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Effect of chemical and mechanical grassland conversion to cropland on soil mineral N dynamics and N_2O emission

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ABSTRACT

Grassland conversion to cropland bears a risk of increased nitrate (NO_3^-) leaching and nitrous oxide (N_2O) emission due to enhanced nitrogen (N) mineralization. This study investigates the dynamics of mineral N and N_2O emissions following chemical and mechanical conversion from permanent grassland to cropland (maize) at two sites with different texture (clayey loam and sandy loam) and fertilization regime (with and without mineral N-fertilization) over a two-year period. Soil mineral N levels increased shortly after conversion and remained elevated in converted plots compared to permanent grassland or long-term cropland in the second year of investigation. Fluxes of N_2O were higher from converted plots than permanent grassland or cropland. However, soil mineral N contents and cumulative N_2O emissions did not differ between conversion types. Only the distribution of N_2O losses over the two years differed: while losses were of similar magnitude in both years in mechanically converted plots, the major part of N_2O loss in chemically converted plots occurred in the first year after conversion while emissions approximated grassland level in the second year. N_2O fluxes were mainly controlled by water-filled pore space and soil NO_3^- levels. Despite differences in N levels at the two sites, these key findings are similar on both study sites. They indicate strongly accelerated mineralization after conversion, an effect that still lasted in the converted plots at the end of the two-year investigation irrespective of the conversion type used.

1. Introduction

Permanent grassland is one of the most important land use types in the European Union. It combines milk and meat production with various ecological functions of permanent grassland in agricultural ecosystems regarding biodiversity and soil, water, and climate protection (Nitsch et al., 2012). In Germany, 28% of the agricultural land is covered with grassland, which is predominantly used for livestock farming – either grazing-based or cutting-based (EUROSTAT, 2013). However, the agricultural grassland area in Germany decreased over a long period of time: between 1990 and 2006, it declined at an annual rate of 0.8% – a trend which even intensified in the years after 2005 (Nitsch et al., 2012). Between 2000 and 2013, a conversion of 427,000 ha grassland to cropland took place, which corresponds to 3.6% of the total agricultural area in Germany (EUROSTAT, 2013). One reason for the conversion of permanent grassland to cropland was the expansion of maize cropping for biogas production (FNR, 2013). Another reason was a change in the feeding structure in dairy production. Modernization and intensification including a shift from small to big dairy farms supports year-round animal housing and feeding of maize silage in addition to grass and hay (Vellinga et al., 2004; Taube et al., 2014). Since 2014, the conversion of grassland is restricted in the EU due to the greening measures within the EU Common Agricultural Policy (CAP) on the sustainable development of agriculture.

Soils under permanent grassland contain more organic carbon (C) and nitrogen (N) than arable soils (Poeplau et al., 2011). The conversion of permanent grassland to cropland can accelerate both, C and N cycling and is expected to be followed by a significant loss of soil organic matter (SOM), which in turn is associated with net N mineralization (Davies et al., 2001; Poeplau et al., 2011). This is highly critical, since N is the most limiting nutrient for crop production in many of the world's agricultural areas. Hence, a high N use efficiency is desirable and highly important for the economic sustainability of cropping systems. A significantly increased N mineralization bears a risk of

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Table 1

Selected studies on the effect of grassland conversion to cropland on N_2O emissions using the closed-chamber technique. Presented data are from the first year of measurements following grassland conversion and restricted to regions of temperate climate. NA = not available. The dataset contains results from eight field studies of temperate climate regions that were published in peer-reviewed journals and included control parameters like soil texture, sward age, treatment and fertilization. The N_2O emissions were given as the sum of emissions over the reported measurement period. If values from a control plot without any treatment were given, also the increased N_2O emissions in relation to the total N_2O emissions were calculated. The complete dataset was grouped in three parts according to their type of sward before conversion (grassland or grass-clover) and land use after conversion (arable or fallow).

Reference	Country	Soil texture	Sward age years	Tillage practice	N-fertilization kg N ha^{-1}	Measuring period	N_2O fluxes from converted grassland kg N_2O-N ha^{-1} measuring period^{-1}	N_2O fluxes from permanent grassland kg N_2O-N ha^{-1} measuring period^{-1}
Conversion of grassland to cropland								
Pinto et al. (2004)	Spain	Sandy clay loam	17	Plowing	150	< 1 week	0.29[a]	0.28
					150		0.56[b]	0.28
					0		0.05[a]	0.03
					0		0.26[b]	0.03
Baggs et al. (2000)	Scotland	Sandy loam	2	Plowing	0	12 weeks	0.15	NA
Ruan and Robertson (2013)	USA	Sandy loam	22	Chem. sward killing	0	29 weeks	9.55	0.50
				Chem. sward killing + plowing			3.36	0.50
Buchen et al. (2017)	Germany	Peat/silty sand	15	Chem. sward killing + plowing	280*	1 year	3.27	4.13
		sandy	15	Chem. sward killing + plowing	280*	1 year	1.46	0.95
Conversion of grass clover mixture to cropland								
Baggs et al. (2000)	Scotland	Sandy loam	2	Plowing	0	12 weeks	0.22[c]	NA
							0.24[d]	NA
Skiba et al. (2002)	Scotland	Clay loam	12	Plowing	120	2 weeks	0.00	NA
					180		0.03	NA
					40		0.04	NA
					80		0.05	NA
					120		0.04	NA
				Chem. sward killing + plowing	40		0.16	NA
					80		0.38	NA
					120		0.65	NA
Reinsch et al. (2018)	Germany	Sandy loam	17	Plowing	0	1 year	4.06	0.44
					240	1 year	5.70	1.40
Ball et al. (1999)	Scotland	Clay loam	12	Chem. sward killing	80	3 weeks	1.04[f]	NA
							2.31[g]	NA
Conversion of grassland to fallow land								
Davies et al. (2001)	Scotland	Clay loam	7	Plowing	150	7 weeks	1.50	0.10
Grandy and Robertson (2006)	USA	Fine/coarse-loamy	45	Plowing	0	9 weeks	0.19	0.04
MacDonald et al. (2011)	Canada	Silty clay loam	7	Chem. sward killing	369	36 weeks	11.00	0.10
				Chem. sward killing	0		1.70	0.00
				Chem. sward killing + plowing	369		8.00	0.10
				Chem. sward killing + plowing	0		0.70	0.00

* Fertilization of maize differed from that of grassland: it was 150 kg N ha^{-1}.

[a] Plowing 12 days before start of measurements.

[b] Plowing 1 day before start of measurements.

[c] Cut grass/clover.

[d] Uncut grass/clover.

[f] Between direct drill slits.

[g] enclosing direct drill slits.

Table 2
Soil parameters of the experimental sites before conversion. Means and standard errors (n = 4).

Site	Treatment	Depth (cm)	Bulk density ($g\,cm^{-3}$)	Organic C ($t\,ha^{-1}$)	Total N ($t\,ha^{-1}$)	C/N	Clay (%)	Silt (%)	Sand (%)	pH
Planosol	Grassland	0–30	1.3 (0.2)	70.5 (5.0)	7.3 (0.3)	9.7 (0.2)	17.6	31.7	50.7	5.0 (0.1)
		30–60	1.6 (0.0)	15.9 (1.0)	2.0 (0.1)	7.8 (0.6)	23.8	27.4	48.8	5.8 (0.1)
		60–90	1.6 (0.1)	11.8 (2.5)	1.4 (0.3)	8.3 (0.4)	33.8	28.5	37.8	6.4 (0.2)
	Cropland	0–30	1.5 (0.0)	45.0 (0.4)	5.0 (0.1)	9.0 (0.2)	21.1	28.8	50.1	5.9 (0.5)
		30–60	1.6 (0.1)	12.9 (4.3)	1.5 (0.0)	8.8 (2.5)	22.3	24.2	53.5	6.4 (0.1)
		60–70	1.6 (0.0)	2.7 (0.5)	0.5 (0.0)	5.8 (0.7)	30.3	29.0	40.7	6.7 (0.1)
Cambisol	Grassland	0–30	1.3 (0.1)	117.6 (4.8)	11.6 (0.6)	10.1 (0.2)	29.6	46.9	23.6	5.9 (0.5)
		30–60	1.4 (0.0)	34.0 (1.7)	4.7 (0.2)	7.2 (1.8)	34.8	51.3	14.0	7.2 (0.1)
		60–90	1.5 (0.1)	14.6 (2.5)	2.1 (0.3)	6.9 (2.5)	21.5	44.2	34.4	7.5 (0.0)

enhanced nitrate (NO_3^-) leaching and gaseous N losses via direct and indirect nitrous oxide (N_2O) emission (Vellinga et al., 2004; Bateman and Baggs, 2005; Besnard et al., 2007; MacDonald et al., 2011). The risk of NO_3^- leaching is especially high, when N mineralization exceeds the N uptake of the following crop (Vertès et al., 2007). The extent of the observed N losses covers a wide range. Nitrogen mineralization rates given in literature range from 100 – 500 kg N ha^{-1} within the first year after plowing grassland (Vertès et al., 2007) and decrease by about 60% in the following three to five years (Aarts et al., 2001). The controlling processes depend on site and soil conditions, e.g. soil water contents, soil type and C/N ratio, as well as management practices and grass sward age (Besnard et al., 2007; Attard et al., 2011; Poeplau et al., 2011).

