Biogeosciences Discuss., 9, 9289–9314, 2012
www.biogeosciences-discuss.net/9/9289/2012/
doi:10.5194/bgd-9-9289-2012

Biogeosciences Discussions

Nitrous oxide emissions from crop rotations including wheat, rapeseed and dry pea

M. H. Jeuffroy[1,2], E. Baranger[1,2], B. Carrouée[3], E. de Chezelles[1,2], M. Gosme[1,2], C. Hénault[4], A. Schneider[3], and P. Cellier[5,6]

[1]INRA, UMR211, bâtiment EGER, 78850 Thiverval-Grignon, France
[2]AgroParisTech, bâtiment EGER, 78850 Thiverval-Grignon, France
[3]UNIP, 11 rue Monceau, CS 60003, 75 378 Paris Cedex 08, France
[4]INRA, Unité de Science du Sol, 2163 Avenue de la Pomme de Pin, CS 40001 Ardon, 45075 Orléans Cédex 2, France
[5]INRA, UMR1091 Environnement et Grandes Cultures, 78850 Thiverval-Grignon, France
[6]AgroParisTech, UMR Environnement et Grandes Cultures 78850 Thiverval-Grignon, France

Received: 1 July 2012 – Accepted: 3 July 2012 – Published: 27 July 2012

Correspondence to: M. H. Jeuffroy (jeuffroy@grignon.inra.fr) and
P. Cellier (cellier@grignon.inra.fr)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Approximately 65 % of anthropogenic emissions of N_2O, a potent greenhouse gas, originate from soils at global scale, and particularly after N fertilisation of the main crops in Europe. Thanks to their capacity to fix atmospheric N_2 through biological fixation, legumes allow to reduce N fertilizer use, and possibly N_2O emission. Nevertheless, the decomposition of crop organic matter during the crop cycle and during the residue decomposition, and possibly the N fixation process itself, could lead to N_2O emissions. The objective of this study was to quantify N_2O emissions from a dry pea crop (*Pisum sativum*, harvested at maturity) and from the subsequent crops in comparison with N_2O emissions from wheat and oilseed-rape crops, fertilized or not, in various rotations. A field experiment was conducted during 4 consecutive years, aiming at comparing the emissions during the pea crop, in comparison with those during the wheat (fertilized or not) or oilseed rape crops, and after the pea crop, in comparison with other preceding crops. N_2O fluxes were measured using static chambers. In spite of low N_2O fluxes, mainly linked with the site soil characteristics, fluxes during the crop were significantly lower for pea and unfertilized wheat than for fertilized wheat and oilseed rape. The effect of the preceding crop was not significant, while soil mineral N at harvest was higher after pea. These results, combined with the emission reduction allowed by the production and transport of the N fertiliser not applied on the pea crop, should be confirmed in a larger range of soil types. Nevertheless, they demonstrate the absence of N_2O emission linked to the symbiotic N fixation process, and allow us to estimate the decrease of N_2O emissions to 20–25 % by including one pea crop in a three-year rotation. At a larger scale, this reduction of GHG emissions at field level has to be cumulated with the reduction of GHG emissions linked with the lower level of production and transport of the N fertiliser not applied on the pea crop.

BGD

9, 9289–9314, 2012

1 Introduction

N_2O is a potent greenhouse gas (GHG), which accounts for 6 % of the total anthropogenic radiative forcing (IPCC, 2007). It is also one of the main compounds involved in the ozone layer degradation (Crutzen and Ehhalt, 1977). Its concentration increased regularly since the end of the 19th century with more rapid increase in the second half of the 20th century (see e.g. IPCC, 2007; Davidson, 2009). It is widely admitted that microbial production in soils by both nitrification and denitrification is the dominant nitrous oxide source (Firestone and Davidson, 1989), with contribution of these two processes to N_2O emissions varying with climate, soil conditions and soil management (Hénault et al., 1998; Skiba and Smith, 2000). Since the end of the 19th century, the increased use of nitrogen for food and feed production, as both synthetic fertilizer and organic manure, increased the N_2O emission. At present, approximately 65 % of anthropogenic emissions of N_2O originate from soils at global scale (Smith, 2004) or Europe (Leip et al., 2011). But these estimates are still very uncertain and the N_2O emissions are considered as the most uncertain estimate within the main direct GHG. This is mainly due to large uncertainties in emission factors and this is still under debate (see e.g. Crutzen et al., 2008; Davidson, 2009). Since the agricultural sector contributes for more than 20 % of French GHG emissions in 2008 (13.5 % of the global GHG emissions, of which 75 % in the developed countries) and since N_2O represents more than 50 % of the GHG emitted by the agriculture (and 12 % of the French part of the GWP, global warming potential), the alternative practices to decrease N_2O emissions represent key levers to mitigate climatic change. As N_2O emissions generally increase with N-fertilisation, as proposed in the IPCC method, crops that do not require N fertilisation appear as a possible solution to limit N_2O emissions. Legumes, thanks to their capacity to fix atmospheric N_2 through biological nitrogen fixation (BNF), allow a reduction of N fertilizer use, both on the legume crop and on the following crop as soil mineral N availability is higher during the following year (Jensen and Hauggaard-Nielsen, 2003). Using legume crops as a source of nitrogen has thus been envisaged

BGD
9, 9289–9314, 2012

as a solution for decreasing N_2O emissions, but it is still under debate. As a matter of fact, legume crops could produce N_2O by different pathways: during the biological N_2 fixation itself, by decomposition of crop organic matter (esp. fine roots or root exudates), or when legume residues are returned to the soil (Zhong et al., 2009). While the two latter might be a N_2O source, as legume residues have larger N contents than cereal residues (but in lower amounts), the BNF pathway seems less certain. Whereas denitrification is known to occur in legume root nodules, the magnitude of this process and its contribution to soil N_2O emissions could be low compared to the N_2O production by the soil microbial biomass. Hénault and Revellin (2011) showed that N_2O could even be consumed in legume nodules. Under field conditions large emissions were observed over some legumes crops: Duxbury et al. (1982) had reported relatively high cumulative fluxes of 2.3 and 4.2 $\mathrm{kg\,N\,ha^{-1}\,yr^{-1}}$ for an alfalfa field. In contrast, Velthof and Oenema (1997) estimated N_2O–N emissions from grass-clover canopy to vary between 0 and 1 % of biologically-fixed N_2, probably lower than from an equivalent amount of N fertilizer because the biologically-fixed N is released slowly into the soil. More recently, Rochette and Janzen (2005) made a synthesis of published studies on N_2O emissions from legume crops, and concluded that "much of the increase in soil N_2O emissions in legume crops may be attributable to the N release from root exudates during the growing season and from decomposition of crop residues after harvest, rather than from Biological Nitrogen Fixation per se". This led them to propose not to account for N_2O emission from N_2 fixation in legume crops, but only from N residue decomposition after the crop. However, this was based mostly on results from soybean, grass-legume/clover and alfalfa (Stehfest and Bouwman, 2006) and there are very few references on European annual arable grain legumes cultivated in the Europe climatic conditions and harvested at maturity (most of the nitrogen being allocated to seeds and not to straws). For example, values for annual legume crops such as pea resulted from one single reference (Lemke et al., 2007). Moreover, these values were never compared to emissions from other non-leguminous crops, grown in the same conditions, while it is known that N_2O fluxes are highly sensitive to weather and

