

REVIEW

Direct nitrous oxide emissions from oilseed rape cropping – a meta-analysis

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Abstract

Oilseed rape is one of the leading feedstocks for biofuel production in Europe. The climate change mitigation effect of rape methyl ester (RME) is particularly challenged by the greenhouse gas (GHG) emissions during crop production, mainly as nitrous oxide (N₂O) from soils. Oilseed rape requires high nitrogen fertilization and crop residues are rich in nitrogen, both potentially causing enhanced N₂O emissions. However, GHG emissions of oilseed rape production are often estimated using emission factors that account for crop-type specifics only with respect to crop residues. This meta-analysis therefore aimed to assess annual N₂O emissions from winter oilseed rape, to compare them to those of cereals and to explore the underlying reasons for differences. For the identification of the most important factors, linear mixed effects models were fitted with 43 N₂O emission data points deriving from 12 different field sites. N₂O emissions increased exponentially with N-fertilization rates, but inter-year and site-specific variability were high and climate variables or soil parameters did not improve the prediction model. Annual N₂O emissions from winter oilseed rape were 22% higher than those from winter cereals fertilized at the same rate. At a common fertilization rate of 200 kg N ha⁻¹ yr⁻¹, the mean fraction of fertilizer N that was lost as N₂O-N was 1.27% for oilseed rape compared to 1.04% for cereals. The risk of high yield-scaled N₂O emissions increased after a critical N surplus of about 80 kg N ha⁻¹ yr⁻¹. The difference in N₂O emissions between oilseed rape and cereal cultivation was especially high after harvest due to the high N contents in oilseed rape's crop residues. However, annual N₂O emissions of winter oilseed rape were still lower than predicted by the Stehfest and Bouwman model. Hence, the assignment of oilseed rape to the crop-type classes of cereals or other crops should be reconsidered.

Keywords: biofuel, *Brassica napus*, canola, greenhouse gas emission, N₂O, RME

Received 26 May 2014; accepted 6 July 2014

Introduction

Rising concern about the finite nature of fossil fuels and growing awareness about their impact on climate change have led to an intensified discussion on substitutes for gasoline, diesel, and natural gas. In recent years, the discussion also found its way into politics. The European Union (EU) adopted for the first time a legally binding goal for the share of biofuels in the Renewable Energy Directive (RED, 2009). It implies that the share of biofuel in transport energy consumption has to be at least 10% by 2020. As a consequence, the biofuel consumption in the EU is rapidly growing. From 2000 to 2010, it increased 19-fold (Eurostat, 2012) and reached a 5.1% share of total fuel consumption for

transportation in 2012 (Eurostat, 2014b). In the EU, biodiesel is the dominant biofuel with a market share of 75% (Hamelinck *et al.*, 2012). The most common feedstock for its production is rapeseed oil, accounting for 56% in 2010 (Hamelinck *et al.*, 2012). Because car engines need to be modified for the direct use of rapeseed oil, it is commonly converted into methyl ester of rapeseed (RME) (Schubert *et al.*, 2010).

From 2008 to 2013, the oilseed rape cultivation area in the EU increased by 10%, resulting in 6.7 Mha in 2013 for oilseed rape cultivation, mostly in Germany, France, Poland, and the UK (Eurostat, 2014a). In addition to the 10% target, sustainability criteria for biofuel were introduced by the RED (RED, 2009). Accordingly, biofuels may only be accounted for the target if their consumption reduces greenhouse gas (GHG) emissions by 35% as compared to the fossil alternative. From 2017 onward, the necessary GHG reduction is 50%. The

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requirements for biofuels in terms of their GHG balance thus continue to grow.

One of the most important contributions to the GHG balance of biofuels is N₂O that is emitted from soils during biofuel feedstock production (Don *et al.*, 2012). Crutzen *et al.* (2008) argued it may even negate biofuels GHG benefits if all N₂O emissions related to feedstock production are accounted for as it was done in their top-down approach. The ranges of N₂O emissions and total field GHG emissions that are given in life cycle assessments (LCA) of RME are wide. In a meta-study on biofuel LCAs it was shown that 64–90% of total GHG emissions of RME production are due to oilseed rape cultivation and that N₂O field emissions account for 35–47% of these emissions (Hoefnagels *et al.*, 2010).

Winter oilseed rape (referred to as rape in the following) has a high nitrogen (N) demand (Sieling & Kage, 2010). This leads to fertilization rates often exceeding 200 kg N ha⁻¹ yr⁻¹ which is at the upper end of N fertilizer additions to annual crops. Moreover, rape's seasonal dynamics of N uptake are different from those of other annual crops. In autumn, its N uptake is faster as compared to winter cereals (Sieling & Kage, 2010). Soil mineral N content is therefore reduced under young rape. The soil N surplus after harvest of rape, however, is large (Beaudoin *et al.*, 2005) because N uptake by the rape seeds is relatively small (Rathke *et al.*, 2006) and N-rich rape residues (DüV, 2007) mostly remain on the field. With soil mineral N supply being an important driver for N₂O production and direct emission from cropland soils (Bouwman *et al.*, 2002), it can be expected that there are periods during rape cultivation when N₂O emissions are different from those of other arable crops like cereals. Owing to the rape-specific N dynamics, nitrate leaching after harvest is a well-known problem of rape fields (Sieling & Kage, 2006; Henke *et al.*, 2008). Subsequently, rape cultivation's indirect N₂O emissions may also be substantial (Kern *et al.*, 2010; Well & Butterbach-Bahl, 2010).

Regarding direct N₂O emissions from rape cultivation, there is an urgent need for a new integrated analysis to reduce the considerable uncertainty that may strongly influence the outcome of RME LCAs. The great variation mainly arises from the different approaches used to estimate N₂O emissions from soils cropped with rape. In most LCAs, direct N₂O emissions from managed soils are calculated using the International Panel on Climate Change (IPCC) default Tier-1 emission factor (EF) (Cherubini, 2010). According to this EF, 1% of nitrogen added to the soil as synthetic and organic fertilizer, crop residues and by land-use change related organic matter mineralization is lost as N₂O (IPCC, 2006). In contrast to the IPCC EF, the empiric N₂O emission model that constitutes much of its scientific basis is

stratified according to soil type, climate and type of crop (Stehfest & Bouwman, 2006). In this Stehfest & Bouwman model rape is ascribed to the crop-type class 'other' which also includes maize, potatoes and irrigated fields. Compared to the class of cereals, the N₂O emissions of 'other' crops were significantly higher. An exponential influence of N application rate on N₂O emission was found for a dataset with diverse crops. Due to the predicted high N₂O emissions for rape, LCAs of RME that use the Stehfest & Bouwman model to assess direct N₂O emissions from rape fields may calculate higher field GHG emissions than those LCAs using the IPCC EF. Direct N₂O emissions from rape field soils can also be estimated using process-based biogeochemical models like the DeNitrification-DeComposition model (DNDC) (Li *et al.*, 1992) or the recently introduced empirical global nitrous oxide calculator (GNOC), an online tool to estimate soil N₂O emissions from the cultivation of biofuel crops (JRC, 2013). While each site has to be parameterized for N₂O emission predictions by the complex mechanistic DNDC model, for assessments with GNOC only rough classifications of soil parameters and climatic zones are needed to obtain crop-specific EF (Edwards *et al.*, 2012). The class limits and effect values are those derived from the Stehfest & Bouwman (2006) model. However, in GNOC rape was aggregated with the crop-type class of cereals after reevaluation of the Stehfest & Bouwman (2006) dataset. Compared with the Stehfest & Bouwman approach, the application of GNOC would therefore lead to a reduction in N₂O emission accounting in GHG balances and LCAs of rape cultivation.