Several field studies have shown increased N_2O losses within five days to one year after conversion of grassland to cropland (Table 1). Short-term N_2O losses (up to 84 days) ranged from 0 to 3.3 kg N ha^{-1} per month (Ball et al., 1999; Baggs et al., 2000; Davies et al., 2001; Skiba et al., 2002; Pinto et al., 2004; Grandy and Robertson, 2006). Studies that report N_2O emissions during measuring periods of more than 200 days showed enhanced N_2O losses of up to 11 kg N ha^{-1} within 251 days (MacDonald et al., 2011), especially in combination with high N fertilizer application rates. While short-term studies report N_2O fluxes up to 14-times higher from converted fields with different cultivation types than from continuous grassland, Grandy and Robertson (2006) found three- to eight-fold increased emissions within the first three years after conversion of continuous grassland to cropland. However, while there is a range of studies quantifying short-term effects of N_2O losses within 47 days to one year after grassland conversion (e.g. Davies et al., 2001; Velthof et al., 2010; MacDonald et al., 2011), studies reporting effects on N_2O emissions beyond one year after conversion are rare – despite the knowledge that effects of conversion on soil mineral N dynamics may last over a long period of time. Further, only few studies compare different conversion techniques (e.g. mechanical conversion (plowing), chemical conversion (chemical killing of the sward) or a combination of both) despite their potentially different influence on C and N dynamics. MacDonald et al. (2011) and Ruan and Robertson (2013) reported highest total N_2O losses during 36 and 29 weeks after chemical conversion and a combination of chemical and mechanical conversion, respectively.

To the best of our knowledge, to date there is no study that compares chemical and mechanical conversion to cropland for more than one year. In addition, not all studies include reference plots to identify the impact of those management practices. Generally, existing studies are difficult to compare because they differ in many essential details, e.g. measuring period (weeks or months vs. whole year; whole year with or without winter measurements), conversion time in the year (spring vs. autumn), treatment of the plots after conversion (e.g. seeding a crop or leaving the soil fallow) or type of conversion (mechanical vs. chemical). Therefore, no statement can be given about the effect of conversion type on N_2O fluxes and soil mineral N dynamics for more than one year after grassland conversion and general conclusions on the effects are difficult due to insufficient data. For the first time, we compare mechanical and chemical conversion to cropland (silage maize) for a period of more than one year. We aimed to (i) determine the dynamics of mineral N (N_{min}) and N_2O emissions following grassland conversion to maize cropping at two sites differing in soil properties, management and climate over a two-year period (May 2010 – April 2012) in comparison to permanent grassland. We intended to (ii) identify the controlling environmental variables and (iii) investigate the effects of two conversion techniques (mechanical vs. chemical conversion) on dynamics and intensity of N_2O emissions as well as soil N_{min}. We hypothesized that grassland conversion leads to increased N_2O emissions and NO_3^- leaching potential. Further, we hypothesized that mechanical conversion leads to higher N_2O emission and soil NO_3^- concentrations than chemical grassland conversion because of the more intensive mechanical disruption of sward and soil structure.

2. Materials and methods

2.1. Study sites and management

2.1.1. Planosol

The first site, Trenthorst, is located on glacial sediments of the Weichselian glacial period about 12 km southwest of Lübeck, Schleswig Holstein, Germany (53° 46′ 27″ N; 10° 30′ 30″ E). The site is 42 m above sea level and average annual temperature and rainfall are 9.0 °C and 704 mm, respectively (1990–2010). The experimental fields belong to an experimental farm for organic agriculture that has not received mineral fertilizer since 2001. The field plot trial was established on a permanent grassland (> 25 years old) and an adjoining long-term cropland. The crops grown on the long-term cropland the last five years before the start of the experiment were red clover grass (*Trifolium pratense* L., *Lolium spp*.), field peas (*Pisum sativum* L.), winter oilseed rape (*Brassica napus* L.), red clover grass (*Trifolium pratense* L.), and triticale (*Triticosecale* L.). The soil was classified as Planosol (WRB) on sandy loam (subglacial till). Further soil characteristics are given in Table 2.

For the randomized plot experiment, 16 plots of 3.5 by 15 m were established on grassland and cropland, respectively, and the following treatments were applied in quadruplicate: (i) continuing permanent grassland, (ii) mechanical conversion of grassland to silage maize cropping (*Zea mays* L.), (iii) chemical conversion of grassland to silage maize cropping (*Zea mays* L.) and (iv) continuing cropland. The conversion took place on May 17, 2010. In the chemical conversion plots, the sward was killed by application of a broadband herbicide (300 L ha^{-1} water, 4 L ha^{-1} glyphosate solution (Round up, Monsanto), 0.45 L ha^{-1} of the additive Arma (agroplanta)) and maize was sown directly without seedbed preparation. For the mechanical conversion, the sward was destroyed by a rotary tiller. Then, the soil was plowed and the seedbed prepared with a rotary harrow. The cropland was also plowed and the seedbed prepared with a rotary harrow in May 2010. All converted plots and the cropland plots were drilled with maize without any fertilization on June 5, 2010. Maize from converted plots and cropland was harvested on October 6, 2010. Stubbles of approximately 25 cm height were left on the field. In the permanent cropland plots and the mechanically converted plots, stubbles were plowed in on November 1, 2010. In the chemically converted plots, no plowing actions were carried out. The soil was only mulched after harvest. The converted and cropland plots were left fallow over winter. On March 30, 2011, chemically converted plots were treated with herbicide again. On May 3, 2011, both converted plots and the continuing cropland were drilled with maize. In the chemically converted plots, maize was sown directly without seedbed preparation. In the cropland and mechanically converted plots, the soil was plowed and the seedbed was prepared with a rotary harrow. On October 12, 2011, maize from all plots was harvested and stubbles were left on the field. The grassland plots were cut in July and September 2010 and in June and September 2011. As with the arable plots, the grassland plots received no fertilizer. An overview of management actions for the Planosol is given in the supplement (Table S.1).

2.1.2. Cambisol

The second site, Kleve, is located in the lower Rhine area, North-Rhine Westphalia, Germany (51° 47′ 04″ N; 6° 08′ 53″ E). The elevation is 12 m above sea level, and the average annual temperature and rainfall are 10.7 °C and 774 mm, respectively (1990–2010). The field trial was established on a permanent grassland site with conventionally used grassland (> 35 years). The soil is classified as Fluvic Cambisol (WRB) on clayey loam. Basic soil characteristics are given in Table 2.

The experiment was run as a randomized plot experiment (plot size 4.5 by 41 m) with three treatments that were each run in quadruplicate: (i) permanent grassland, (ii) mechanical conversion of grassland to silage maize cropping (*Zea mays* L.) and (iii) chemical conversion of grassland to silage maize cropping (*Zea mays* L.). Due to capacity reasons, no long-term cropland was available at this site. The conversion was conducted on April 27, 2010. For mechanical conversion, the soil was plowed and the seedbed was prepared with a rotary harrow. For chemical conversion, the sward was killed by application of a broadband herbicide (400 L ha^{-1} water, 6 L ha^{-1} glyphosate solution (Round up Ultramax, Monsanto)) and no seedbed preparation was done. The converted plots were drilled with maize on May 4, 2010. At beginning of July, regrowing grass was killed using 3 L ha^{-1} of the herbicide Clio Top BMX Pack (BASF). In the mechanically converted plots, regrowing grass was removed by hand. The four remaining plots were left undisturbed as permanent grassland reference. The converted plots received N fertilization according to N demand: In spring 2010, the soil contained 55 kg N_{min} ha^{-1} in $0-90$ cm and the fertilization target value was 192 kg N ha^{-1} (based on the expected yield). Nitrogen fertilizer was applied as 27 kg N ha^{-1} diammonium phosphate and 110 kg N ha^{-1} ammonium sulfate solution. Between April and October 2010, the grassland plots were cut five times and fertilized with 250 kg N ha^{-1} diammonium phoshate in four dressings (on April 27, June 10, August 5 and September 2, 2010). Maize harvest took place on October 12. The stubbles of approximately 25 cm length were mulched and incorporated with a grubber to a depth of 5–8 cm. All converted plots were left fallow over winter and mechanically converted plots were plowed on December 14, 2010. On April 6, 2011, glyphosate was again applied at the chemically converted plots (400 L ha^{-1} water, 6 L ha^{-1} g Round up Ultramax, Monsanto). On May 11, 2011, all arable plots were drilled with maize. No fertilizer was applied because soil N_{min} contents were above the target value of 192 kg N ha^{-1}. Between March 2011 and October 2011, the grassland was cut five times and fertilized with 280 kg N ha^{-1} in four dressings (March 23, May 10, June 20, and August 3, 2011). On October 5, 2011, maize from all arable plots was harvested and stubbles were left on the field. An overview of management actions for the Cambisol is given in the supplement (Table S.2).