BGD
9, 9289–9314, 2012

soil conditions (Philibert et al., 2012). Thus, it is difficult to compare the values of N_2O emissions from legumes, synthesized by Rochette and Janzen (2005), with values from fertilized crops, from other experiments, and to conclude to the increase or decrease in N_2O emissions when legumes are grown instead of fertilized crops. Consequently, more references are needed on emissions from annual legume crops as a component of crop rotations in cropping systems.

The objective of this study was to quantify N_2O emissions from a pea crop and from the subsequent crops in comparison with N_2O emissions from wheat and oilseed-rape crops, fertilized or not, in various rotations. Our approach was to analyse the different crop stages where N_2O emissions may arise from N_2 fixation, i.e. during and after the legume crop in a crop rotation. We assessed whether the N_2O emissions during a dry pea crop were similar to a non-fertilized crop, and whether the N_2O emissions in autumn following a dry pea crop were higher than following a wheat crop or an oilseed rape crop. Finally, we estimated to what extent it was interesting to include a legume crop in a crop rotation.

2 Material and methods

2.1 Experimental site

A field trial was conducted at INRA Grignon experimental unit (Paris Basin, 48.9° N, 1.9° E) from 2007 to 2010, combining the comparison of several crops during each year, and the comparison of the effect of several preceding crops on the current crop. The focus was on the pea crop in order to estimate N_2O emissions during the crop cycle and during the subsequent period (residue decomposition before sowing of the next crop and during the subsequent crop cycle). The trial was set up over a 0.19 ha experimental field divided in three blocks, with each treatment having one replicate in each block. The soil was a clay loam with 25.7 % clay, 66.6 % loam and 7.7 % sand,

BGD
9, 9289–9314, 2012

$1.29\,g\,kg^{-1}$ total N and $18\,g\,kg^{-1}$ organic C. Weather data were available at a meteorological station nearby the field.

2.2 Treatments

Eight different rotations were set up in the field to obtain different combinations of three crops (pea, wheat and oilseed rape) with their preceding crops (Table 1) in order to analyse the different effects of the pea crop during its cycle or during the next crop. A winter wheat crop (cv. Isengrain, 250 seeds m^{-2}) was grown after wheat, pea or oilseed rape; a winter oilseed rape (cv. Mendel, 52 seeds m^{-2}) crop was grown after wheat or pea; a winter pea crop (cv. Cartouche, 92 seeds m^{-2}) was always grown after wheat. Each rotation was repeated three times and randomized in a complete 3-block design. Each plot area was 60 m^2. The rape and the wheat crops were either fertilised at the optimum (using recommended decision support tools) or not fertilized. The pea crop was not fertilised. The sowing dates as well as the dates and amounts of fertiliser application are given in Table 2. The non-fertilized areas were always at the same place from year to year. Crops were fully protected against weeds and pests by chemical treatments, to prevent growth limitation due to these factors. Each year, crop residues were incorporated and a 20 cm deep ploughing was done before each sowing.

Due to practical limitations, it was not possible to measure N_2O emissions on all plots every year. Consequently, measurements were made on fertilized wheat (W), fertilized oilseed rape (R), non-fertilized wheat (W0N) and pea (P) on selected rotations in order to take samples over the different crops with the preceding crop including pea or not. The plots on which N_2O measurements were made are indicated in Table 1.

2.3 Measurements

N_2O fluxes were measured using the static closed chamber technique (Hutchinson and Livingston, 1993). Two chambers were set up on each of the three replicates per treatment, i.e. six chambers per treatment in total. The bases of the chamber were installed

BGD
9, 9289–9314, 2012

at the beginning of the crop cycle, over several seeded rows, and were inserted about 5 cm into the soil. They remained in place during the whole crop cycle. Care was taken to disturb the soil as little as possible during the installation process. Their internal area was 0.185 m^2. Their internal volume was determined by measuring the height above ground of the chambers. It was in average 40 dm^3 at the beginning of the cycle. When the crop grew, a 60 cm high extension was added to avoid any damage of the plants. The volume of the chambers increased to approximately 170 dm^3 afterwards. Measurements were performed approximately twice a month, and the frequency was increased to twice a week during the two weeks following fertilizer application. At each date of measurement, all the treatments were measured, whether they received N fertilizer or not. For each chamber, the air was sampled in a pre-evacuated 10 ml vial at the closure of the chamber, and 45 min, 90 min and 135 min afterwards. After sampling, the tubes were analysed in the lab by using a gas chromatograph with an electron-capture detector (Model 3400 Cx, Varian, Walnut Creek, USA). On the same days, the soil was sampled in the upper soil layer by taking three soil cores in the 0–30 cm layer using an auger in each treatment. The soil samples were mixed together and analysed in order to determine the mineral nitrogen content and the soil water content. Soil inorganic N was determined in a KCl extract with a Skalar Autonalyser, using copper reduction and the Griess-Ilosvay reaction for nitrate and the indophenol method for ammonium. Soil water content was determined by weighing before and after oven drying during 48 h at 105 °C. Measurements occurred during the crop cycle in spring (from the end of winter in February until harvest) in 2008 (14 dates of measurement), 2009 (20 dates) and 2010 (18 dates), and during the autumn (from September until December) in 2008 (8 dates of measurements), 2009 (8 dates) and 2010 (5 dates).

At harvest, the amount of N in the crop residues was measured. Three micro-plots (0.35 m^2 each for wheat, 0.875 m^2 for pea, and 1 m^2 for oilseed rape) per block and per treatment were sampled. Vegetative parts and grains were separated just after sampling and subsequently weighted after oven-drying (48 h, 80 °C). Vegetative organs were then ground and N content was determined with the Dumas method. This involves

BGD
9, 9289–9314, 2012

the combustion of dehydrated and ground plant tissue at about 1800 °C, reduction of nitrogen oxides by reduced Cu at 600 °C and analysis of N_2 by catharometry (NA 1500 analyser, Fisons Instruments).