The objective of this study was to compile available data on N₂O emissions from rape to answer the following questions:

- 1 How much N₂O is directly emitted from soils cultivated with rape?
- 2 How is the rape's N₂O emission influenced by nitrogen fertilization?
- 3 Do N₂O emissions of rape and cereals differ systematically?
- 4 Are there periods with rape-specific high or low N₂O emissions?

The evaluation may help to deduct rape-specific EF and recommend balance periods that are adequate to assess direct N₂O emissions induced by rape cultivation.

Material and methods

Data collection and aggregation

For the collection of data on direct N₂O emission from oilseed rape cropping, we extracted all studies including N₂O

measurements in rape fields from the Stehfest & Bouwman (2006) dataset and extended this dataset by studies recently published in peer reviewed literature. Therefore, ISI-Web of science and Google Scholar were searched for the catchwords 'rape', 'canola', 'brassica napus' in combination with 'N₂O' and 'nitrous oxide'. Furthermore, data published in PhD thesis and data from extensive datasets that have been used for previous publications were considered. Authors were contacted to acquire selected datasets with a high temporal resolution: Potsdam (J. Kern, Leibniz Institute for Agricultural Engineering, Germany), Rostock (S. Leidel, University of Rostock, Germany) and Lincolnshire (J. Drewer, CEH Edinburgh, UK). All the studies were tested for several quality criteria: Only direct field measurement based N₂O flux data were included but no data obtained from generic process modeling. At least monthly measurements had to be performed. However, most of the considered studies (90%) were based on weekly or biweekly measurements.

To keep the dataset as consistent as possible only studies with winter oilseed rape were taken into account. To include the N₂O emissions during winter in the evaluation only studies with a minimum measurement period of 300 days were considered. In some studies (28% of the data points) the measurement frequency was reduced during winter.

To test soil and climate parameters as driving factors for N₂O emissions from soils, major site characteristics were extracted from the studies and grouped according to classes described in Stehfest & Bouwman (2006): Soils with pH values <5.5 were classified as low pH soils, >7.3 as high pH soils and those with pH from 5.5 to 7.3 as medium pH soils. For SOC concentration, the respective limits were 1% and 3%. The soil textures were assigned to the classes coarse, medium, and fine if they had less than 18% clay and more than 65% sand, less than 35% clay and less than 65% sand or more than 35% clay respectively. Where climate and weather data information were not sufficiently provided by the authors, data of the weather stations closest to the respective study sites were used from Germany's National Meteorological Service (DWD) or www.weatherbase.com to ascribe them to climate classes according to eco-climatic zones (IPCC, 2006).

Measures of N₂O emission

Cumulated N₂O emissions were recalculated where possible to start with the first nitrogen fertilizer application to the rape and stop with the first nitrogen fertilizer application to the successive crop. In 22% of the included measurement years, the rape has been fertilized in autumn. In these cases, the authors based the calculations of annual N₂O emissions on measurements in the balance period from this autumn fertilization until harvest. In 78% of the remaining measurement years the rape plots received the first nitrogen fertilization in spring, measurements started at that point and the balance period for annual N₂O emissions included the winter after rape harvest. If mean and annual N₂O emissions were not given in the study, they were calculated as the total N₂O that was emitted during the entire measurement period divided by the length of the measurement period or adjusted to 1 year, respectively. This was

done to produce a consistent set of N₂O emission data for comparison between studies with different lengths of measurement periods. Cumulated N₂O emissions were calculated if necessary by linear interpolation between measurement events.

Fertilizer related N₂O emissions (FRE in %) were calculated as the percentage of fertilizer N (in kg N ha⁻¹ yr⁻¹) that was lost as N₂O (in kg N₂O-N ha⁻¹ yr⁻¹). The background N₂O emissions of unfertilized plots were not accounted for. Thus, the FRE is an approximation of the fertilizer induced N₂O emissions. It serves for comparisons of different sites and fertilizer levels in our dataset but the comparison with the IPCC EF for managed soils is not directly possible. In the IPCC approach, also N inputs by crop residues or by mineralization are separately accounted for while in FRE the N₂O emissions are entirely referred to the only considered N input, the N fertilizer input.

For all sites with available yield data, the yield-scaled N₂O emissions were calculated as annual N₂O emissions divided by rape seed yield. The respective N surplus was calculated as N addition by fertilizer minus N withdrawn by harvested rapeseed. Where data regarding N contents of the rapeseeds and rape residues were missing, a dry matter content of 91% for seeds and 86% for straw and N concentrations of 22.5 kg N t⁻¹_{fresh} in the rapeseed and 7 kg N t⁻¹_{fresh} in the rape straw respectively was assumed (DüV, 2007). The ratio of seeds to straw dry mass was assumed to be 1 : 1.7 (DüV, 2007).

Complete data basis and subsets

In total, 36 studies with N₂O measurements in oilseed rape at 36 different sites were found, of which 12 studies with 18 measurement years (1 year measured at one site) fulfilled the quality criteria described above and were used for this meta-analysis (Table 1). Due to different fertilization levels and treatments that were not explicitly considered in this evaluation (crop rotation, tillage and compaction), a total of 43 data points with annual N₂O emissions could be obtained (Table S1 in Data S1). The Stehfest & Bouwman (2006) dataset was therefore increased by more than 200% with respect to winter oilseed rape-specific data that derived from measurements longer than 300 days.

This set of 43 data points (subset 1) was further reduced to subsets corresponding to the different research questions. For the comparison of N₂O emissions from rape to those from cereals the dataset was limited to studies with simultaneous measurements in winter oilseed rape and winter cereals at the same site (subset 2). Subset 2 included seven sites with 12 measurement years (31 and 46 data points for rape and cereals, respectively). The reference cereal crops were rye, wheat and barley, all cultivated as winter crops. In subset 3, those studies of subset 2 were compiled where annual N₂O emissions were divisible into N₂O emitted in the main growing season and N₂O emitted in postharvest autumn and winter (five sites, eight measurement years or 22 and 24 data points for rape and cereals, respectively).