2.2. Soil sampling and analysis

For the site characterization, in April 2010, one soil core down to 90 cm depth was taken from each plot with a pile-driven sampler which contained an internal PVC liner (Ø 10 cm, Röhrenwerk Kupferdreh Carl Hamm, Essen, Germany). Each soil core was divided into three depth sections ($0-30$ cm, $30-60$ cm and $60-90$ cm). For determination of soil texture and C and N contents, the samples were dried at 40 °C until constant weight and sieved ≤2 mm. Soil texture was analyzed according to DIN ISO 11277 with a combined sieving and sedimentation method. For C and N analyses, subsamples were milled and total C and N were determined with a C/N analyzer (LECO TruMac, LECO Instruments, Mönchengladbach, Germany). Soil carbonates were determined after DIN 10693 using a Scheibler Apparatus and subtracted from total C contents to give organic C. The soil pH was determined potentiometrically, with dried soil samples suspended in calcium chloride (0.01 M), measured with a pH electrode (Mettler Toledo™ FE20 FiveEasy™ Benchtop pH Meter, Fisher Scientific, Gießen, Germany). For the determination of bulk density, soil cores (100 cm^3) were taken in April 2010, 2011 and 2012.

Soil samples for the determination of soil mineral N (N_{min} = sum of NO_3^- and NH_4^+) dynamics were taken weekly from $0-10$ cm and $10-30$ cm using a Goettinger gouge auger with a diameter of 18 mm and 14 mm slot (Nietfeld GmbH, Quakenbrück, Germany). Additionally, composite samples of each plot (n = 1) were taken in April 2010, April 2011 and January 2012 in three depths (0–30 cm, 30–60 cm and 60–90 cm) for fertilization planning and identification of N_{min} allocation to the deeper soil of the Cambisol. Soil extracts for N_{min} were prepared after DIN 19746 with fresh soil and $CaCl_2$ (0.01 M) with a ratio of 1:4. Extracts were analyzed for $NO_3^- - N$ and $NH_4^+ - N$ concentration. A continuous flow analyzer was used in Trenthorst (Planosol) (Seal Auto Analyzer 3, Seal Analytical, Norderstedt, Germany) and Kleve (Cambisol) (CFA, Skalar, Breda, Netherlands).

The soil moisture content was determined gravimetrically on subsamples from the N_{min} sampling according to ISO 11465. For the Cambisol, water content was measured on a few dates only. Therefore, soil moisture for the Cambisol had to be modeled to obtain a continuous data set to evaluate moisture effects. The measured soil water contents were interpolated by the use of the process based model HYDRUS1D 4.14 (Šimůnek et al., 2005). As upper boundary condition, precipitation plus potential evaporation and potential transpiration according to Penman Monteith were set. The data was derived from the climate station at Kleve (Haus Riswick). For the chemically converted plots, the killed sward was taken into account as follows. Potential evaporation and transpiration were modified by the dead leaf area index via Beer's law, i.e. partitioning between incoming radiation between canopy and soil (Impens and Lemeur, 1969) and the canopy resistance (Allen et al., 1998). As lower boundary condition, free drainage was used. The initial condition values were taken from measurements on a nearby grassland. The parameters of the van Genuchten function (Van Genuchten, 1980) were quantified by pedotransfer functions implemented in HYDRUS1D and afterwards fitted by the use of the measured soil water content values. The water-filled pore space (WFPS) was calculated from the gravimetric water content and the bulk density.

2.3. Plant sampling and analysis

Aboveground biomass of the grassland plots on the Planosol was determined for each cut (one cut in 2010 and two cuts in 2011) from a representative area of 1 m^2. The maize yields were determined via harvest of 15 maize plants per plot. For the Cambisol, aboveground biomass of the grassland plots was determined for each cut (five cuts per year) on a representative area of 12.5 m^2. Maize plants were harvested on a representative area of 7.5 m^2. Plant materials were dried at 70 °C until constant weight, ground and N content was analyzed. Total dry matter was determined on subsamples that were dried at 105 °C.

2.4. Gas sampling and analysis

Nitrous oxide and CO_2 fluxes were measured weekly with a static closed chamber system (Hutchinson and Mosier, 1981) starting in May (Cambisol) and June 2010 (Planosol). Briefly, a PVC-collar (height: 15 cm, Ø 30 cm) was installed into approximately 5 cm depth at each plot. Collars were placed between plant rows in the converted plots with maize and the long-term cropland. Collars remained permanently in the soil. They were only removed for tillage and harvest events. For measurements, PVC chambers (height 30 cm), each fitted with a venting tube and a septum for gas sampling, were placed on the collars and sealed air tight with rubber bands. The chamber remained closed for 60 min and gas samples were collected at 0, 20, 40 and 60 min after chamber closure. The samples were collected in evacuated (< 1 mbar) glass vials with a Teflon stopcock (100 mL volume). Gas samples were analyzed for N_2O and CO_2 concentrations using a gas chromatograph (GC 2014, Shimadzu, Duisburg, Germany) with an automated rack (P 65, Loftfields Anaytical Solutions, Neu Eichenberg, Germany) and a ^{63}Ni electron capture detector (ECD) (Loftfield et al., 1997). The GC system was calibrated for each sample run using four standard gases ranging from 320 to 3000 ppb N_2O and 380–4000 ppm CO_2. Gas sampling intervals were optimized for N_2O fluxes. For obtaining quantitative CO_2 fluxes, shorter sampling intervals would have been necessary. Further, autotrophic and heterotrophic respiration were not determined separately. Therefore, the CO_2 data is only of qualitative nature and thus was only used as a proxy of plant and microbial respiratory activity.

The CO_2 and N_2O fluxes were calculated using linear regression, robust linear regression (Huber and Ronchetti, 1981) and Hutchinson-Mosier regression (Pedersen et al., 2010) with the approach described by Leiber-Sauheitl et al. (2014). Due to operational reasons, we were not able to start our gas measurements before June 7, 2010 (Planosol)/ May 11, 2010 (Cambisol). Therefore, data is lacking for the first two (Cambisol) or three (Planosol) weeks after conversion. To evaluate the uncertainty arising from this gap and estimate possible fluxes during this period, we calculated average N_2O fluxes from converted grasslands on sandy and loamy soils from the available literature (Baggs et al., 2000; Ruan and Robertson, 2013; Buchen et al., 2017; Reinsch et al., 2018), which were found to be 0.12/0.18 kg $N_2O-N\,ha^{-1}$ and 0.19/0.31 kg $N_2O-N\,ha^{-1}$ within the first two/three weeks after chemical and mechanical conversion, respectively.

An overview of all measured variables is given in the supplement (Table S.3).

2.5. Statistical analyses

Statistical analyses were performed using R 3.5.0 (RCoreTeam 2018). For all statistical analyses, the significance level was set to $p \leq 0.05$. In order to ensure variance homogeneity of residuals, cumulative N_2O fluxes were $\log_{10}$ transformed (Stehfest and Bouwman, 2006). Variance homogeneity and approximate normality of residuals was assessed using diagnostic plots. Outliers, i.e. standard errors $>$ 120 µg $N_2O-N\,m^{-2}\,h^{-1}$ and a few negative fluxes below -60 µg $N_2O-N\,m^{-2}\,h^{-1}$ were removed. Thereafter, the median of the standard error (SE) was 4.2 µg $N_2O-N\,m^{-2}\,h^{-1}$ for the Planosol and 6.2 µg $N_2O-N\,m^{-2}\,h^{-1}$ for the Cambisol. An offset of 35 µg $N_2O-N\,m^{-2}\,h^{-1}$ (amount of the maximal accepted uptake rate) was applied to the whole dataset in order to keep negative fluxes after $\log_{10}$ transformation (Deppe et al., 2016). An analysis of variance (ANOVA) followed by the Tukey test was carried out in order to analyze the effects of treatment and year on the cumulative N_2O fluxes as well as on yields and yield-related N_2O fluxes.

To investigate the impact of explanatory variables on N_2O fluxes, a regression analysis was run by fitting generalized additive models (GAM) as implemented in the R package mgcv version 1.8-11 (Wood and Augustin, 2002; Wood, 2011). These models are able to test non-linear relationships in a non-parametric way by fitting additive smoother terms in which the degree of smoothing is determined by penalized maximum likelihood estimation. The environmental control quantities included were WFPS and NO_3^- contents, CO_2 flux (as a proxy for microbial and plant respiratory activity) and soil temperature in 5 and 20 cm soil depth (these data were taken from nearby weather stations from the German Meteorological Service – No. 1590 (Geldern Walbeck) for the Cambisol and No. 3086 (Lübeck-Blankensee) for the Planosol). To cope with the randomized plot design of the experiment, all models contained a random intercept term. Since WFPS and NO_3^- were available for two soil depths ($0-10$ cm and $10-30$ cm), the GAM was run for both soil depths separately.

3. Results

3.1. Soil mineral nitrogen (N_{min})

3.1.1. Planosol

In the unfertilized Planosol, soil N_{min} dynamics (NO_3^- and NH_4^+) were dominated by NO_3^- contents. Soil NH_4^+ contents in $0-30$ cm soil depth showed a slight seasonal variation, but overall remained at a low level (< 8 kg $NH_4^+-N\,ha^{-1}$; Fig. 1). The trends for the individual soil depths ($0-10$ cm and $10-30$ cm) were comparable for both, NO_3^- and NH_4^+, but at a lower level in the deeper soil depth, likely due to increased mineralization in the top soil due to rhizosphere effects or lower temperatures in $10-30$ cm (Fig. S.1a).