After harvest, soil mineral N content was measured. Three soil cores of each of the three layers (0–30 cm, 30–60 cm, 60–90 cm) per block and per treatment were mixed in order to get one sample per layer. Soil inorganic N content was determined in a KCl extract with an autoanalyser (Skalar).

2.4 Statistical analysis

Mixed models were fitted to the data in order to analyse the effects of the crop, and the preceding crops (considered as fixed effects), and taking into account the effects of block and date of measurement (considered as random effects). As nitrogen fertilizer application may interfere with N_2O emission, the crop cycle was divided into 3 periods: (i) before the first N application of the season (before Napp) including the autumn dates of measurement, (ii) more than 14 days after the last N fertilizer application (after Napp), and (iii) between these two dates (following Napp). The same period distinction was applied for all crops during each cropping season. The period was included in the mixed model as a fixed effect, as well as the two-way interactions between period and respectively crop and preceding crop. Each effect was tested by comparing the same models with and without the considered effect with a likelihood ratio test. In the case of significant interactions, a new factor was created by taking the combination of the two interacting factors (e.g. crop_period). When the effect was not significant, it was suppressed from the model. In the case of significant effects, multiple comparisons with Tukey contrasts were performed in order to compare the treatments.

In order to study the effect of crop residues in more detail, a further analysis was conducted on the mean N_2O emissions during autumn (from the beginning of September until the end of December) for each year, because we assumed that during this period, the effect of the current crop had not appeared yet, and that the N_2O emissions

BGD
9, 9289–9314, 2012
Nitrous oxide emissions from crop rotations
M. H. Jeuffroy et al.

linked with the crop mainly resulted from residues decomposition. The preceding crop was considered as a fixed effect and the year and block as random effects.

We also analysed the effect of the crop, and the preceding crop on the soil mineral nitrogen content measured after harvest, and on the amount of N present in the crop residues at harvest, as both variables represent sources of N_2O emission which must be considered according to the IPCC guidelines (IPCC, 2006). The same approach was taken, starting from a model including crop and preceding crop as fixed effects, and year and block as random effects, on the amount of nitrogen contained in the crop residues remaining on the ground after harvest, or on the amount of soil mineral nitrogen content measured at harvest.

All analyses were performed using R statistical software, with packages *lme4* (Bates and Maechler, 2009) for the mixed models and *multcomp* (Hothorn et al., 2008) for the multiple comparison tests. The assumptions of the linear mixed model were checked by visual examination of the plot of residuals against predicted values and *qqplots* for the residuals and the random effects.

3 Results

3.1 Measured N_2O fluxes

N_2O emissions measured during the four cropping seasons on the four crops are presented in Fig. 1 for both the autumn and spring periods. The measured fluxes were relatively low, ranging between −4 and 10 g ha^{-1} day^{-1} with negative fluxes at several periods. They show a high variability of N_2O emissions on fertilized wheat and rape along the crop cycle. Despite low values, significant differences can be observed between crops, with fertilised wheat and rapeseed having larger fluxes than unfertilized wheat and the pea crop, especially after fertilizer application. The maximum fluxes were not always observed just after fertilizer application, but sometimes 2–3 weeks

BGD
9, 9289–9314, 2012

after. N_2O emission during autumn was even lower, around ±1 g ha^{-1} day^{-1}. The same trends were observed during the three years.

3.2 Effect of crops and preceding crops on N_2O emissions

The comparison of the mixed models for N_2O emissions showed significant date and block random effects ($p < 0.001$ and $p = 0.008$ respectively). The interaction between preceding crop and period of measurement was not significant ($p = 0.8$) and was thus suppressed from the model. The interaction crop x period was highly significant ($p < 0.001$), indicating that N_2O emissions varied along the crop cycle differently according to the crop. Consequently the analysis was carried out on the combinations of crop x period (i.e. on a new variable crop_period). The results then showed that there was no effect of the preceding crop ($p = 0.48$) but a highly significant crop_period effect ($p < 0.001$). The multiple comparison tests showed that for the fertilized crops, emissions were higher after N fertilisation than before, with intermediate values during the period of N application (Fig. 2). For non-fertilized crops (W0N and P), emissions were not significantly different among the three periods.

As preceding crop had no significant effect, mean daily fluxes were calculated for each crop, during the two complete cropping seasons, 2008–2009 and 2009–2010, whatever the preceding crop. Average values were 0.91 g ha^{-1} day^{-1} and 1.77 g ha^{-1} day^{-1} for wheat, 1.09 g ha^{-1} day^{-1} and 1.30 g ha^{-1} day^{-1} for rape, 0.37 g ha^{-1} day^{-1} and 0.38 g ha^{-1} day^{-1} for pea, 0.14 g ha^{-1} day^{-1} and 0.57 g ha^{-1} day^{-1} for non-fertilized wheat, during 2008–2009 and 2009–2010 respectively.

3.3 Effects of crop residues on N_2O emissions during autumn

When the mean N_2O emissions during autumn of each year were analysed separately, there was a significant (random) year effect ($p < 0.001$) but no significant effect of block ($p = 0.38$). There was also no significant effect of the type of residues (i.e. preceding

BGD
9, 9289–9314, 2012

crop) ($p = 0.49$). Figure 3 shows the mean emissions during autumn for the different preceding crops and years.

3.4 Soil mineral N content after harvest

Figure 4 shows the mineral N content in soil after harvest of each crop during each year. Values highly varied according to the crop and, to a lesser extent, according to the year. The comparison of the mixed models showed a significant effect of the year ($p = 0.035$) but no block effect ($p = 1$). There was no effect of the preceding crop ($p = 0.17$) but a highly significant effect of the crop ($p < 0.0001$). The multiple comparisons showed that soil mineral content after harvest was lower for oilseed rape and non-fertilized wheat than for fertilized wheat and pea (Fig. 4), both being non significantly different.

3.5 N content in crop residues at harvest

The N contents in crop residues at harvest highly varied according to the year and the crop. The comparison of the mixed models showed significant year and block effects ($p < 0.0001$ and $p = 0.0023$, respectively). There was a significant effect of the preceding crop ($p = 0.003$) as well as a significant effect of the crop ($p < 0.0001$; Fig. 5). The multiple comparisons showed that the crop effect was only due to the difference between the residues of unfertilized wheat and oilseed rape vs. pea, fertilized wheat and oilseed rape, and the effect of the preceding crop is only visible through the significant difference between unfertilized wheat after unfertilized wheat and unfertilized wheat after pea (Fig. 5).