All considered studies were conducted on mineral soils in the temperate climate zone and only mineral fertilizer was used with an application range from zero to 293 kg

Table 1 Site characteristics of included studies: MAP: mean annual precipitation, MAT: mean annual temperature, C_{org} : soil organic carbon concentration in topsoil

Site	Country	Latitude	Longitude	MAP (mm)	MAT (°C)	pH	C_{org} (%)	Clay (%)	Silt (%)	Sand (%)	Reference
Bandow	Germany	53.92	12.02	590	8.2	6.2	0.85	NA	NA	NA	(Schulz & Schumann, 2004)
Canstein	Germany	51.38	8.90	670	7.6	7.3	1.10	21	44	35	(Teepe <i>et al.</i> , 2000)
Chalons	France	48.95	2.42	629*	10*	8.1	1.67	31	41	28	(Henault <i>et al.</i> , 1998)
Gauna	Spain	42.82	-2.48	782*	11.4*	7.6	1.12	31.2	25.2	43.6	(Merino <i>et al.</i> , 2012)
Göttingen	Germany	51.53	9.98	634	8.7	7.5	1.60	3	60.4	36.6	(Schmädeke, 1998; Schmädeke <i>et al.</i> , 1998)
Grignon	France	48.90	1.90	646*	9*	8.2	1.80	25.7	66.6	7.7	(Jeuffroy <i>et al.</i> , 2013)
Lincolnshire	United Kingdom	53.32	-0.57	605	9.8	6.4	1.48	15	32	53	(Drewer <i>et al.</i> , 2012)
North Berwick	United Kingdom	56.05	-2.72	611	9.4*	6.5	1.90	NA	NA	NA	(Ball <i>et al.</i> , 1999)
Potsdam	Germany	52.42	12.98	595	8.6	6.0	0.90	6.2	61.2	32.6	(Kavdir <i>et al.</i> , 2008; Hellebrand <i>et al.</i> , 2010)
Rostock	Germany	54.08	12.10	593	8.1	6.5	0.85	NA	NA	NA	(Leidel, 2000; Leidel <i>et al.</i> , 2000)
Timmerlah	Germany	52.28	10.45	638	8.7	7.4	0.94	10	85	5	(Kaiser <i>et al.</i> , 1998)
Völkenrode	Germany	52.28	10.45	619	8.9	5.7	0.88	8	47	45	(Kohrs, 1999)

*At weather stations closest to the respective study sites, obtained from DWD (2014) and weatherbase (weatherbase, 2014). NA, not available.

$N \text{ ha}^{-1} \text{ yr}^{-1}$. Five of the studies included an unfertilized rape treatment. Different N-fertilizer rates were involved in 5 studies. The texture classes ranged from medium to coarse, the pH classes from medium to high and the SOC classes from low to medium. Yield information was available for 8 sites and a total of 12 measurement years. The main reason to exclude results on N_2O emission from rape from our evaluation was the insufficient length of measurement period.

Statistics

Prior to statistical evaluations, the N_2O emission data were log₁₀-transformed. This was done to enable comparisons with previous N_2O emission reviews and models that used log-transformed N_2O emission data (Stehfest & Bouwman, 2006; Rees *et al.*, 2013) and to achieve homoscedasticity of model residuals. The R software environment (version R-3.0.2, R core team, 2013) and in particular the lme4 (package version 1.1-6, Bates *et al.*, 2014) was used to fit linear mixed effects models for annual N_2O emissions of rape. The study site and year of measurement were included as random factors. While it was sufficient to include a random intercept for the factor 'site', a random intercept and slope for the factor 'year' resulted in the best model according to Akaike's information criterion (AIC). Nitrogen fertilization rate, soil parameter classes (pH, texture and SOC concentration), and climate parameter (precipitation and mean annual temperature) as well as the distinction between balance periods with winter emissions before and those after rape harvest were tested as fixed factors influencing the annual N_2O emissions. Additionally, the differentiation into N_2O emissions from rape or cereals was tested as fixed factor

for examining the crop-type effect on annual N_2O emissions. The respective best models were selected using the AIC.

Regarding evaluations of N_2O emissions in the period after harvest, linear mixed effects models were fitted with mean N_2O emission data of the period after harvest as related to mean annual N_2O emissions. Here, the interaction of site and measurement year was included as the only random effect. If emissions are assumed to be always positive, no intercept will occur here. The fit was therefore forced through the origin and the random effect was only influencing the slope of the model fit. Also for this model, fertilization rate and crop type were tested as additional fixed effects.

The 95% confidence intervals for the identified fixed effects were calculated and for the best fits R^2 were calculated as the quadratic correlation coefficient between modeled and measured log-transformed N_2O emissions.

A segmented linear model (Muggeo, 2003) was fit to describe the dependency of yield-scaled N_2O emissions (square-root transformed) on the N surplus data using R package segmented (Muggeo, 2008). Such models describe 'broken-line' relationships, which can occur due to a change in underlying processes. Because of the very limited data, the potential influence of sites was neglected for this and observations were assumed to be independent.

Results and discussion

Rape-specific N_2O emission

The annual N_2O emission of rape varied widely between study sites, N fertilizer rates and years

(0.3–5.7 kg N ha⁻¹ yr⁻¹) and FRE ranged between 0.2% and 5.1%. Despite this large variability in FRE, N-fertilization rate was detected as significant factor for the N₂O emission, when site and year were included as random effects in the mixed effects model (Fig. 1; Table 2). Most of the data's variability was explained by these random effects as illustrated by the large difference between the *R*²s of the complete best mixed effects model (*R*² = 0.92) and the one of the model without consideration of random effects (*R*² = 0.11). The strong influence of different sites on the rape-specific N₂O emission model is also illustrated by the span of colored lines that represent model predictions of the respective sites in Fig. 1a. As the respective depiction of the measurement years' random effect shows (Fig. 1b), the site's influence on N₂O emission and on the response to N fertilization greatly varies between years.