Soil NO_3^- contents in the top 30 cm increased quickly after killing the sward after conversion compared to the permanent grassland plots. The increase was much more pronounced in the chemically converted plots (maximum of 92 kg $NO_3^--N\,ha^{-1}$ in the beginning of August) than in the mechanically converted plots (maximum of 33 kg $NO_3^--N\,ha^{-1}$ in early July 2010; Fig. 1). With increasing N uptake of the growing maize in all conversion plots, soil NO_3^- contents started to decrease. They came down to grassland levels in November 2010. The permanent cropland also showed increased NO_3^- contents in the soil after plowing in spring, but these were lower than observed in the converted plots (Fig. 1). From the beginning of November 2010 until beginning of March 2011, soil NO_3^- contents ($0-30$ cm) in the converted plots stayed at a level similar to the permanent grassland and cropland plots.

In the second year after conversion, soil NO_3^- contents ($0-30$ cm) started to increase again with increasing temperature in spring 2011, thereby exceeding values of the permanent grassland and cropland (Fig. 1). This increase was visible in both soil depths (Fig. S.1a). Differences between conversion types were not visible any more during the second year after conversion. The continuous cropland showed a similar pattern in NO_3^- dynamics as the converted plots, however at a lower level. Again, NO_3^- contents in the converted plots decreased with increasing N uptake of the growing maize. They reached a level of < 10 kg $NO_3^--N\,ha^{-1}$ in mid-July (mechanical conversion) and mid-August (chemical conversion) and then remained at grassland level.

3.1.2. Cambisol

In the fertilized Cambisol, NH_4^+ levels increased in the converted plots, particularly during the first weeks after fertilization (diammonium phosphate and ammonium sulfate solution) in the end of May 2010 (Fig. 2). Regarding the individual depth data (Fig. S.1b), these peeks were similar in both investigated soil depths, but much more pronounced in $0-10$ cm, which may, in addition to increased mineralization in the top soil due to rhizosphere effects or lower temperatures in $10-30$ cm, derive from fertilization. Also, in the grassland plots, the NH_4^+ content peaked during the first one to two weeks after each fertilization dose (Fig. 2). Overall, NH_4^+ levels remained higher in the converted plots compared to the permanent grassland until maize harvest in October 2010, ranging between 10 and 20 kg $N\,ha^{-1}$ during

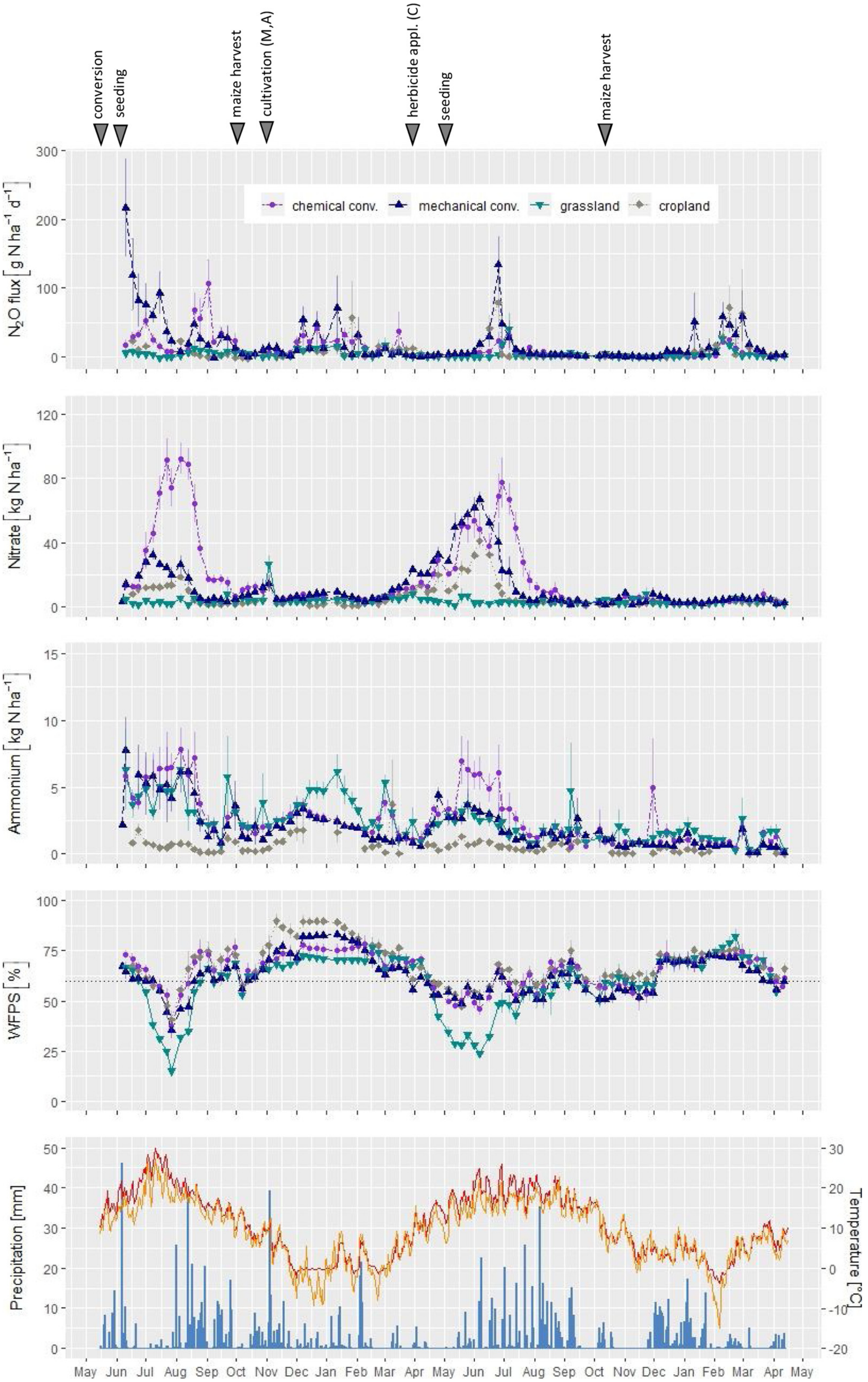

Fig. 1. N_2O emissions, concentration of soil nitrate (NO_3^-), ammonium (NH_4^+) and water-filled pore space (WFPS) in 0-30 cm soil depth, as well as temperature in the air (orange line) and in 5 cm soil depth (red line) and precipitation from May 2010 to April 2012 for the unfertilized Planosol. Arrows mark management actions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

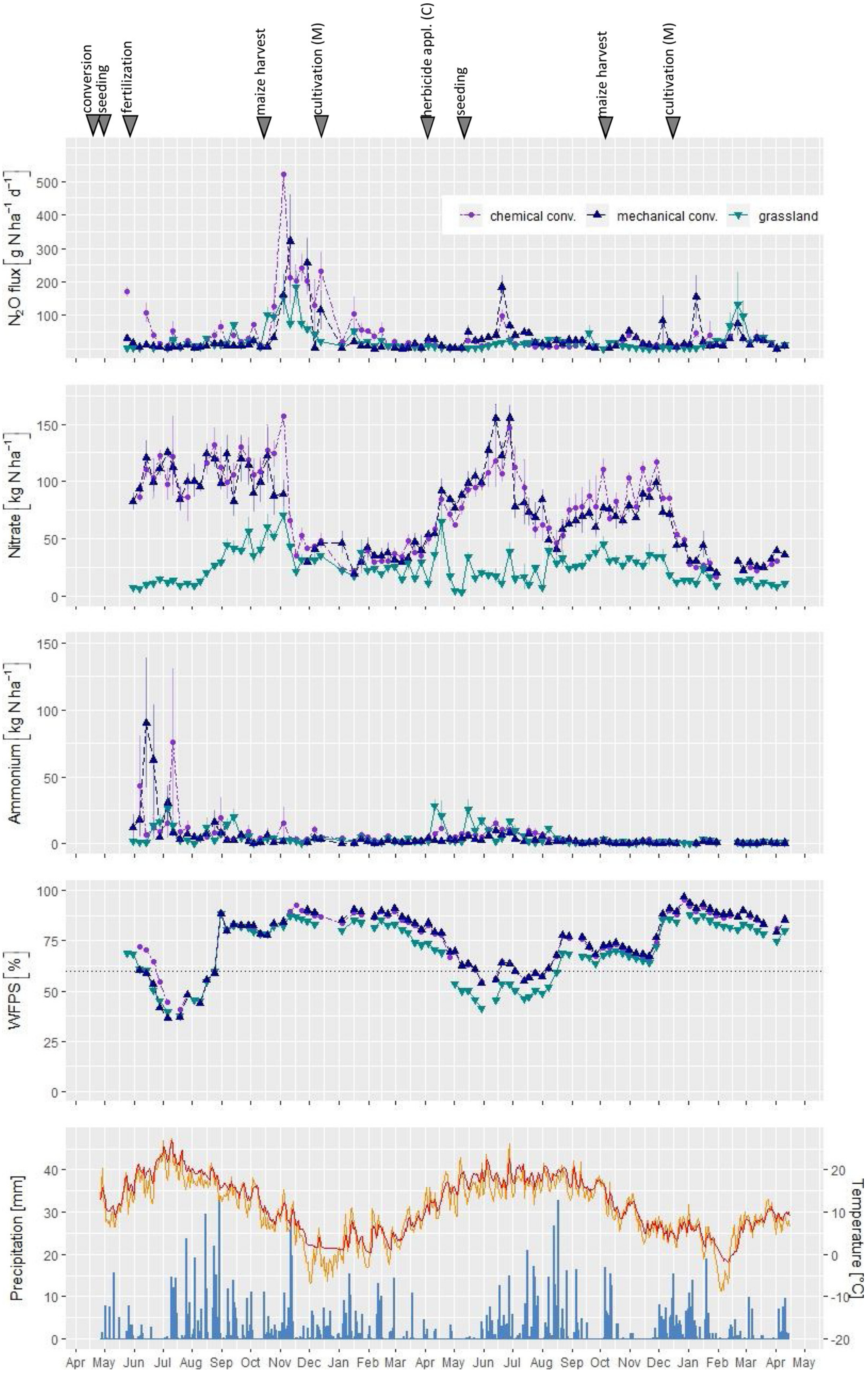

Fig. 2. N_2O emissions, concentration of soil nitrate (NO_3^-), ammonium (NH_4^+) and water-filled pore space (WFPS) in 0-30 cm soil depth, as well as temperature in the air (orange line) and in 5 cm soil depth (red line) and precipitation from May 2010 to April 2012 for the fertilized Cambisol. Arrows mark management actions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