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

BGD

9, 9289–9314, 2012

Nitrous oxide emissions from crop rotations

M. H. Jeuffroy et al.

4 Discussion

4.1 N_2O emissions for the different crops in the crop rotations

As a whole, N_2O emissions were low for all crops on the Grignon site, with background emission lower than 1 g ha^{-1} day^{-1} and averages after fertilization between 2 and 3 g ha^{-1} day^{-1}. Most values were below 10 g ha^{-1} day^{-1}. Consequently, the total emissions over the crop cycle were relatively low, with low variability between years (Fig. 1). Loubet et al. (2011) and Laville et al. (2011) observed similar fluxes over a nearby site with similar soil conditions and agricultural practices, using automated chambers with continuous measurements (16 values per day). However, they also observed much larger fluxes under three circumstances: in summer 2007 after barley harvest and residues incorporation, in December 2007 after a low temperature period, and in May 2008 after N application over maize. In the first case, the summer was cooler than the average but much wetter, which certainly favoured N_2O emission from residues decomposition. Large emission in May 2008 was linked to the conjunction of large N inputs for maize fertilization (130 kg N ha^{-1} as ammonium nitrate following 107 kg N ha^{-1} as slurry), high temperature (monthly average almost 2 °C above the average) and larger rainfall than the average. This was not observed on our plots because of limited N availability due to low inputs at this period (Table 2). But the main reason for the low emissions observed during the 3 yr could be the low rainfall which occurred all along the year (458, 388 and 406 mm during the cropping period, from October until June, respectively in 2008, 2009 and 2010) and especially during the period of fertilizer application in 2009 and 2010, where rainfall was much lower (71 and 48 mm respectively) than the average over this site (89 mm), with only 4 days with rainfall larger than 2 mm day^{-1} in 2009 (max = 6.2 mm day^{-1}) and 2010 (max = 3.5 mm day^{-1}). The last reason might be that, due to their low measurement frequency (two measurements per week or per month), manual chamber did not succeeded in catching up the N_2O emission pulses which contributes significantly to the annual emissions. For instance, Parkin (2008) estimated that sampling at time intervals larger than one week could lead to underestimate cumulated fluxes by approx. 30 %, while Smith and Dobbie (2001) and Laville et al. (2011) estimated that the bias was less than 15 %.

As expected, a clear effect of fertilization was observed, with emissions five to tenfold larger than background emissions (Fig. 2). However a surprising feature was that emissions were larger after two weeks after N application. Once again, this might be attributed to the relatively dry conditions. Le Cadre (2004) observed that pellet dissolution, which is necessary to make N available to the soil, and thus to nitrification or denitrification, may take more than 10 days under dry soil conditions. Moreover soil microorganisms might have a low activity in the top soil layers under such situations.

Despite such low fluxes, significant differences were observed both between crops and between periods, as related to fertilization events (Fig. 2) for the three years of the experiments (data not shown). The robustness of this observation was strengthened by the experimental protocol organized in blocks and the methods used for statistical analysis. It can then be considered that, even if the cumulated fluxes are biased, due to low observation frequency, the relative differences and hence the effects, can be considered with confidence.

On the opposite, no effect of the preceding crop was observed on N_2O fluxes, either on the whole crop cycle, or during the shorter period of autumn. This result was observed each of the three years. It brings new elements against the hypothesis that N_2O emissions in legumes should mainly be linked with the decomposition of their residues after harvest (Rochette and Janzen, 2005). It is consistent with previous results from Lemke et al. (2002), who did not find significantly higher N_2O emissions after a pea crop than after a wheat crop. Our result is also consistent with the observations on the possible sources of nitrogen for N_2O emissions: soil mineral nitrogen after harvest was not higher after pea than after wheat, and N in crop residues was not significantly different between pea and fertilized rape and wheat. In contrast, Hauggaard-Nielsen et al. (2003) found a significantly higher N amount in pea straw than in barley straw. More data should be gathered to confirm this result.

BGD
9, 9289–9314, 2012

Concerning the amount of N in pea residues, it has to be reminded that this experiment concerns a dry pea crop. Vining pea crop (or garden pea) is the same botanical species but it is harvested at an earlier stage, before the translocation of N from the leaves to the seeds. Consequently, the total N amount of vining pea residues and their N / C ratio are significantly higher than for dry pea or wheat residues (Carrouée et al., 2006): different results concerning N mineralization and possibly N_2O emissions could then be observed. The references published in the literature dealing with "pea crop" do not always precise clearly which type of pea is concerned: they have to be gathered with caution.

4.2 N_2O emission from the pea crop

Our results clearly evidenced the lower emissions over the pea crop, compared with the fertilized wheat or rapeseed crops, with an average ratio 1 : 4–1 : 6 respectively over the growing season for the three years, and a range of 1 : 3–1 : 12 respectively according to the considered year. They were not significantly different from those of the unfertilized wheat crop. Moreover, these results were observed systematically over the three years. The cumulated fluxes were not larger than emissions under natural vegetation as estimated by Stehfest and Bouwmann (2006). They are in the low range of N_2O emissions from legumes, as published in the synthesis by Rochette and Janzen (2005). They are even lower than the values given by Lemke et al. (2007), which is the only reference over a pea crop in Rochette and Janzen (2005). While they measured cumulated fluxes of 0.38–0.74 kg $N\text{-}N_2O\ ha^{-1}\ yr^{-1}$, our estimates ranged from 0.03 to 0.1 kg $N\text{-}N_2O\ ha^{-1}\ yr^{-1}$ over the growing season. This confirms the option of Rochette and Janzen (2005), agreed by IPCC (2006), that BNF should not be considered as a N_2O source in N_2O emission inventory.

The total N in crop residues and in soil after harvest was similar or larger for the pea crop compared to the other fertilized crops. However, the N_2O emissions resulting from residue decomposition, as estimated from measurements between harvest and the next crop were not significantly different between the three crops. This shows that

BGD
9, 9289–9314, 2012

the pea residues are not a larger N_2O source than wheat/rapeseed residues. This also means that the other possible source of N_2O in a pea crop, N-rich root exudates, did not add significant emissions while the contribution of roots to the N pool of the soil has been shown to reach 22–25 % relative to total plant-N at maturity (Mahieu et al., 2007). We could then consider that there were no subsequent effects of the pea crop that would imply to consider this crop as a larger or a lower N_2O emitter than a cereal or an oilseed crop.

These data should be confirmed in other conditions of higher emissions, particularly in another soil type. Moreover, in order to avoid underestimate due to unfrequent sampling and catch up emission pulses, it should be more precise to measure N_2O fluxes by using automated chambers or to model daily fluxes. Models simulating N_2O fluxes are currently being enhanced and more precise and their quality of prediction can be improved by real data assimilations (Lehuger et al., 2009).