The model's fixed intercept indicates a mean emission of 0.82 kg N₂O-N ha⁻¹ yr⁻¹ for unfertilized rape fields. An annual fertilization of 100 kg N ha⁻¹ results in an additional, fertilizer induced N₂O emission of 0.54 kg N₂O-N ha⁻¹ yr⁻¹. Because of the exponential relationship, N₂O emissions increase fast with higher fertilization rates. For rape fields fertilized with 200 kg N ha⁻¹ yr⁻¹, the additional N₂O emission of 1.44 kg N₂O-N ha⁻¹ yr⁻¹ or a total of 2.26 kg N₂O-N ha⁻¹ yr⁻¹ is predicted by this model. Hence, N application rate as the most important management-related factor influencing N₂O emissions from cropland (Bouwman *et al.*,

2002) is in particular applicable for rape because of its typically high N-fertilization rates. While the IPCC EF does not change with N-fertilization rates, several studies have already shown that the response of N₂O emission to N addition follows an exponential trend (Kaiser & Ruser, 2000; Stehfest & Bouwman, 2006; Van Groenigen *et al.*, 2010). For maize grown in the temperate humid climate Grant *et al.* (2006) explained the observed nonlinearly increasing N₂O emissions with rising residual soil mineral N levels, indicating that N input was exceeding crop demand. This was in turn made responsible for the sharply increasing N₂O emissions.

As observed in several studies with different arable crops (Kim *et al.*, 2013; Rees *et al.*, 2013) the N₂O emissions from unfertilized plots were also substantial for rape in some of the studies in our dataset. The highest emissions of N₂O among the unfertilized rape fields were measured at the Timmerlah study site. Here, 3.2 kg N₂O-N ha⁻¹ yr⁻¹ were emitted in 1996, which was the third year after establishment of differently fertilized research plots (Heinemeyer *et al.*, 1998; Kaiser *et al.*, 1998). The respective emissions from the plot with 172 kg N ha⁻¹ yr⁻¹ fertilization at this site were 4.0 kg N₂O-N ha⁻¹ yr⁻¹. Kaiser *et al.* (1998) explained the high N₂O emissions from the treatment without fertilization with the soil's potential to provide N that was still high after many years of substantial fertilization. Correspondingly, the zero and reduced fertilization treatments

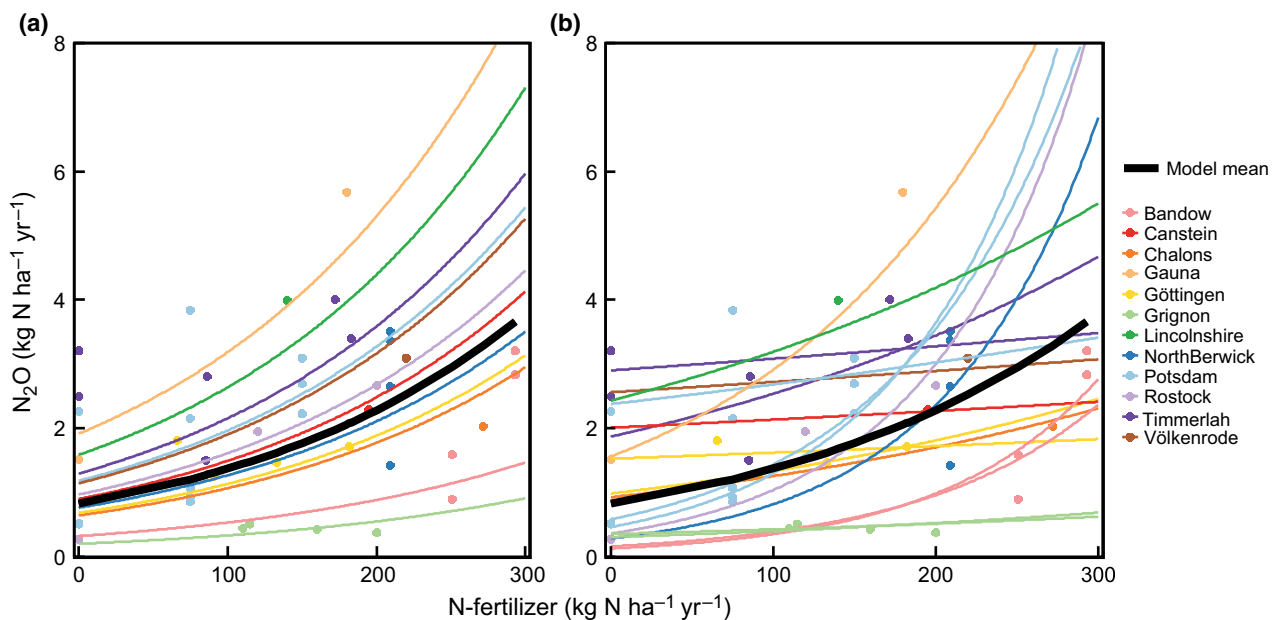


Fig. 1 Annual N₂O emissions of winter oilseed rape as related to N-fertilization rates of the different study sites and years of measurement included in subset 1; black solid line: fixed effect part of the best linear mixed effects model for this dataset; colored lines: site (a) and measurement years (b) specific variation in the model.

Table 2 Best linear mixed effects models for rape-specific annual N₂O emissions (N₂O_{annual} in kg N ha⁻¹ yr⁻¹), N₂O_{annual} of rape as compared to cereals and mean postharvest N₂O emissions (postharvest N₂O_{mean} in µg N m⁻² h⁻¹); the variance explained by the random effects, the residual variance and R² of the models with fixed effects only and R² of the complete models are given

	Coefficients (95% confidence interval)			Random effect		R ² fixed effects only	R ² complete model
	a	b	c	On intercept (variance)	On slope (variance)		
log ₁₀ (N ₂ O _{annual}) = a + b • N _{fert} + c • (crop == rape)							
Back-transformed to natural scale: N ₂ O _{annual} = 10 ^a • 10 ^(b•N_{fert}) • 10 ^c (crop == rape)							
Rape-specific model (subset 1)	-0.085 (-0.42 to 0.24)	0.0022 (0.00044-0.0038)	-	Site, year (0.09, 0.13)	Year (0.000004)	0.016	0.11
Rape-cereal model (subset 2)	-0.21 (-0.63 to 0.2)	0.0026 (0.0009-0.0043)	0.087 (0.026-0.15)	Site, year (0.07, 0.19)	Year (0.000004)	0.017	0.05
	Coefficients (95% confidence interval)						
	a	b		Random effect on slope (variance)	Residual variance	R ² fixed effects only	R ² complete model
Postharvest N ₂ O _{mean} = (a + b (crop == rape)) • annual N ₂ O _{mean}							
Postharvest model (subset 3)	0.85 (0.56-1.15)	0.24 (0.12-0.36)	Measurement year (22)	0.14	0.72	0.93	

showed relatively high soil nitrate contents. It is expected, that the differences in N₂O emissions and soil nitrate contents between the plots will increase after some more years without fertilizer application. It was apparent in Potsdam in 2002, when summer precipitation was high that wet soil conditions may cause high N₂O emission from fertilized as well as unfertilized plots. This further demonstrates the importance of inter-annual variability which may potentially superimpose the effect of additional driving variables.