the vegetation period of maize from May to October (Fig. 2). In the fallow period over winter, values fluctuated at around 5 kg $NH_4^+ - N\,ha^{-1}$. In the second year after conversion, the converted plots received no N-fertilizer, because the N_{min} content in the $0-90$ cm soil profile taken in spring 2011 was 246 and 249 kg N ha^{-1} and thus exceeded the expected N demand of maize (N_{min} target value was 192 kg N ha^{-1} based on the expected yield of maize). In this year, the NH_4^+ level of the grassland plots (which received 180 kg N fertilizer ha^{-1} in 2011) was slightly higher than that from converted plots.

As seen for the Planosol, soil NO_3^- contents in the top 30 cm of the Cambisol increased quickly after killing the sward for both, mechanical and chemical conversion compared to the permanent grassland plots (Fig. 2 and S.1b). At this site, soil NO_3^- dynamics were similar for both conversion types. Soil NO_3^- levels remained high ($\geq$95 kg $NO_3^- - N\,ha^{-1}$) until shortly after harvest (October 6, 2010) and then decreased to grassland levels within five weeks after harvest (Fig. 2). From mid-November 2010 until beginning of March 2011, soil NO_3^- contents ($0-30$ cm) in the converted plots stayed at a level similar to the grassland plots.

With increasing temperature in spring 2011, soil NO_3^- contents ($0-30$ cm) started to increase again as seen for the Planosol, thereby exceeding values of the permanent grassland (Fig. 2). This increase was noticeable in both soil depths again (Fig. S.1b). Similar to the first year after conversion, there were no differences between conversion types during the second year after conversion for the Cambisol. Soil NO_3^- contents decreased with growing crop stand as seen for the Planosol, but remained slightly higher in the converted plots of the Cambisol compared to the permanent grassland until the end of the experiment in the end of April 2012.

At this site, in addition to the regular N_{min} sampling in $0-30$ cm depth, a 90-cm N_{min} depth profile was taken once a year for fertilization planning (Fig. 3). In spring 2010, the N_{min} content in $0-90$ cm amounted to 67 kg N ha^{-1} in the chemically converted plots and 44 kg N ha^{-1} in the mechanically converted plots, about 60% of which was located in the first 30 cm. In spring 2011, the N_{min} content had strongly increased to amounts of 246 and 249 kg N ha^{-1} in mechanically and chemically converted plots, respectively. The increase in N_{min} was observed in all three investigated soil depths, but it was most pronounced in the deepest soil layer ($60-90$ cm) where it increased by more than ten-fold (from 4 and 6 kg N ha^{-1} in 2010 to 70 and 66 kg N ha^{-1} in 2011 in the mechanically and chemically converted plots, respectively). In spring 2012, the overall N_{min} content had decreased to 146 and 152 kg N ha^{-1} in the plots after chemical and mechanical conversion. However, it was still increased compared to the grassland plots, especially in the deeper layers.

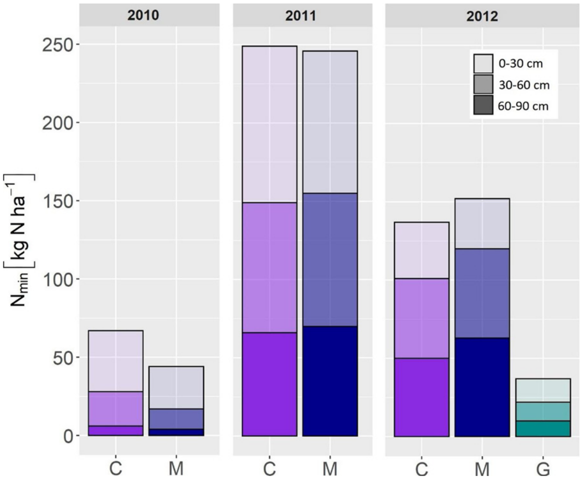

Fig. 3. Soil depth profile of mineral nitrogen (N_{min}) in the Cambisol taken in spring for the years 2010, 2011 and 2012 after chemical (C) and mechanical conversion (M) as well as in continuous grassland (G, only 2012).

3.2. *N_2O emissions*

3.2.1. *Planosol*

The N_2O fluxes measured before conversion (April 14, 2010) ranged from 3.6–10.3 g $N_2O-N\,ha^{-1}\,d^{-1}$ (data not shown). At the time of the first measurement after conversion, the N_2O flux from mechanically and chemically converted plots amounted 216.5 and 17.3 g $N_2O-N\,ha^{-1}\,d^{-1}$, respectively (Fig. 1). The N_2O fluxes from converted plots were elevated compared to the grassland and cropland plots until mid of July, i.e. two months after conversion (Fig. 1). Between mid-August through September, scattered high flux events up to 106.7 g $N_2O-N\,ha^{-1}\,d^{-1}$ for chemical conversion were observed on all converted plots, but not for the long-term cropland (Fig. 1). After September, N_2O fluxes remained low until end of November 2010 ($\leq$ 10 g $N_2O-N\,ha^{-1}\,d^{-1}$) and increased in December 2010 and January 2011 to an average of 31 g $N_2O-N\,ha^{-1}\,d^{-1}$ with maximum fluxes of 73 g $N_2O-N\,ha^{-1}\,d^{-1}$ (Fig. 1). From February 2011 until end of April 2011 when the arable plots were drilled again with maize, the overall emission level was low (< 14 g $N_2O-N\,ha^{-1}\,d^{-1}$; Fig. 1). In the second year after conversion, the observed time course of N_2O fluxes was similar to the first year. Increased fluxes were observed between June 2011 and August 2011 as well as in January and February 2012, but the overall level remained below that of the first year after conversion.

The sum of N_2O emitted over the two years (May 2010 to April 2012) was significantly higher on the converted plots – both, for chemical and mechanical conversion – compared to permanent grassland and long-term cropland (Table 3). Total N_2O losses from converted plots amounted 9.4 and 14.9 kg $N_2O-N\,ha^{-1}$ (for chemical and mechanical conversion, respectively) compared to 7.0 kg $N_2O-N\,ha^{-1}$ from permanent cropland and 3.4 kg $N_2O-N\,ha^{-1}$ from permanent grassland. A difference in the sum of N_2O emissions between conversion types was not observed. However, the distribution of the emissions over the two years differed between chemical and mechanical conversion (Table 3): while N_2O losses after mechanical conversion were more or less balanced over the two years investigated with a trend of less emissions in the second year, the major part of N_2O in the chemically converted plots was emitted in the first year after conversion. Emissions from chemically converted plots were not significantly different from those of the permanent grassland in the second year. Although we are lacking gas flux data for the first three weeks after conversion, our finding remains the same when adding the average N_2O fluxes after chemical and mechanical conversion of grasslands on sandy to loamy soils within the first three weeks for chemical (0.18 kg $N_2O-N\,ha^{-1}$) and mechanical (0.31 kg $N_2O-N\,ha^{-1}$) conversion from the available literature (Baggs et al., 2000; Ruan and Robertson, 2013; Buchen et al., 2017; Reinsch et al., 2018).

Table 3

Cumulated N_2O loss over the first year, second year and the sum of both years. Means and standard errors (n = 4). Small letters indicate significant differences between treatments per site, capital letters mark significant differences between years ($p < 0.05$).