4.3 GHG budget of the pea crop compared to other crops

Besides reducing GHG emissions during the crop cycle, the reduction of GHG budget of a pea crop is also linked with the reduced consumption of GHG by production and transport due to the avoided nitrogen fertilizer which is not applied on the pea crop, and which rate is reduced on the following crop: mean values reach 0.7 to 1.4 t eq CO_2 ha^{-1} less than a crop receiving 180 kg N ha^{-1} of mineral fertilizer mineral (ADEME-DIREN, 1997; Nemecek et al., 2000). Moreover, on this crop, reduction of energy use and GHG emissions are also linked with the suppression of the machinery cost of the fertilizer application. Using the emission factors of IPCC, a crop fertilized with 180 kg N ha^{-1} leads to an emission of 2.8 g N_2O ha^{-1}, i.e. 0.8 t eq CO_2 ha^{-1} (IPCC, 2006). With our results, showing a reduction of the N_2O emissions during the pea crop of 75–80 % compared with a fertilized crop, the overall GHG emission economy can reach up to 2.5 t eq CO_2 ha^{-1}. Through LCA modeling, the comparison of N_2O emission linked with several crops underlined similar trends with 70 % of reduction in favour to pea crop compared to fertilized arable crops (T. Nemecek, personal communication, 2012).

BGD
9, 9289–9314, 2012

4.4 Assessment of N_2O emissions of a segment of three years of a crop succession

Our punctual measurements could be extrapolated at the level of the year scale to calculate the N_2O emissions of cropping systems over several years. If our data are confirmed, when we extrapolate them over a three year segment of crop rotation, including one pea crop, compared with 3 fertilized crops segment, leads to a significant 20–25 % reduction of GHG emissions in the fields at the rotation scale. This value is consistent with the 14 % reduction of GHG emissions for a 20 % introduction of pea in rotations calculated by Nemecek et al. (2008) through Life Cycle Assessments.

Acknowledgements. This work was supported by grants from CASDAR 7-175. We acknowledge the technical team of UMR Agronomie for assistance during the experiment and the Experimental Unit of Versailles-Grignon for managing the trial.

References

ADEME-DIREN: Inventaire environnemental des intrants agricoles en production végétale, Compte rendu de la FAT,46, 1997.

Bates, D. and Maechler, M.: lme4: Linear mixed-effects models using S4 classes, http://CRAN.R-project.org/package=lme4, 2009.

Carrouee, B., Bourgeais, E., and Aveline A.: Nitrate leaching related to dry pea in arable crop rotations, in: Grain legumes and the environment: how to assess benefits and impacts?, edited by: AEP-Paris, 18–19 November 2004, Agroscope FAL Reckenholz, Zurich, Switzerland, 117–124 , 2006.

Crutzen, P. J. and Ehhalt, D. H.: Effects of nitrogen fertilizers and combustion on the stratospheric ozone layer, Ambio, 6, 112–117, 1977.

Crutzen, P. J., Mosier, A. R., Smith, K. A., and Winiwarter, W.: N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels, Atmos. Chem. Phys., 8, 389–395, doi:10.5194/acp-8-389-2008, 2008.

Davidson, E. A.: The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860, Nat. Geosci., 2 , 659–662, 2009.

Duxbury, J. M., Bouldin, D. R., Terry, R. E., and Tate, R. L.: Emissions of nitrous oxide from soils, Nature, 298, 462–464, 1982.
Firestone, M. K. and Davidson, E. A.: Microbiological basis of NO and N_2O production and consumption in soil, in: Exchange of Trace Gases Between Terrestrial Ecosystems and the Atmosphere, edited by: Andreae, M. O. and Schimel, D. S., Wiley, 721 pp., 1989.
Hénault, C. and Revellin, C.: Inoculants of leguminous crops for mitigating soil emissions of the greenhouse gas nitrous oxide, Plant Soil, 346, 289–296, 2011.
Hénault, C., Devis, X., Page, S., Justes, E., Reau, R., and Germon, J. C.: Nitrous oxide emission under different soil and land management conditions, Biol. Fertil. Soils, 26, 199–207, 1998
Hothorn, T., Bretz, F., and Westfall, P.: Simultaneous Inference in General Parametric Models, Biometrical J., 50, 346–363, 2008.
Hutchinson, G. L. and Livingston, G. P.: Use of chamber systems to measure trace gas fluxes, in: Agricultural Ecosystem Effects on Trace Gases and Global Climate Change, edited by: Harper, L. A., Mosier, A. R., Duxbury, J. M., and Rolston, D. E., ASA Special Publication, ASA, CSSA, SSSA, Madison, WI, 55, 63–78, 1993.
IPCC 2006: IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, edited by: Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K., IGES, Japan, 2006.
IPCC: Climate Change 2007: The Fourth Assessment Report (AR4), edited by: Salomon, S., Quin, D., Manning, M., and Chen, Z., Cambridge University Press, Vol II The Physical Science Basis, 996 pp., 2007
Jensen, E. S. and Hauggaard-Nielsen, H.: How can increased use of biological N_2 fixation in agriculture benefit the environment?, Plant Soil, 252, 177–186, 2003.
Lehuger, S., Gabrielle, B., Van Oijen, M., Makowski, D., Germon, J. C., Morvan, T., and Hénault, C.: Bayesian calibration of the nitrous oxide emission module of an agro-ecosystem model, Agr. Ecosyst. Environ., 133, 208–222, doi:10.1016/j.agee.2009.04.022, 2009.
Loubet, B., Laville, P., Lehuger, S., Larmanou, E., Fléchard, C., Mascher, N., Génermont, S., Roche, R., Ferrara, R. M., Stella, P., Personne, E., Durand, B., Decuq, C., Flura, D., Masson, S., Fanucci, O., Rampon, J. N., Siemens, J., Kindler, R., Gabrielle, B., Schrumpf, M., and Cellier P.: Carbon, nitrogen and Greenhouse gases budgets over a four years crop rotation in northern France, Plant and Soil, 343, 109–137, doi:10.1007/s11104-011-0751-9, 2011.
Laville, P., Lehuger, S., Loubet, B., Chaumartin, F., and Cellier, P.: Effect of management, climate and soil conditions on N_2O and NO emissions from an arable crop rota-

tion using high temporal resolution measurements, Agr. Forest Meteorol., 151, 228–240, doi:10.1016/j.agrformet.2010.10.008, 2011.

Le Cadre E.: Modélisation de la volatilisation d'ammoniac en interaction avec les processus chimiques et biologiques du sol, Thèse INA P-G, Paris, 30 mars 2004, 211 pp., 2004.