It is well known that N₂O emissions exhibit a large variability due to interannual changes in climatic conditions (Rees *et al.*, 2013) and site-specific differences in soil and climate parameters (Jungkunst *et al.*, 2006; Flechard *et al.*, 2007). However, neither the inclusion of climate variables nor the consideration of soil parameter classes (pH, texture or SOC) as fixed effects improved the model performance in our study. This may be due to the limited data basis and the fact that there was too little variation in soil parameter classes or climatic conditions in the data. However, the dataset's narrow range of site conditions results from winter oilseed rape being cultivated under climatic and soil conditions that create favorable economic yield in competition to other crops so we believe we included the range of current potential conditions under which oilseed rape is grown. These specific conditions are also reflected by the site selection of the published studies.

At the site-level the relation of N₂O emissions with climate variables is more evident. Jeuffroy *et al.* (2013) showed that the generally low N₂O emissions from the Grignon site in France with different crop rotations including rape were a result of the low rainfall, especially after fertilization. At this generally low N₂O emitting site, no effect of the crop rotation or fertilization levels could be identified. Substantial differences between two different years' FRE from rape with the same tillage treatment in Bandow, Germany, were explained by climatic differences between the years (Schulz & Schumann, 2004). High precipitation with abrupt rewetting of the soil in summer and pronounced freeze-thaw cycles in winter resulted in up to 3.5 times higher N₂O emissions from rape in 2002/2003 as compared to the 2003/2004 cropping season.

Rape seed yield and N₂O emissions

Yield-scaled N₂O emissions from rape were also highly variable (0.09–53.3 kg N₂O-N Mg⁻¹_{dm}, with a median of 2.7 kg N₂O-N Mg⁻¹_{dm}). Not only N₂O emissions were very site specific but also the yield response to N fertilization is typically dependent on site parameters like the climatic yield potential and the soil's ability to supply additional N (Dobermann & Cassman, 2002).

However, the extreme value of 53.3 kg N₂O-N Mg⁻¹_{dm} at site Timmerlah in 1995 was excluded from further evaluation due to the unrealistic low yield (0.09 Mg_{dm}) at the unfertilized rape plot. Relating yield-scaled N₂O emissions to the N surplus as a measure for the N use efficiency showed that the risk of high yield-scaled N₂O emissions increased at N surplus values of 45 ± 24 kg N ha⁻¹ yr⁻¹ (Fig. 2). This is consistent with Van Groenigen *et al.* (2010) who showed that yield-scaled N₂O emissions rapidly increase beyond a certain threshold of N surplus. However, our results propose a lower threshold for rape than for the collection of different non-leguminous annual crops (90 kg N ha⁻¹ yr⁻¹; Van Groenigen *et al.*, 2010). Higher yields also imply larger amounts of N taken up by the plants (Dobermann & Cassman, 2004). As a consequence, soil mineral N available for N₂O production during the growing period decreases with increasing yields for a constant N-fertilization rate. Yield-scaled N₂O emissions did increase with increasing N surplus in the growing period but not in the postharvest period (data not shown) when other factors influence N₂O emissions to a greater extent. Van Groenigen *et al.* (2010) showed by means of data derived from measurements mainly in the growing season that yield-scaled N₂O emissions were negatively correlated with N use efficiency. Due to the particularly

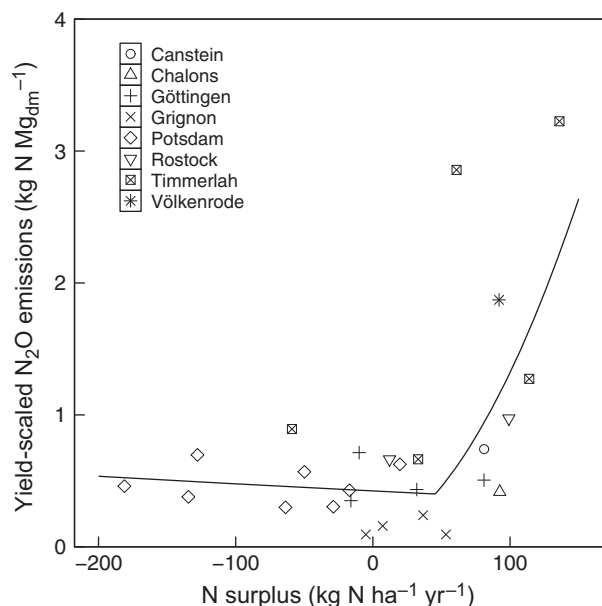


Fig. 2 Ratio of annual winter oilseed rape N₂O emission to rape yield in kg N₂O-N Mg⁻¹_{dm} as related to N surplus (N_{fertilizer} - N_{yield} in kg N ha⁻¹ yr⁻¹) of the different study sites (subset 1); not shown is the unfertilized oilseed rape plot in Timmerlah 1996 (53.3 kg N₂O-N dt⁻¹_{dm} where rape yield was only 0.06 dt_{dm}); the black line shows the segmented linear model.

high N-fertilization rates of oilseed rape and the low N use efficiency the fertilization management is a key issue to reduce RME GHG emissions. Thus, high N surplus during the growing period should be avoided by adjusting N-fertilization rates for the release of mineral N from decomposition of organic matter and by adapting the timing of N fertilization to the crop's demand.

Direct comparison of N₂O emissions of rape and cereals

We found significantly ($P < 0.01$) higher N₂O emissions from rape as compared to cereals (Fig. 3; Table 2) despite a reduced dataset of only 7 sites with simultaneous N₂O emission measurements from rape and cereals. The annual N₂O emissions of unfertilized rape predicted by this model for subset 2 (0.75 kg N₂O-N, 95% confidence interval ranging from 0.25 to 2.25 kg N₂O-N ha⁻¹ yr⁻¹) were in the same range as those predicted for unfertilized cereals (0.62 kg N₂O-N ha⁻¹ yr⁻¹, 95% confidence interval ranging from 0.24 to 1.72 kg N₂O-N ha⁻¹ yr⁻¹). A higher N fertilizer addition to rape has a particular influence on N₂O emissions due to the exponential relationship between fertilization and N₂O emissions. However, the differentiation by crop type was additive to fertilizer influence in our model and is therefore independent from the fertilization rate. Rape fields were predicted to emit 22% (95% confidence interval ranging: 6–41%) more N₂O-N than land cropped with cereals fertilized at the same rate as rape. At N fertilizer level of 100 kg N ha⁻¹ yr⁻¹ the absolute difference was 0.25 kg N₂O-N ha⁻¹ yr⁻¹ and due to the exponential shape of the model it increased to 0.46 kg N₂O-N ha⁻¹ yr⁻¹ at a fertilization level of 200 kg ha⁻¹ yr⁻¹. Hence, the reasons for this crop-specific difference are beyond N fertilizer rates and might originate from differences in postharvest N₂O emissions.

