LOSA	0–30	7.5	46	9	1.1
		30–40	7.2	80	5	0.2
		40–70	7.6	87	3	0.1
10a	LOSA	0–25	6.1	56	14	0.8
		25–65	6.1	61	6	0.6
		65–80	6.2	68	9	0.3
11ab	LOSI	0–30	7.5	24	18	1.9
		30–80	7.5	18	25	2.3
		80–95	7.7	14	28	1.2
12ab	SALO	0–25	7.7	40	19	1.5
		25–40	7.0	46	17	1.4
		40–50	7.9	55	13	0.8

APPENDIX 2

Regional crop rotations displaying the annual mean % of crops grown in conventional and organic system constructed from the main grown crops reported in the statistics for the period 2005–2017. cc = catch crops.

Grieskirchen

Conventional

Corn – corn – winter cereals – winter cereals – winter rape – cc – corn – soybean - winter cereals – winter cereals – winter cereals – cc – corn – corn – summer cereals - winter cereals – winter cereals – winter cereals – cc-.

Organic

Green – green – winter cereals – winter cereals – cc – corn – soybean - winter cereals – winter cereals – cc – summer cereals - winter cereals – winter cereals – cc – corn – soybean - winter cereals – winter cereals – cc – summer cereals - cc – green – green - winter cereals – winter cereals – cc – corn – summer cereals - winter cereals – winter cereals – cc - soybean - winter cereals – winter cereals – cc – potato -.

Oststeirisches Huegelland

Conventional

Corn – corn – summer cereals - winter cereals – cc – corn – corn – soybean – corn – corn – pumpkin - winter cereals – cc – corn – corn – pumpkin – corn - winter cereals –.

Organic

Green – green - winter cereals – cc – corn – pumpkin - winter cereals – winter cereals – cc - corn – soybean - winter cereals – cc - corn – summer cereals – green – green - winter cereals – winter cereals – cc – corn – pumpkin - winter cereals – winter cereals – cc – soybean - winter cereals – winter cereals – cc – corn - winter cereals – cc – summer cereals – cc – soybean – winter cereals – cc – corn – pumpkin -.

Marchfeld

Conventional

Winter cereals – cc – beet – corn – summer cereals - winter cereals – cc – vegetable – soybean - winter cereals – winter cereals – winter cereals – cc – beet – corn – summer cereals - winter cereals – cc – vegetable – beet - winter cereals – winter cereals – cc – soybean – vegetable - winter cereals – winter cereals –.

Organic

Green – green - winter cereals – cc – vegetable - corn – summer cereals - winter cereals – cc – vegetable - winter cereals – winter cereals – cc – soybean - winter cereals – winter cereals – cc - corn – soybean - winter cereals – cc – vegetable - winter cereals – winter cereals –.