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29 % N₂O emission reduction from a modelled low-greenhouse gas cropping system during 2009-2011

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1 **29% N₂O emission reduction from a modelled low-greenhouse gas**
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4 **cropping system during 2009-2011**
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Abstract

Atmospheric concentration of nitrous oxide (N₂O), a potent greenhouse gas (GHG), is rising, largely due to agriculture. N₂O emissions from crops are affected by single agricultural practices (e.g. fertilisation, tillage and residue management), but the latter are intricately related within cropping systems. Strategies to reduce impact of farming on climate should therefore be sought at this level. However, data are scarce for cropping systems because N₂O emission monitoring is time-consuming. Agro-ecosystem models offer an alternative, simpler mean of estimating N₂O emissions.

Here, we developed a methodology combining ecosystem modelling and field measurements to assess the effect of agronomic management on N₂O emissions. The model was evaluated against series of daily to monthly N₂O emission data. It was subsequently used to evaluate the N₂O abatement potential of a cropping system specifically designed to halve greenhouse gas emissions (low emissions) when compared to a system with high productivity and environmental performance (reference), close to current practice.

Here, an estimated 29% N₂O abatement potential was achieved from a cropping system specifically designed to halve greenhouse gas emissions when compared to the reference system during 2009-2011. This result was affected by the interplay between climatic conditions and crop management on the occurrence of emission peaks. Among N₂O abatement strategies, reduction of mineral fertiliser inputs proved to be the most effective while variable effects were obtained with reduced tillage and the introduction of legumes.

Keywords: N₂O emissions, cropping systems, agro-ecosystem model, leguminous crops, residues, fertiliser application

1. Introduction

Nitrous oxide (N₂O) is a potent greenhouse gas contributing an estimated 6% to global anthropogenic radiative forcing (Houghton et al. 2001). N₂O emissions occur mostly through the denitrification and nitrification processes in agricultural soils, and are thus driven by the applications of fertilizer nitrogen (N) and animal manure, soil tillage and crop type, with their effects largely dependent on soil and weather conditions (Saggar, 2010). In addition to climate forcing, cropping systems affect N₂O emissions, with a large spatial and temporal variability (Kariyapperuma et al. 2011; Li et al. 2012).

Emissions of N₂O from cropping systems may be directly measured in field trials using micrometeorological systems or accumulation chambers (Laville et al. 2011). Due to the low magnitude of N₂O fluxes, direct measurements are expensive and time consuming, and their use is limited (Rochette and Eriksen-Hamel 2008). In lieu of direct measurements, biophysical models (DAYCENT, DNDC, CERES-EGC), simulating most of the processes governing N₂O emissions, have been proposed (Lehuger et al. 2009; Li et al. 2012). The latter model was tested for these impacts with European data, with reasonable success (Lehuger et al. 2009, 2011). In principle, models allow to estimate and compare annual emissions of large numbers of plots and replicates that characterize long-term agronomical trials.

Several attempts at estimating N₂O emissions from crops and assessing potential abatement options using a model were carried out (Smith et al. 2008; Lehuger et al. 2009; Chirinda et al. 2010; Hastings et al. 2010; Ludwig et al. 2011; Li et al. 2012). However, they covered a limited set of rotations (Li et al. 2012), crops (Smith et al. 2008), agricultural techniques and climatic conditions (dry years in Lehuger et al. (2011)), a different geographical area (northern Europe in Chirinda et al. (2010)) or evaluating cropping systems with other aims than reducing greenhouse gas emissions (Ludwig et al. 2011). The objective of this work was to evaluate, by mean of CERES-EGC model and direct measurements, the N₂O abatement potential of a cropping system specifically designed to halve greenhouse gas emissions compared to a system with high productivity and environmental performance, close to current practice.

2. Material and methods

2.1. Model description and parametrisation

CERES-EGC comprises sub-models for the major processes governing the cycles of water, carbon and nitrogen in agro-ecosystems, as detailed in Lehuger et al. (2009). The latter, predicting N₂O production and reduction rates through both nitrification and denitrification pathways, was adapted from the semi-empirical model NOE. It involves a total set of 15 parameters of which four are site-specific. CERES-EGC runs on a daily time step and was provided with daily rain, mean air temperature and Penman potential evapo-transpiration data taken from a weather station located less than 1 km away from the field trials under study.