Depicting FREs (Fig. 4, median of all sites and years: 1.35% for cereals and 1.53% for rape, respectively), the difference between crops is not as apparent as from the model results but still visible. For the calculation of FREs, as for IPCC EF, a linear relationship between N₂O emissions and N fertilization is assumed which appears to be less appropriate than an exponential model. Also other controls of N₂O emission captured by the mixed effects models, especially the strong intersite and inter-annual variation, were neglected and confound the crop-specific evaluation of FREs.

Völkenrode in Northern Germany was the only site within subset 2, where N₂O emissions of the cereal plots exceeded those of the rape plot (Fig. 4). Even N₂O emissions from the unfertilized cereal plot were as high as those from rape that received 220 kg N ha⁻¹ yr⁻¹ (Kohrs, 1999). Because the measurement period of N₂O

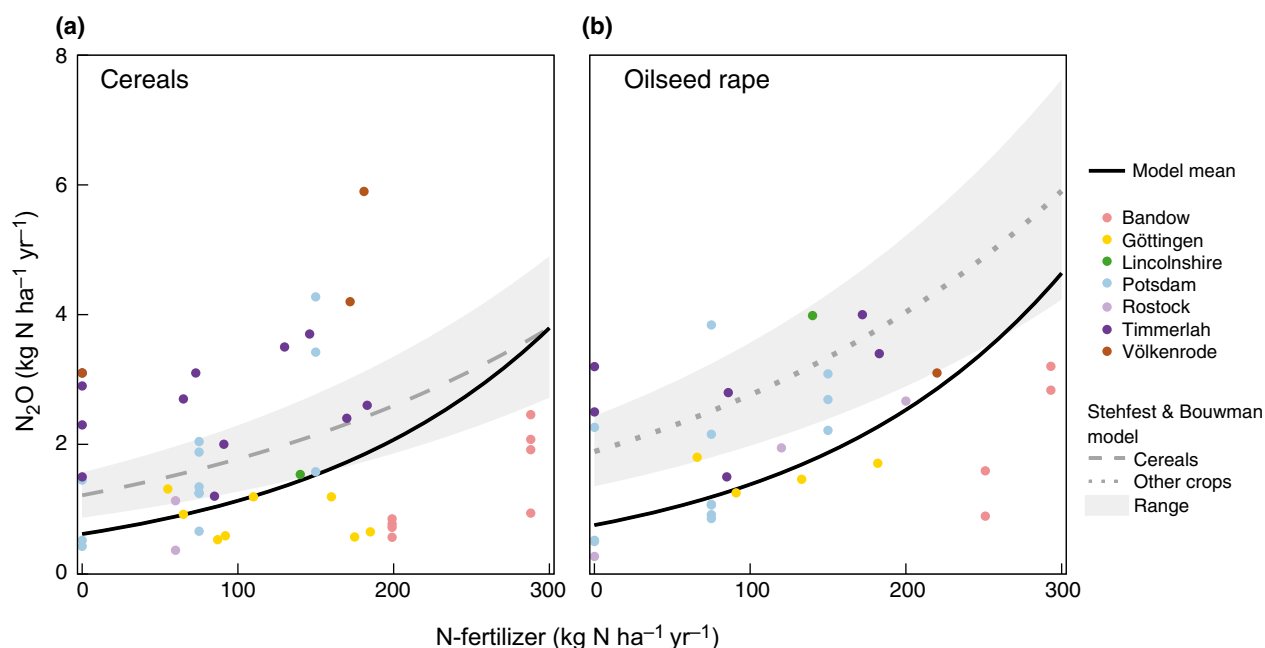


Fig. 3 Annual N_2O emission of cereals and oilseed rape as related to N-fertilization rates of the different study sites (subset 2); black solid lines: fixed effect part of the best linear mixed effects model for cereals and oilseed rape; dashed and dotted lines: models as calculated by Stehfest & Bouwman (2006) for the categories 'cereals' and 'other' with soil and climate parameters as represented in this dataset; shaded in gray: range from minimal to maximal 'cereals' and 'other' N_2O emission predicted by Stehfest & Bouwman (2006) models for this dataset.

emissions was from sowing to harvest at this site, the annual N_2O emissions of rape and wheat included winter N_2O emissions that were characterized by residues of the previous crops, winter wheat and sugar beet, respectively and the N uptake dynamics of young rape and wheat. However, the resulting difference in winter N_2O emissions from rape and wheat (Kaiser *et al.*, 1998) only partly explained the higher annual N_2O emissions of wheat at this research site with a long but varying history of fertilization studies.

Additionally tested fixed factors for soil properties or climate variables had no significant influence on the model performance possibly due to the small number of studies in this dataset. In the general N_2O emission model for agricultural fields from Stehfest & Bouwman (2006) that was fitted on a much more comprehensive data basis, all soil parameter classes were included as factors with significant influence.

Comparing our model to the Stehfest & Bouwman approach showed that our predictions for cereals are similar to the Stehfest & Bouwman prediction for N_2O emissions from cereal fields with soil properties as they are predominant in our dataset (Fig. 3). However, much higher N_2O emissions were predicted by the Stehfest & Bouwman (2006) model for 'other' crops which include rape as compared to our mean predicted N_2O emissions for rape. In addition to rape, also crops with high N_2O

emissions like vegetables (Dobbie *et al.*, 1999; Pfab *et al.*, 2011) and potatoes (Ruser *et al.*, 1998; Snowdon *et al.*, 2013), were grouped in the crop-type class 'other'. If only rape studies with a measurement length of more than 300 days in the Stehfest & Bouwman dataset are regarded, the median FRE turns out to be 1.58% which is very close to the median FRE of our dataset (1.53%). The classification of rape as 'other' crop should therefore be reconsidered. Nevertheless, the aggregation with cereals as it is done for GNOC (JRC, 2013) would lead to an underestimation of N_2O emissions from rape as shown by our direct comparison of N_2O emissions of rape and cereals.