Leip, A., Achermann, B., Billen, G., Bleeker, A., Bouwman, A. F., de Vries, A., Dragosits, U., Doring, U., Fernall, D., Geupel, M., Herolstab, J., Johnes, P., Le Gall, A. C., Monni, S., Neveceral, R., Orlandini, L., Prud'homme, M., Reuter, H. I., Simpson, D., Seufert, G., Spranger, T., Sutton, M. A., van Aardenne, J., Vos, M., Winiwarter, W.: Integrating nitrogen fluxes at the European scale, in: The European Nitrogen Assessment, edited by: Sutton, M. A., Howard, C. M., Erisman, J. W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., and Grizzeti, B., Sources, Effects and Polilicy Perspectives, Cambridge, Cambridge University Press, 345–376, 2011.

Lemke, R. L., Zhong, Z., Campbell, C. A., and Zentner R.: Can Pulse Crops Play a Role in Mitigating Greenhouse Gases from North American Agriculture?, Agron. J., 99, 1719–1725, doi:10.2134/agronj2006.0327s, 2007.

Luo, G. J., Brüggemann, N., Wolf, B., Gasche, R., Grote, R., and Butterbach-Bahl, K.: Decadal variability of soil CO_2, NO, N_2O, and CH_4 fluxes at the Höglwald Forest, Germany, Biogeosciences, 9, 1741–1763, doi:10.5194/bg-9-1741-2012, 2012.

Nemecek, T., Heil, A., Huguenin, O., Erzinger, S., Blaser, S., and Dux, D.: Life cycle inventories of agricultural production systems. Final report Ecoinvent 2000 No 15, Dübendorf, CH, FAL Reckenholz, FAT Tänikon, Swiss Centre For Life Cycle Inventories, 2003.

Nemecek, T., von Richthofen, J.-S., Dubois, G., Casta, P., Charles, R., and Pahl, H.: Environmental impacts of introducing grain legumes into European crop rotations, Eur. J. Agron., 28, 380–393, 2008.

Mahieu, S., Fustec, J., Faure, M. L., Corre-Hellou, G., and Crozat, Y.: Comparison of two ^{15}N labelling methods for assessing nitrogen rhizodeposition of pea, Plant Soil, 295, 193–205, 2007.

Parkin, T. B.: Effect of Sampling Frequency on Estimates of Cumulative Nitrous Oxide emissions, J. Environ. Qual., 37, 1390–1395, doi:10.2134/jeq2007.0333, 2008.

Philibert, A., Loyce, C., and Makowski, D.: Assessment of the quality of meta-analysis in agronomy, Agr. Ecosyst. Environ., 148, 72–82, 2012.

Rochette, P. and Janzen, H.: Towards a revised coefficient for estimating N_2O emissions from legumes, Nutr. Cycl. Agroecosys., 73, 171–179, 2005.

Skiba, U. and Smith, K. A.: The control of nitrous oxide emissions from agricultural and natural soils, Chemosphere – Global Change Science, 2, 379–386, 2000.

Smith, K. A. and Dobbie, K. E.: The impact of sampling frequency and sampling times on chamber-based measurements of N_2O emissions from fertilized soils, Glob. Change Biol., 7, 933–945, 2001.

Stehfest, E. and Bouwmann, A.: N_2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions, Nutr. Cyc. Agroecosys., 74, 207–228, doi:10.1007/s10705-006-9000-7, 2006

Velthof, G. L. and Oenema, O.: Nitrous oxide emission from dairy farming systems in the Netherlands, Neth. J. Agr. Sci., 45, 347–360, 1997.

Zhong, Z., Lemke, R. L., and Nelson, L. M.: Nitrous oxide emissions associated with nitrogen fixation by grain legumes, Soil Biol. Biochem., 41, 2283–2291, doi:10.1016/j.soilbio.2009.08.009, 2009.

BGD

9, 9289–9314, 2012

Nitrous oxide emissions from crop rotations

M. H. Jeuffroy et al.

Table 1. Crop sequences in the field trial along the five years (in the first column, W = winter wheat; R = rapeseed; P = pea).

No	Rotation	2006–2007	2007–2008	2008–2009	2009–2010	2010–2011
1	WRW		Winter wheat[a,b]	Oilseed rape[a]	Winter wheat	Winter wheat
2	WPR	Winter	Winter wheat[a,b]	Winter pea	Oilseed rape[a]	Winter wheat
3	WPW	wheat	Winter wheat	Winter pea[a]	Winter wheat	Winter wheat
4	WWR	(1 block)	Winter wheat[a,b]	Winter wheat	Oilseed rape[a]	Winter wheat[a,b]
5	RWW	and winter	Oilseed rape[a]	Winter wheat[a]	Winter wheat	Winter wheat
6	RWP	barley	Oilseed rape[a]	Winter wheat	Winter pea[a]	Winter wheat[a]
7	PRW	(2 blocks)	Winter pea[a]	Oilseed rape[a]	Winter wheat[a]	Winter wheat
8	PWW		Winter pea[a]	Winter wheat[a,b]	Winter wheat[a,b]	Winter wheat[a,b]

[a] Treatments with N_2O emissions measurements.
[b] Measurement of N_2O emissions also on the non-fertilised treatment.

BGD
9, 9289–9314, 2012

Table 2. Sowing dates of each crop, total rate, dates and amounts of nitrogen fertilizer applied on each crop according to each rotation.

No	Rotation	Year	Crop	Sowing date	Fertilisation: amount in kg ha^{-1} *(date)*			
					Total	1st appl.	2nd appl.	3rd appl.
1	WRW	2007–2008	W	12 Oct	220	50 *(19 Feb)*	130 *(9 Apr)*	40 *(9 May)*
		2008–2009	R	4 Sep	200	60 *(13 Mar)*	140 *(9 Apr)*	–
		2009–2010	W	28 Oct	150	50 *(10 Mar)*	60 *(12 Apr)*	40 *(14 May)*
2	WPR	2007–2008	W	12 Oct	220	50 *(19 Feb)*	130 *(9 Apr)*	40 *(9 May)*
		2008–2009	P	20 Nov	0	–	–	–
		2009–2010	R	8 Sep	110	60 *(10 Mar)*	50 *(12 Apr)*	–
3	WPW	2007–2008	W	12 Oct	220	50 *(19 Feb)*	130 *(9 Apr)*	40 *(9 May)*
		2008–2009	P	20 Nov	0	–	–	–
		2009–2010	W	28 Oct	160	50 *(10 Mar)*	70 *(12 Apr)*	40 *(14 May)*
4	WWR	2007–2008	W	12 Oct	220	50 *(19 Feb)*	130 *(9 Apr)*	40 *(9 May)*
		2008–2009	W	20 Oct	160	50 *(13 Mar)*	70 *(9 Apr)*	40 *(18 May)*
		2009–2010	R	8 Sep	115	60 *(10 Mar)*	55 *(12 Apr)*	–
5	RWW	2007–2008	R	19 Sep	170	50 *(19 Feb)*	120 *(9 Apr)*	–
		2008–2009	W	20 Oct	160	50 *(13 Mar)*	70 *(9 Apr)*	40 *(18 May)*
		2009–2010	W	28 Oct	220	50 *(10 Mar)*	130 *(12 Apr)*	40 *(14 May)*
6	RWP	2007–2008	R	19 Sep	170	50 *(19 Feb)*	120 *(9 Apr)*	–
		2008–2009	W	20 Oct	160	50 *(13 Mar)*	70 *(9 Apr)*	40 *(18 May)*
		2009–2010	P	29 Oct	0	–	–	–
7	PRW	2007–2008	P	12 Nov	0	–	–	–
		2008–2009	R	4 Sep	160	60 *(13 Mar)*	100 *(9 Apr)*	–
		2009–2010	W	28 Oct	170	50 *(10 Mar)*	80 *(12 Apr)*	40 *(14 May)*
8	PWW	2007–2008	P	12 Nov	0	–	–	–
		2008–2009	W	20 Oct	160	50 *(13 Mar)*	70 *(9 Apr)*	40 *(18 May)*
		2009–2010	W	28 Oct	220	50 *(10 Mar)*	130 *(12 Apr)*	40 *(14 May)*