Site	Treatment	N_2O loss (kg $N_2O-N\,ha^{-1}$)		
		First year	Second year	Σ Both years
Planosol	Chem. conversion	7.6^{abA} (1.3)	1.8^{aB} (0.1)	9.4^{a} (1.2)
	Mech. conversion	9.8^{abA} (1.7)	5.1^{aA} (1.9)	14.9^{a} (3.0)
	Grassland	2.1^{cA} (0.7)	1.3^{aA} (0.3)	3.4^{b} (0.9)
	Cropland	3.9^{bcA} (1.2)	3.1^{aA} (0.8)	7.0^{ab} (1.2)
Cambisol	Chem. conversion	25.8^{aA} (3.9)	6.5^{aB} (1.5)	32.3^{a} (4.6)
	Mech. conversion	14.7^{bA} (1.7)	10.9^{aA} (2.6)	25.6^{a} (3.6)
	Grassland	9.8^{bA} (1.2)	6.6^{aA} (0.9)	16.4^{b} (1.8)

3.2.2. Cambisol

The N_2O fluxes were generally higher in the fertilized Cambisol than in the unfertilized Planosol. Before conversion (April 21, 2010), the N_2O fluxes ranged from 4.2–6.8 g $N_2O-N\ ha^{-1}\ d^{-1}$ (data not shown). At the time of the first measurement after conversion, the chemically converted plots (170.5 g $N_2O-N\ ha^{-1}\ d^{-1}$) showed higher emissions than mechanically converted plots (30.4 g $N_2O-N\ ha^{-1}\ d^{-1}$) or the permanent grassland (2.8 g $N_2O-N\ ha^{-1}\ d^{-1}$; Fig. 2). From end of June 2010 until harvest (October 4, 2010), fluxes of converted and grassland plots stayed < 30 g $N_2O-N\ ha^{-1}\ d^{-1}$ except for a single flux event > 50 g $N_2O-N\ ha^{-1}\ d^{-1}$ each in chemically converted and in grassland plots. After harvest, fluxes from converted plots increased considerably, with maximum fluxes of 520.8 g $N_2O-N\ ha^{-1}\ d^{-1}$ in chemically converted plots and 322.2 g $N_2O-N\ ha^{-1}\ d^{-1}$ in mechanically converted plots (Fig. 2). The grassland plots also showed increased N_2O fluxes in fall, but these generally remained lower than emissions from converted plots. Similar to the Planosol, the emission level was low from February 2011 until end of April 2011 (< 14 g $N_2O-N\ ha^{-1}\ d^{-1}$; Fig. 2), when the converted plots were drilled again with maize. Also, in line with observations from the Planosol, the time course of N_2O fluxes in the second year after conversion was similar to the first year. Increased fluxes were observed between June 2011 and August 2011 as well as between December 2011 and February 2012, but fluxes stayed at a lower level than in the first year after conversion.

The sum of N_2O over the two years (May 2010 to April 2012) was significantly higher on the converted plots – both, for chemical (32.3 kg $N_2O-N\ ha^{-1}$) and mechanical conversion (25.6 kg $N_2O-N\ ha^{-1}$) – compared to the permanent grassland (16.4 kg $N_2O-N\ ha^{-1}$; Table 3). A difference in the sum of N_2O emissions between conversion types was not observed. However, in line with findings from the Planosol, the distribution of the emissions over the two years differed between chemical and mechanical conversion: Fluxes were similar in both years investigated after mechanical conversion while they were significantly higher in the first than the second year after conversion for chemically converted plots (Table 3). No significant differences between cumulative N_2O fluxes between converted plots and permanent grassland were found in the second year after conversion. As with the Planosol, adding the average N_2O fluxes on sandy to loamy soils within the first two weeks after chemical (0.12 kg $N_2O-N\ ha^{-1}$) and mechanical (0.19 kg $N_2O-N\ ha^{-1}$) conversion of grasslands from the available literature (Baggs et al., 2000; Ruan and Robertson, 2013; Buchen et al., 2017; Reinsch et al., 2018) to our summed N_2O emissions does not change the statement from our findings.

3.3. Yields and yield-related N_2O emissions

3.3.1. Planosol

Total dry matter (DM) yields of the grassland plots on the unfertilized Planosol were 3.1 t DM ha^{-1} (2010) and 4.4 t DM ha^{-1} (2011; Table 4). Yield-related N_2O emissions, i.e. the amount of N_2O emitted per t DM yield, ranged from 0.1 to 0.3 kg $N_2O-N\ t^{-1}$ DM yield at this site. Grain yields of maize were higher after mechanical conversion (9.1 t DM ha^{-1} and 10.7 t DM ha^{-1} in 2010 and 2011, respectively) compared to chemical conversion or the permanent cropland with 4.6–6.6 t DM ha^{-1}.

The yield-related N_2O emissions (yield of a year divided by the cumulative N_2O flux of that year) were higher in the first year after conversion than after the second year. In the first year, 1.1–1.2 kg $N_2O-N\ t^{-1}$ DM yield were lost from mechanically and chemically converted plots, respectively (Table 4). The long-term cropland emitted 0.7 kg $N_2O-N\ t^{-1}$ DM yield. In the second year, yield-related N_2O emissions were similar on converted plots and long-term cropland with $0.4-0.5$ kg $N_2O-N\ t^{-1}$ DM yield.

3.3.2. Cambisol

On the fertilized Cambisol, grassland yields derived from five cuts were 13.0 t DM ha^{-1} in 2010 and 11.2 t DM ha^{-1} in 2011 and yield-related N_2O emissions ranged from 0.5 to 0.8 kg $N_2O-N\ t^{-1}$ DM yield (Table 4). Grain yields of maize did not differ between chemically and mechanically converted plots with 17.8–18.2 t DM ha^{-1} in 2010 and 20.8–21.5 t DM ha^{-1} in 2011, respectively.

The yield-related N_2O emissions were higher in the first year after conversion than after the second year as seen for the Planosol. Emissions of 1.4 kg $N_2O-N\ t^{-1}$ DM yield were observed from chemically converted plots compared to 0.8 kg $N_2O-N\ t^{-1}$ DM yield after mechanical conversion. In the second year, yield-related N_2O emissions of converted plots were 0.4 and 0.6 kg $N_2O-N\ t^{-1}$ DM yield.

3.4. N_{min} stocks in relation to fertilization and crop-N yield for the Cambisol

The initial plant-available N in 2010 was calculated as the sum of fertilizer-N and the N_{min} contents in $0-90$ cm in spring 2010 (Table 5) and amounted 204 kg ha^{-1} and 181 kg ha^{-1} in the converted plots (chemical and mechanical conversion, respectively) and 287 kg ha^{-1} in the permanent grassland. Total N removal via harvest of silage maize was similar for both conversion treatments with 223 and 225 kg N ha^{-1}. In the permanent grassland, 351 kg N ha^{-1} were removed by five cuts in 2010. Because no fertilization took place in 2011, the N_{min} from the depth profiles (246 and 249 kg N ha^{-1} for mechanical and chemical conversion, respectively) was similar to the total amount of initial plant-available N in 2011 (Table 5). The grassland received 280 kg N ha^{-1} fertilizer and had a total initial plant-available N amount of 317 kg N ha^{-1}. The amount of harvested N in 2011 was 242 and 245 kg N ha^{-1} for mechanical and chemical conversion, respectively and 304 kg N ha^{-1} for the permanent grassland (five cuts). In 2012, the N_{min} depth profile in spring contained 137 and 152 kg N ha^{-1} for chemically and mechanically converted plots and 317 kg ha^{-1} for the permanent grassland. Harvested crop-N was 161 kg N ha^{-1} and 208 kg N ha^{-1} in the chemically and mechanically converted plots and 342 kg N ha^{-1} in the permanent grassland (Table 5).

Table 4

Dry matter (DM) yield and yield-related N_2O of all treatments on both sites. Grassland yield is summarized from single cuts (one cut in for the Planosol in 2010, two cuts in 2011; 5 cuts per year for the Cambisol). Means and standard errors (n = 4). Small letters indicate significant differences between treatments per site ($p < 0.05$).

Site	Treatment	Yield (t DM ha^{-1})		Yield-related N_2O (kg N_2O t^{-1} DM)	
		2010	2011	2010	2011
Planosol	Chem. conversion	6.6 (0.5)^b	4.6 (0.5)^a	1.2 (0.4)^a	0.4 (0.0)^a
	Mech. conversion	9.1 (0.9)^c	10.7 (1.0)^b	1.1 (0.4)^a	0.5 (0.4)^a
	Grassland	3.1 (0.2)^a	4.4 (0.4)^a	0.3 (0.2)^a	0.1 (0.0)^a
	Cropland	6.0 (0.3)^b	5.8 (0.4)^a	0.7 (0.4)^a	0.5 (0.3)^a
Cambisol	Chem. conversion	18.2 (0.8)^b	20.8 (0.5)^b	1.4 (0.4)^b	0.4 (0.2)^a
	Mech. conversion	17.8 (0.7)^b	21.5 (0.7)^b	0.8 (0.2)^a	0.6 (0.3)^a
	Grassland	13.0 (0.6)^a	11.2 (0.9)^a	0.8 (0.2)^a	0.5 (0.1)^a

Table 5

Measured N_{min} stocks in 0-90 cm soil depth, N input as fertilizer and harvested crop-N for the Cambisol.

Treatment	N_{min} spring ($kg\ ha^{-1}$)	Fertilizer-N input ($kg\ ha^{-1}$)	Initial plant-available N ($kg\ ha^{-1}$)[#]	Harvested crop-N ($kg\ ha^{-1}$)[a]
2010				
Chem. conversion	67	137	204	223
Mech. conversion	44	137	181	225
Grassland	37*	250	287	351
2011				
Chem. conversion	249	0	249	244
Mech. conversion	246	0	246	242
Grassland	37*	280	317	304
2012				
chem. conversion	137	0	137	161
mech. conversion	152	0	152	208
grassland	37	280	317	342

* For 2010 and 2011, no N_{min} data was available for the permanent grassland. Since the grassland was permanent grassland for a long period of time, it was considered in steady state and therefore, we adapted the grassland data from 2012 to the previous years.