Postharvest N_2O emissions

To identify the main periods with higher N_2O emissions from rape compared with cereals we partitioned the N_2O emissions into two periods, the growing season and the postharvest period. The postharvest N_2O emissions of rape (median of all sites and years: $21 \mu\text{g N m}^{-2} \text{h}^{-1}$) tended to be higher than N_2O emissions in the growing season (median of all sites and years: $18 \mu\text{g N m}^{-2} \text{h}^{-1}$). Regarding cereals, there is an opposite trend (median after harvest: $10 \mu\text{g N m}^{-2} \text{h}^{-1}$ and during the growing season: $16 \mu\text{g N m}^{-2} \text{h}^{-1}$). When substantial intersite and interyear variability is accounted for in the linear

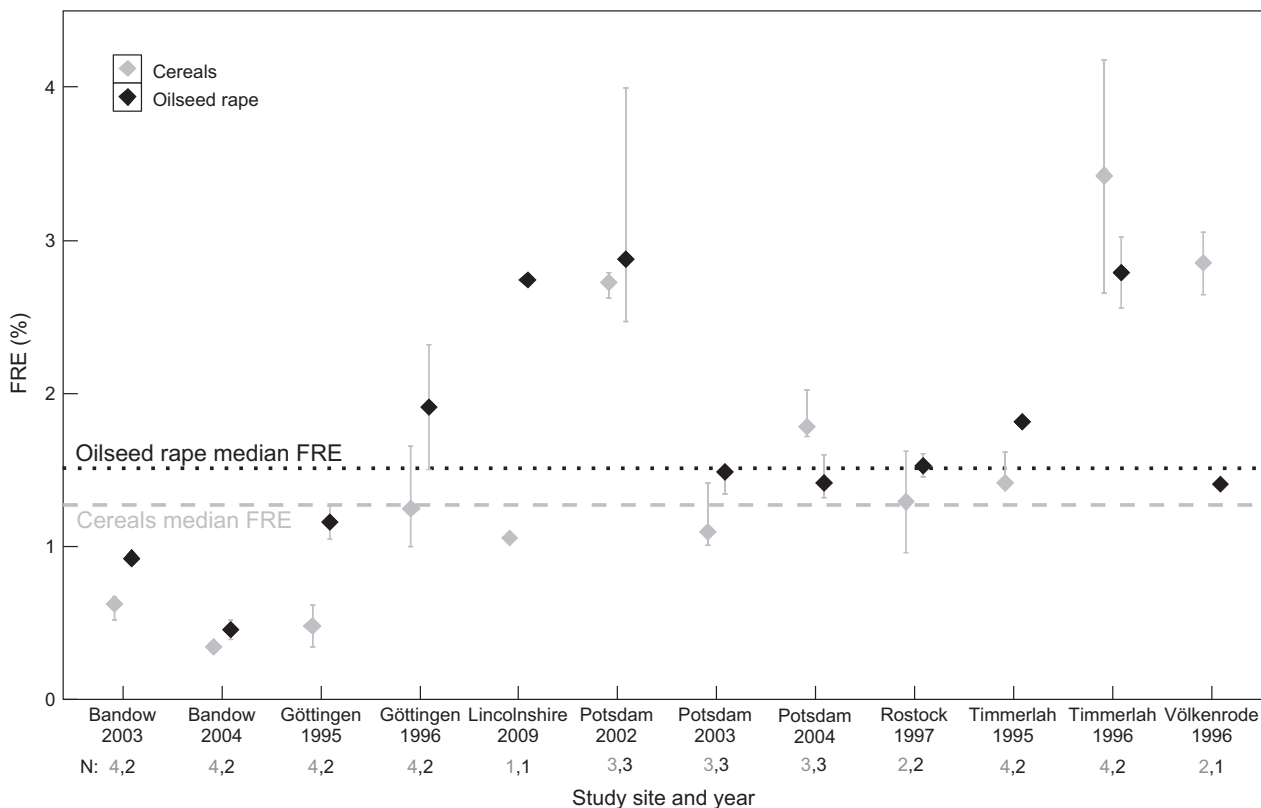


Fig. 4 Median \pm quartiles of winter cereal and winter oilseed rape fertilizer related N_2O emissions (FRE in %) at different study sites and in different years of measurement (subset 2); FRE: N_2O emission ($kg\ N_2O-N\ ha^{-1}\ yr^{-1}$) divided by nitrogen fertilizer application ($kg\ N\ ha^{-1}\ yr^{-1}$); N , numbers of observations are given for cereal in gray and oilseed rape in black below the x -axis; dashed and dotted lines: overall median FRE of all cereal and oilseed rape median FREs.

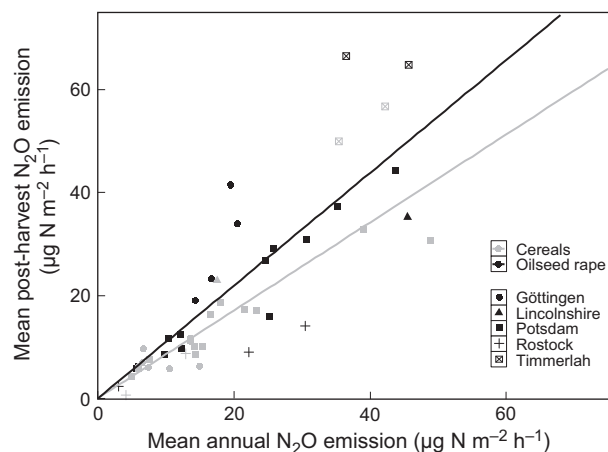


Fig. 5 Mean N_2O emission of oilseed rape and cereals in period after harvest in $\mu g\ N\ m^{-2}\ h^{-1}$ as related to the mean annual N_2O emissions; different symbols indicate different sites (subset 3); the lines represent the fixed effect part of the best linear mixed effects model for cereals (gray) and oilseed rape (black).

mixed effects model, the influence of crop type on the dependency of postharvest N_2O emission on mean annual N_2O emission was significant (Fig. 5; Table 2).

The direct impact of N fertilization on N_2O emissions is largest shortly after its application (Kaiser & Heinemeyer, 1996; Drewer *et al.*, 2012). The postharvest N_2O emissions of most crops were found to be rather residue-driven than dependent on N-fertilization rates (Kaiser *et al.*, 1998). However, the amount of crop residues and therefore the amount of N added to the soil with crop residues is influenced by the N fertilization (Trinsoutrot *et al.*, 2000). Consequentially, the influence of fertilization rate on the relationship of postharvest to annual N_2O emissions is negligible as our results showed. At the time of rape harvest, the direct influence of the N fertilizer rate on soil mineral N contents is negligible (Schmädeke *et al.*, 1998). However, differences in residual soil mineral N between crop types may exist (Beaudoin *et al.*, 2005; Gan *et al.*, 2012) due to different N uptake dynamics.

In Potsdam, rape yields were higher in the wetter year 2002 than in the dry year 2003. As a result, more N was added to the field as crop residues in 2002. Because the winter 2002/03 was also characterized by more freeze-thaw cycles than the winter 2003/04 (Kavdir *et al.*, 2008) more N_2O was emitted from the fields after rape cultivation in winter 2002/03 than in winter 2003/

04. Remarkably, the difference between postharvest N₂O emission between rape and cereal in Potsdam was also largest in 2002.