BGD
9, 9289–9314, 2012

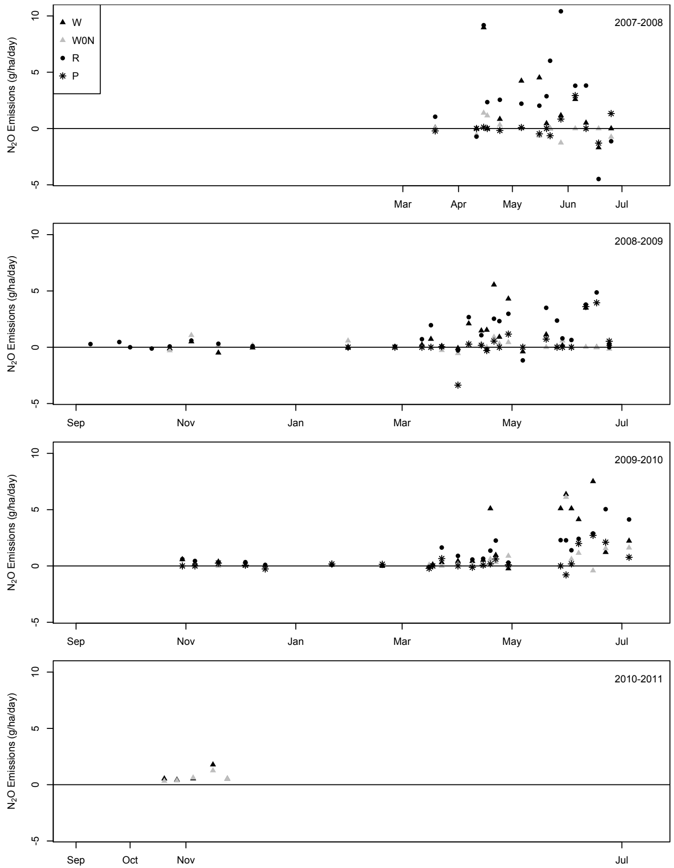

Fig. 1. Mean N_2O fluxes (mean over all blocks and preceding crops) against date for the different crops (W = wheat, W0N = unfertilized wheat, R = oilseed rape, P = pea) for each cropping season. Dates of fertilization have not been included in the figure as they vary according to the crop and preceding crop.

BGD
9, 9289–9314, 2012

Nitrous oxide emissions from crop rotations

M. H. Jeuffroy et al.

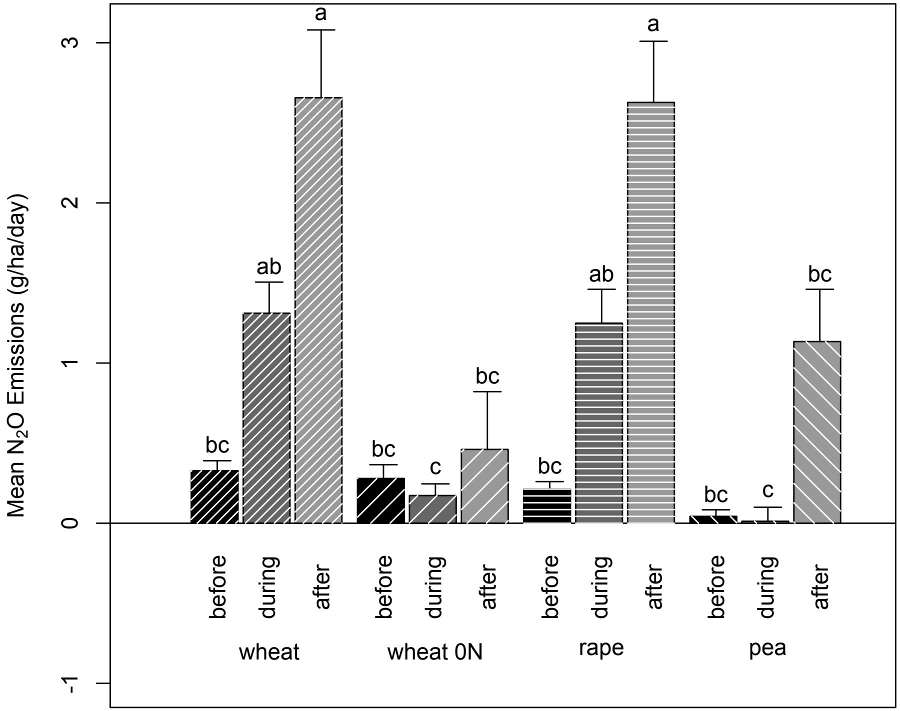

Fig. 2. Mean N_2O emissions as a function of the crop (wheat, winter oilseed rape or pea), fertilized or not (0N) and period of observation (before the first N fertilisation, more than 14 days after the last N fertiliser or during the period of N fertilization). Bars with the same letter are not significantly different. Error bars = standard error of the mean.