[#] Initial plant-available N = soil N_{min} spring + fertilizer input.

[a] No N measurements from harvested plant materials was available in 2010 and 2011 – N content of plant material was therefore estimated from the data derived in 2012.

3.5. Relationship of N_2O emissions with soil mineral N and environmental variables

3.5.1. Planosol

The applied GAM explained 41% of the variance in the log-scaled N_2O fluxes. There was a significant treatment effect for both, chemical ($p < 0.05$) and mechanical conversion ($p < 0.001$). Soil NO_3^- and WFPS in 0 – 10 cm were significant independent of land use ($p < 0.001$ for converted plots and cropland and $p < 0.05$ for grassland, Table S.4a) and thus improved the goodness of fit of the GAM for predicting N_2O emissions. This finding was corroborated when using the controlling variables of the deeper soil layer (10 – 30 cm; $p < 0.001$ for converted plots and cropland and $p < 0.05$ for grassland; data not shown). Further, soil temperature and CO_2 flux (Fig. S.2b, c), which served as an indicator for microbial activity, had an effect on N_2O emissions independent of treatment ($p < 0.001$). N_2O fluxes increased with increasing CO_2 flux and with increasing temperature. Further, they were elevated at temperatures < 5 °C (possibly related to frost-thaw events; Fig. S.2c). Highest N_2O fluxes in the Planosol were observed at WFPS levels > 60% and at around 30 $kg\ ha^{-1}$ $NO_3^- - N$ (Fig. S.2a).

3.5.2. Cambisol

The applied GAM explained 40% of the variance in the log-scaled N_2O fluxes. Similar to the Planosol, N_2O emissions from the Cambisol were affected by NO_3^- and WFPS in 0 – 10 cm independent of treatment ($p < 0.001$ for converted plots and permanent grassland; Table S.4b). Highest fluxes were observed at WFPS > 85% and at NO_3^- contents around 100–150 kg $NO_3^- - N\ ha^{-1}$ (Fig. S.3a). Similarly, temperature and CO_2 flux affected N_2O emissions as seen for the Planosol (Fig. S.3b – c). Again, the model was corroborated for the deeper soil layer ($p < 0.001$ for converted plots and permanent grassland; data not shown).

4. Discussion

4.1. N budget and soil mineral N dynamics

The impact of grassland conversion to cropland on N dynamics can be evaluated based on temporal soil N_{min} patterns in combination with the N budget (Buchen et al., 2017). The results from the 0 – 90 cm depth profiles taken once a year in spring from the Cambisol point to a high net-N mineralization after conversion. Since we did not determine important N losses such as leaching of NO_3^- below 90 cm depth or emission of N_2, total net-N mineralization induced by grassland conversion was probably even considerably higher than the amount of N_{min} present in the soil profile after winter (Buchen et al., 2017).

The N_{min} dynamics that were determined weekly in the top 30 cm of the soil at both investigated sites also indicate increased net N mineralization following grassland conversion. Generally, high N_{min} levels after conversion are a consequence of a lower crop uptake of plant-available N directly after conversion (Ball et al., 1999; Velthof et al., 2010) and increased production of plant-available N and C after SOM mineralization (Grandy and Robertson, 2006; Velthof et al., 2010; MacDonald et al., 2011). Moreover, high N_{min} levels after conversion represent an increased N substrate supply to nitrification and denitrification (Grandy and Robertson, 2006; Ruan and Robertson, 2013; Buchen et al., 2017). In addition to that, incorporation of the former grass sward into the soil enhances denitrification though O_2 consumption during decomposition and supplying labile organic C as an energy source. Due to the generally low C/N ratios of grass swards (Whitehead, 2000), the flush of plant litter decomposition often entails a net N mineralization (Kaiser et al., 1998; Reinsch et al., 2018). Therefore, N_{min} contents remained higher in the converted plots than in permanent grassland or cropland until harvest indicating that the synchrony between soil N_{min} contents and consumption by plants was still disturbed in the converted plots (Grandy and Robertson, 2006). Also, in the second year after conversion, N_{min} levels remained considerably increased in the converted plots compared to permanent grassland or long-term cropland. The elevated N_{min} levels in all conversion plots are an indication of ongoing enhanced N mineralization. It might take several years until the converted soils will approach a new equilibrium (Poeplau et al., 2011).

Considerable N losses after grassland renovation or grassland conversion as seen for the soils studied here have been reported in several studies (Shepherd et al., 2001; Velthof et al., 2002 and references therein; Seidel et al., 2009; Reinsch et al., 2018). Conversion in spring instead of fall is recommended to reduce N losses, because N mineralized from the decomposing sward can be used by the upcoming crop (Ball et al., 1999; Shepherd et al., 2001; Velthof et al., 2010; MacDonald et al., 2011; Reinsch et al., 2018). However, despite grassland conversion in spring followed by a crop with high N demand (silage maize with an N demand > 200 $kg\ ha^{-1}$, Velthof et al., 2002), we found considerable net N mineralization clearly exceeding crop demand for the fertilized Cambisol (Table 5). This indicates that the time of conversion and adjustment of N fertilization may probably help to reduce negative effects of grassland conversion to cropland on N dynamics, but is not sufficient to completely avoid these effects.

Quantifying N_{min} stocks in spring can help to find the adequate fertilization rate but it does not account for enhanced N mineralization during the following cropping period. Since the Cambisol was fertilized with N in addition to the N mobilized by the conversion, the excess N with respect to crop demand was extraordinarily high in the first year, and the crop following conversion was not capable of using all available mineral N. Thus, the soil was not fertilized in the second year after conversion, since the N_{min} values in 0 – 90 cm soil depth (246 and 249 $kg\ N\ ha^{-1}$) exceeded the fertilization target value of 192 $kg\ N\ ha^{-1}$ (based on the expected yield). The results from this as well as from previous studies (e.g. Velthof et al., 2002 and references therein; Velthof et al., 2010) emphasize the need of taking into account the N mineralization after conversion in the fertilization planning for the cropping period following conversion in order to account for enhanced N mineralization as also proposed by Buchen et al. (2017) and Reinsch et al. (2018). So far, recommendations for N fertilizer application rates after grassland conversion are barely available. The German Fertilizer Ordinance (2017) suggests a reduction of the fertilization of at least

20 kg N ha^{-1} if the previous crop was grassland. Yet, depending on the age of grassland and the type of utilization (pasture, meadow), especially after conversion of old grassland (> 15 years) reductions of 180 – 220 kg N ha^{-1} seem to be more appropriate (Velthof et al., 2002 and references therein; Velthof et al., 2010; MacDonald et al., 2011; Buchen et al., 2017; Reinsch et al., 2018).

While it is evident that grassland conversion enhances N mineralization, the question arises whether the *type of conversion* affected the magnitude in net N mineralization. In the fertilized Cambisol, closeness of total N_{min} stocks in 0 – 90 cm of both conversion treatments suggest that there were no clear differences in net N mineralization between conversion treatments. This is further supported by the N_{min} topsoil data at this site, where we found no differences in N_{min} levels between conversion techniques. We suspect that the effect of conversion on soil N_{min} dynamics was masked by the already higher N_{min} levels due to fertilization. In the unfertilized Planosol, soil N_{min} levels were significantly higher in the chemically converted plots compared to mechanical conversion in the first year after conversion ($p < 0.05$) pointing to a more intense mineralization or increased nitrification activity after chemical conversion than after mechanical conversion. Since the amount of organic matter of the sward was similar for both types of conversion, these differences likely derive from the different treatment of the soil and grass sward resulting from the different management practices: In the chemically converted plots, the killed sward remained at the soil surface while it was incorporated into the soil in mechanically converted plots. These differences in sward location may have led to differences in sward mineralization and in different conditions for nitrification and denitrification. This is in line with findings by Groffman (1984), who observed residue decomposition and mineralization almost entirely at the soil surface of a non-tilled soil. They found higher nitrification activity in the upper soil depth of the soil under no-tillage compared to conventionally tilled soil, which they attributed to greater NH_4^+ availability in the top soil layer due to the observed mineralization behavior. In the mechanically converted soil, tillage incorporated the sward material into the soil and likely led to a disruption of soil macroaggregates (Six et al., 2000; Bronick and Lal, 2005), which also increased mineralization for some period (Scott et al., 2002; Grandy and Robertson, 2006; Rochette et al., 2008). However, in the course of mineralization, particulate organic matter from the sward within the soil matrix likely served as a core for the build-up of new soil aggregates, which then protected it from further mineralization (Tisdall and Oades, 1982; Golchin et al., 1997). This protecting mechanism was not given in the chemically converted plots so that mineralization may have taken place for a longer period. During the vegetation period of the second year after conversion, no more differences in soil N_{min} between conversion types were found at either study site. For both soils, our findings do not support our hypothesis that mineralization would be higher after mechanical than chemical conversion due to the more intensive soil physical changes induced by tillage (e.g. chopping sward residues into smaller pieces, mixing them with the soil, breaking up soil aggregates and increased soil aeration).