The differences in N contents and structure of crop residues from cereals and rape (Kaiser *et al.*, 1998), C : N ratios (Novoa & Tejeda, 2006) imply different degradability. The amount of mineral N that is available for N₂O production after harvest therefore differs greatly among these two crop types. The oxygen consumption during decomposition may lead to anoxic conditions that stimulate N₂O production via denitrification, underlining the importance of crop residue mineralization on N₂O production. Novoa & Tejeda (2006) showed in a meta-analysis of cropland N₂O emissions due to crop residues that the N content in crop residues significantly influenced N₂O emissions. Dry matter-to-N-content ratio and the C : N ratio of the crop residues were found to be good predictors for the postharvest N₂O emission (Kaiser *et al.*, 1998; Baggs *et al.*, 2000). Another good predictor for N₂O emissions from crop residues is the mineralizable N content in crop residues which accounted for up to 74% of the variance in N₂O emission from a sandy soil amended with different crop residues (Velthof *et al.*, 2002). However, the best predictor for winter N₂O emissions seems to be the nitrate content in topsoil during winter that described more than 90% of the variance of differently managed cropland soils (Ruser *et al.*, 2001). The combination of high amounts of N available for N₂O production with freeze-thaw events or high water contents induce particularly high emission peaks in winter (Flessa *et al.*, 1995; Kaiser & Ruser, 2000). Nevertheless, soil mineral N appears to be the driving factor for the observed difference between crop types.

If measurements shorter than 300 days were included in the consideration of the relation of postharvest to annual N₂O emissions, the variation became wider (data not shown). The tendency to extreme values for those datasets that include only a short time after harvest (Henault *et al.*, 1998; Ball *et al.*, 1999; Pennock & Corre, 2001) may arise from potentially missed or over proportionally accounted for N₂O emission peaks such as those in the freeze-thaw periods and shortly after harvest. This particularly illustrates the risk of under- or overestimation by short-term emission measurements and emphasizes the need of frequent measurements for at least one entire year.

Effects of agricultural management on rape N₂O emissions

Timing of fertilization and N uptake of the different crops play an important role regarding the differences in N₂O emission dynamics between crop rotations and different managements. In general timing and amount of N fertilization should match crop N demand and

take into account net release of mineral N from decomposition of organic matter. Even though rape has the ability to take up relatively high amounts of N in autumn (Barraclough, 1989), yield effects of autumn fertilization could not be affirmed reviewing winter oilseed rape studies (Sieling & Kage, 2010). The results suggest that applying the first N fertilization to winter oilseed rape in spring should be preferred with respect to efficient fertilizer use and reduced N₂O emissions. Rape that was sown in August took up more N as compared to rape sown in September (Henke *et al.*, 2009), indicating that the nitrate content during winter may also be reduced by early sowing. This, however, refers to the winter before rape harvest. As the timing of sowing is generally determined by the harvest of the previous crop, the selection of entire crop rotations needs to be considered in the discussion on soil mineral N during winter.

The most critical period with respect to N₂O emissions from rape is the autumn and winter after harvest (see above). Due to its effects on mineralization and denitrification, the management of crop residues can influence postharvest N₂O emissions (Malhi *et al.*, 2006). As discussed above, the incorporation of crop residues with high N contents increases soil nitrate concentrations and N₂O emissions (Kaiser *et al.*, 1998; Baggs *et al.*, 2000; Velthof *et al.*, 2002). However, removing rape residues after harvest cannot be recommended as measure to reduce N₂O emissions because the production of N-rich litter starts already before harvest (i.e., fall of leaves), no alternative economically sound utilization of rape straw is established, and from the perspective of N use efficiency residue N of rape should be efficiently recycled via uptake by the following crop. Management options to reduce the risk of high N₂O emissions and nitrate leaching after rape should instead target an efficient and complete use of residual N in the crop rotation. Increased soil mineral N contents after rape emphasizes the relevance of rape for the N supply of the successive crop (Shepherd & Sylvesterbradley, 1996) and its function in crop rotations. At the same time, it indicates the particular risk of high N losses during winter after rape cultivation. To minimize N₂O emissions after rape the soil mineral N has to be reduced as fast as possible. It is essential that the remaining plant available N pool is accounted for in fertilization of the successive crop (DüV, 2007).

Henke *et al.* (2008) suggested noncruciferous catch crops in combination with reduced tillage to minimize nitrate leaching after rape. Also volunteer rape reduced soil mineral N during autumn to a similar extent (Henke *et al.*, 2008). Hence, it may help to save N for the following main crop and to reduce postharvest N₂O emissions. However, winter catch crops can only be integrated in rotations if rape is followed by a summer

crop. Adequate measures to reduce soil mineral N after rape always needs to be designed and optimized in the respective crop rotation. The role of entire crop rotations not only has to be considered in fertilization planning but also need to be enhanced in N₂O emission accounting, especially regarding crops like rape that have longer term impacts on N supply.

Conclusions

Direct annual and especially postharvest N₂O emissions of winter oilseed rape are higher than those of cereals. This holds also true at same N fertilizer rates. Yet, the classification of rape as 'other' crop in the Stehfest & Bouwman model is not appropriate because it overestimates N₂O emissions from rape. We propose that N₂O emissions from rape should be assessed separately. Our rape-specific N₂O emission model predicts annual emissions of 2.26 kg N₂O-N ha⁻¹ yr⁻¹ at a common fertilizer rate of 200 kg N ha⁻¹ yr⁻¹. Particularly high postharvest N₂O emissions suggest that reducing mineral N contents in autumn and winter is an effective measure to reduce total N₂O emissions from rape. Including the winter after harvest in the balance period for N₂O emissions is crucial. Consideration of entire crop rotations would result in even more accurate assessments of rape's impact on N dynamics and greenhouse gas emissions. For a holistic evaluation of GHG savings by the use of RME, also indirect emissions need to be considered. However, the allocation of direct and indirect GHG emissions to different crops within a rotation remains a big scientific challenge. For example savings of N fertilizer or higher yields in crops after rape have to be accredited to rape. The growing demand for biofuels highlights the need for assessing thorough GHG balances and due to its high global warming potential good estimates of N₂O emissions in particular. Our study finding casts further doubt on the benefits of RME with regard to GHG savings, as N₂O emissions during rape production turned out to be particularly high.

Acknowledgements

The work presented in this study was funded by the German Federal Ministry of Food and Agriculture (FNR Grant 22403212) and the German Federal Ministry of Education and Research (BMBF), and is part of the BEST Research Framework (<http://www.best-forschung.de>).

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1. Site information (site) and study parameters (study) of the studies used in the meta-analysis; data of subset 1, subset 2 and subset 3; legend for all supplementary data tables.