BGD
9, 9289–9314, 2012

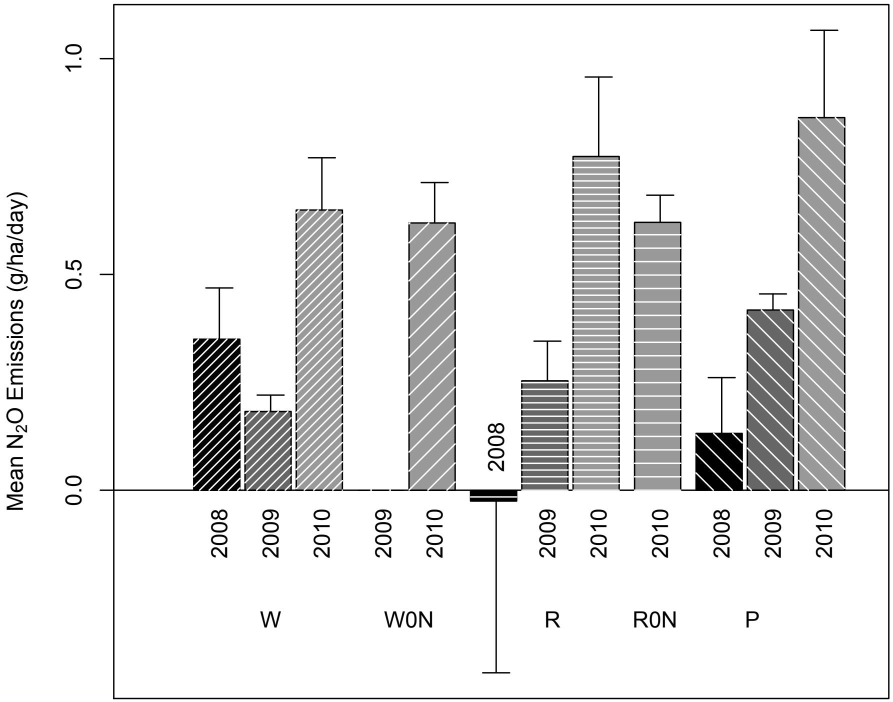

Fig. 3. Mean N_2O emissions during autumn as a function of the preceding crop (W = Wheat, R = oilseed Rape, P = Pea, W0N = unfertilized wheat) and year. Error bars = standard error of the mean.

BGD
9, 9289–9314, 2012

Nitrous oxide emissions from crop rotations

M. H. Jeuffroy et al.

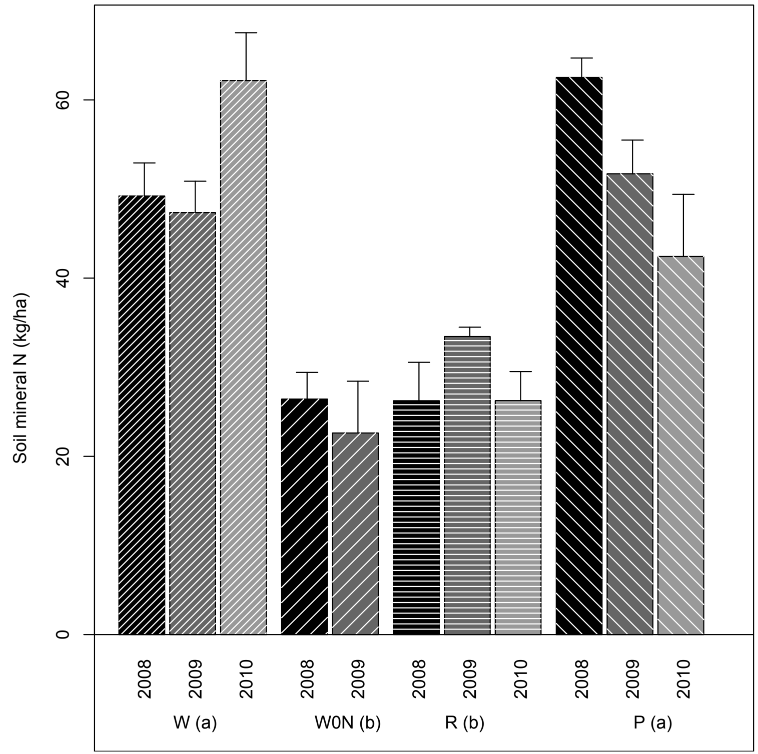

Fig. 4. Soil mineral content (kg ha^{-1}) after harvest in the whole soil profile according to the crop (which was just harvested: W = wheat, W0N = unfertilized wheat, R = oilseed rape, P = pea) and the year. Groups of bars with the same letter are not significantly different. Error bars = standard error of the mean.

BGD
9, 9289–9314, 2012

Nitrous oxide emissions from crop rotations

M. H. Jeuffroy et al.

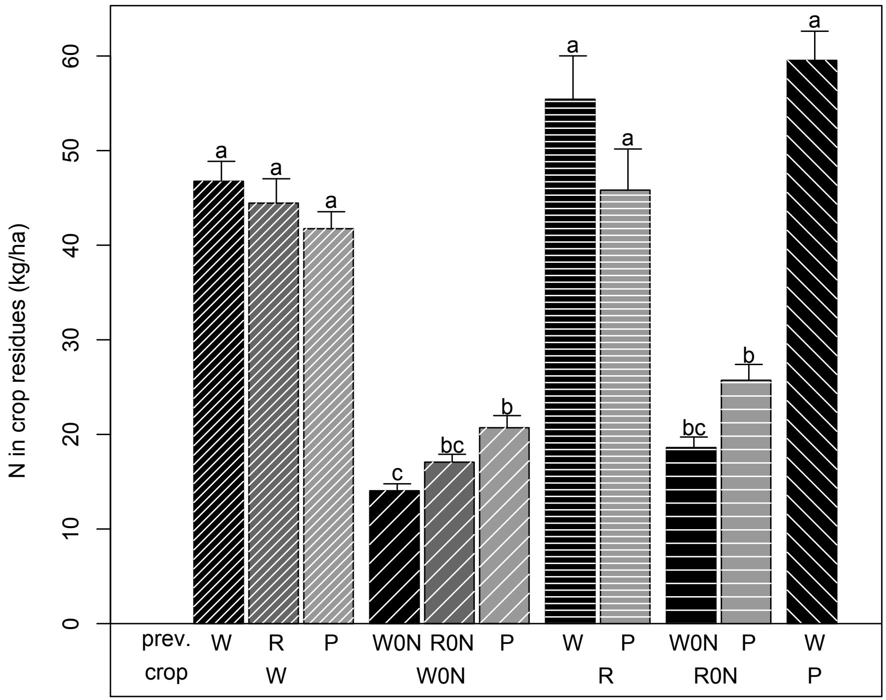

Fig. 5. N in crop residues (kg ha^{-1}) at harvest according to the crop and the previous crop. Bars with the same letter are not significantly different. Error bars = standard error of the mean.

BGD
9, 9289–9314, 2012

Nitrous oxide emissions from crop rotations

M. H. Jeuffroy et al.