4.2. N_2O fluxes and cumulative N_2O emissions

This study is the first one that comparatively investigated N_2O fluxes after chemical and mechanical conversion of grassland to cropland (silage maize) for a two-year period. In line with our hypothesis, in sum over the two years investigated, both, mechanical and chemical grassland conversion led to significantly higher N_2O emissions in the converted plots than in the permanent grassland ($p < 0.001$). Our observations are in the range of results from previous studies (Table 1). We further hypothesized that emissions would differ between conversion types with emissions being lower after chemical conversion than after mechanical conversion due to less intensive mechanical disturbance of soil and grass sward. However, in sum over two years after conversion, we found no evidence that chemical conversion reduces N_2O emissions compared to conversion by plowing at either of the study sites despite different emission levels due to differences in fertilization regime. Only the distribution of N_2O emissions over the two years investigated differed between conversion types, again, at both sites investigated. While emissions from mechanically converted plots remained at a higher level in the second year after conversion, they strongly decreased in the second year compared to the first one in the chemically converted plots. This different distribution of N_2O emissions between conversion treatments can be explained from a variety of treatment effects on the control factors of N_2O fluxes as follows.

Tillage, as carried out in the mechanically converted plots, is known to cause changes in soil porosity, aeration and moisture (Yamulki and Jarvis, 2002) and the lack of plant cover after conversion may have increased soil temperature (MacDonald et al., 2011). Particulate organic matter, in this case the material from the former grass sward, enhances water retention and thus lowers aeration (Kravchenko et al., 2017). Further, tillage chopped the sward into pieces and then incorporated this easily degradable material into the soil. Additionally, soil macroaggregates are known to be sensitive to tillage (Bronick and Lal, 2005; Six et al., 2000). They may break up, which in turn leads to exposure of substantial amounts of easily degradable substrates (Scott et al., 2002; Grandy and Robertson, 2006). Labile organic matter affects N_2O fluxes by several effects. First, NH_4^+ and NO_3^- are formed by mineralization and by nitrification in interaction with the dynamics of plant N uptake (Müller and Clough, 2014). Oxygen consumption by respiration favours the build-up of anoxic microsites and thus denitrification (Groffman et al., 2009). Moreover, labile C enhances denitrification as an electron donor of the process. The combination of greater microbial activity, increased C and N availability and changes in soil temperature, aeration and moisture in the mechanically converted plots likely accelerated N_2O emissions for some period. This was also supported by the applied GAM which pointed out that soil NO_3- contents and WFPS were the main variables driving N_2O emissions, followed by temperature and microbial activity. However, in the course of mineralization of the easily degradable dead sward material, particulate organic matter from the sward within the soil matrix likely served as a core for the build-up of new soil aggregates, which then protect it from further mineralization (Tisdall and Oades, 1982; Golchin et al., 1997). In the mechanically converted plots, the incorporation of the sward thus slowed down the decomposition and diluted residues from the grass sward with the tilled soil so that the enhancement of denitrification was less intense but lasted longer.

Chemical conversion involved direct drilling after chemical killing of the sward, i.e. no soil-sward mixing took place and the killed grass sward remained on the soil surface. Therefore, the major part of this easily degradable material may have been mineralized in the first year after conversion without the protecting effect of soil aggregation – leaving hardly any easily degradable material in the following year. This would also be in accordance with the higher soil N_{min} contents observed in the top 30 cm of the chemically converted plots in the first year after conversion compared to mechanical conversion although only significant for the Planosol (Boeckx and Van Cleemput, 2001; Ruser et al., 2006). Therefore, the combined effect of induced wetness and intense mineralization and O_2 consumption apparently induced the high N_2O fluxes of the first year.

Overall, however, the difference in N_2O emissions between sites was much more pronounced than those between treatments, reflecting that soil type, soil management at either site (fertilization versus no fertilizer) and environmental conditions (i.e. SOM, water saturation) had a much greater influence on N_2O emissions than conversion treatments at the investigated sites. This is in agreement with results from previous studies (Buchen et al., 2017; Reinsch et al., 2018).

4.3. Plant growth and yield-related N_2O emissions

With 3 – 4 t DM ha^{-1}, yields of the permanent grassland on the unfertilized Planosol were on an overall low level. Depending on climate, management and fertilization, average grassland yields roughly range from 6 to 14 t DM ha^{-1} (Whitehead, 2000). Reinsch et al. (2018) observed yields of 9 − 10 t DM ha^{-1} on unfertilized grassland. The fertilized Cambisol yielded 11 − 13 t DM ha^{-1}, which corresponds to DM yields of 10 − 13 t ha^{-1} observed on fertilized grassland in Germany (e.g. Buchen et al., 2017; Reinsch et al., 2018). The yield-related N_2O emissions of the grassland were higher on the fertilized Cambisol (0.5 − 0.8 kg N t^{-1} DM) than on the unfertilized Planosol (0.1 − 0.3 kg N t^{-1} DM) indicating that fertilization not only increased grassland yields, but also enhanced the N_2O emission level. Generally, the yield-related emissions observed in our study were higher than those observed for other unfertilized or fertilized German grasslands, e.g. fertilized grassland on a Plaggic Anthrosol near Oldenburg (0.1 kg N t^{-1} DM; Buchen et al. (2017) or unfertilized and fertilized grassland on an Eutric Luvisol near Kiel (0.04 and 0.1 kg N t^{-1} DM, respectively; Reinsch et al. (2018)). However, the study sites investigated by Buchen et al. (2017) and Reinsch et al. (2018) were more sandy (90% and 60%, respectively) and less clayey (3% and 11%, respectively) than the Planosol (50.7% sand and 17.6% clay) or Cambisol (23.6% sand and 29.6% clay).

Silage maize yields on the unfertilized Planosol were higher after mechanical conversion than after chemical conversion or in the permanent cropland. This suggests that the growing crop on the mechanically converted plots benefited from the mineral N released after mechanical conversion in this long-term unfertilized soil. However, in the chemically converted plots, this was not the case. Suboptimal crop emergence (also reflected by the lower DM yields at harvest) in combination with (up to five times) higher soil N_{min} contents in 0 − 30 cm from end of June until end of September after chemical than mechanical conversion indicate that the young plants on the chemically converted plots did not profit from the N released after conversion. The decomposing sward on the soil surface in the chemically converted plots may have hindered plant growth and upcoming weeds concurred with the young maize plants. In the mechanically converted plots, plowing improved the physical and chemical soil conditions (i.e. aeration, mixing of the sward material) and may have reduced the number of weed plants in the upcoming vegetation after conversion, which in turn may have increased vitality of the young maize plants in mechanically converted plots (Velthof et al., 2002). A quickly growing plant population is essential in directly drilled soils in order to minimize the impact of concurring weeds and grasses sprouting from the old sward (Velthof et al., 2010). On the Cambisol, however, maize yields were high on the converted plots in both years with no differences between conversion types (18 − 22 t DM ha^{-1}) and are in the range of maize yields reported for other converted grasslands on fertilized soils (e.g. Buchen et al., 2017; Reinsch et al., 2018). Due to fertilization in combination with plant-available N released during the decomposition of the killed sward, soil N_{min} was available at excess so that it was not limiting plant growth at any time at this site. Even in the second year, where no fertilization was carried out, the yields did not decrease and soil N_{min} contents were still close to 100 kg ha^{-1} at the time of harvest.

On the Planosol, the plots with the lower yields also had overall lower N_2O emissions so that yield-related N_2O emissions did not differ between conversion treatments at this site. However, they were more than twice as high in the first year after conversion than in the second year where they were already at cropland-level likely due to the enhanced mineralization directly after grassland conversion (Ruan and Robertson, 2013). On the Cambisol, yield-related emissions were nearly twice as high in the first year after chemical conversion than mechanical conversion. Yields were similar for the two conversion types at this site, but N_2O emissions were higher in the first year after chemical conversion. Overall, the yield-related N_2O emissions did not differ considerably between the investigated sites despite the difference in fertilization and therefore the overall N level in the soils.

5. Conclusions

Both sites exhibited enhanced N_2O emissions, net-N mineralization, and strongly increased risk of NO_3^- leaching following grassland conversion to maize cropping. We found no evidence that chemical grassland conversion combined with direct seeding of maize results in lower N_2O emission and net-N mineralization than conventional grassland conversion by plowing. There were minor differences in temporal patterns of mineral N availability and dynamics of N_2O emissions between the applied grassland conversion techniques, but total N_2O emission over two years were not significantly different. Despite differences in soil type and fertilization (fertilized soil versus unfertilized soil), these key messages are similar for both investigated sites. The findings from this study underline the relevance of considering these typical conversion effects in terms of greenhouse gas budgets, N use efficiency and potential leaching irrespective of the conversion method used. In order to minimize excess of available N, which triggers NO_3^- leaching and N_2O emissions, dynamics and amount of net-N mineralization following grassland conversion needs to be taken into account in the fertilization planning already in the year of conversion. Quantifying N_{min} stocks in spring can help to find the adequate fertilization rate but it does not account for enhanced N mineralization during the following cropping period. Therefore, the extent of N mineralization after conversion needs to be estimated and the fertilization amount adapted. Additionally, the site management following conversion is crucial considering environmental and climate-relevant N losses – a fast uptake of the following crop is important as well as year-round vegetation, i.e. by using catch crops.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

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