2.2. The NitroEurope trial

The NitroEurope trial is described in details in Laville et al. (2011), and is briefly summarised here. The trial had the following rotation: maize (*Zea mays* L.), winter wheat (*Triticum aestivum* L.), triticale (*XTriticosecale* (Camus) Wittm.), barley (*Hordeum vulgare* L.). In August 2009, after harvest, crop residues were left on the soil surface, and 40 m³ ha⁻¹ (98.5 kg N-NH₄ ha⁻¹) of cattle slurry were spread and incorporated. In the following month, the soil was tilled and in mid-October triticale was sown. Mineral fertilizer inputs were split into two applications of N solution (half urea, half ammonium-nitrate): 60 kg N ha⁻¹ on March 17th 2011 and 40 kg N ha⁻¹ on April 6th 2011. Triticale was harvested in mid-July 2011. N₂O monitoring was carried out by means of six automatic chambers every 90 minutes (see Laville et al. (2011), for details). N₂O concentrations were measured by infrared absorption spectrometry. Fluxes were calculated from the variations over time in the slopes of gas outlet concentration. For the NitroEurope trial, CERES-EGC was run from August 1st, 2009 to July 31st, 2010 covering the growing season of triticale.

2.3. The innovative cropping systems under constraints (ICC) trial

The agronomic trial on innovative cropping systems under constraints was established next to the NitroEurope trial, on a similar soil type. Each cropping system has three randomly distributed replicates. N₂O measurements were carried out on two cropping systems: (1) the reference system (also called PHEP), which aims at reaching altogether High Environmental Performances and Productivity and (2) a cropping system under a greenhouse gas mitigation constraint (low emissions, also called less GHG), aiming at halving greenhouse gas emissions compared to the reference system, both by increasing C sequestration in the soil and decreasing N₂O emissions. Aside from greenhouse gas emissions, this system was assigned the same environmental criteria as the reference system (Colnenne David et al. 2012).

The reference cropping system was designed with the following agronomical principles: to reduce N fertilizer inputs by including legumes in the rotation; to use crop varieties with high N use efficiency and a high level of resistance to diseases; to lengthen crop rotations; to increase crop diversity and to achieve a satisfactory yield. The rotation is as follows: faba bean (*Vicia Faba* var *minor* (Harz) Beck), winter wheat, winter rapeseed (*Brassica napus* L.), winter wheat, white mustard (*Sinapis arvensis* L.) or black mustard (*Brassica nigra* L.) as a catch crop and spring barley. In 2011-2012 season, faba bean was preceded by a cover crop of buckwheat (*Fagopyrum esculentum* Moench). Crop management data for each plot of the reference system are given in Table 1 (Colnenne David et al. 2012).

The low emissions cropping system maximizes accumulation of soil organic carbon with the use of high biomass yielding cereals and by increasing the rate of crop residue return to soils, reducing tillage operations, while still maintaining a satisfactory yield. N₂O emissions are mitigated by reducing mineral nitrogen fertiliser inputs with the introduction of legumes as both main crops in the rotation and cover crops. Cover crops were also introduced to decrease the accumulation of soil nitrate and subsequent N₂O emissions from denitrification. The rotation is: (cover crop) faba bean, winter rapeseed, (cover crop) winter wheat, (cover crop) winter barley, (cover crop) maize, triticale. Crop management data are detailed in Table 1 (Colnenne David et al. 2012).

N₂O emissions were measured with static chambers in triplicates, following Rochette and Eriksen-Hamel (2008) with a gas chromatograph equipped with an ECD (Electron Capture Detector). Each chamber covered a surface area of 0.25 m² and had a height above the soil surface of 0.2 m. From March 2010 on, chambers were sampled once a month except in months with frozen soil. After fertiliser application, chambers were sampled every three days for two weeks; while after residues incorporation and the killing of faba beans chambers were sampled twice every ten days after a significant rainfall event occurred (>10 mm). Gas concentrations were utilized to make a regression, tested for linearity according to Rochette and Eriksen-Hamel (2008) and elaborated following Pedersen et al. (2010). For each plot, flux values were averaged and a confidence interval was calculated (Jarecki et al. 2008). Cumulated fluxes were computed by summing daily N₂O emission rates predicted by the CERES-EGC model. Cumulated fluxes for each crop were allocated from time of harvest of the previous main crop to time of harvest of current main crop.

2.4. Statistical analysis

Model results were tested against field data by calculating mean difference between simulated and observed N₂O emission rates (bias), and the Root Mean Square Error of Prediction (RMSEP), as: $RMSEP = (\sum(O_i - P_i)^2/n)^{1/2}$, where O_i and P_i are observed and predicted variables, and n is the number of data points. Model efficiency is defined as: $ME = 1 - (\sum(O_i - P_i)^2 / \sum(O_i - \bar{O})^2)$, where \bar{O} is the mean of observed variables.

3. Results and Discussion

Section 3.1 presents results on the performance of the CERES-EGC model in both trials (NitroEurope and Innovative cropping system under constraints), with respect to previous research. Section 3.2 focuses on the evaluation of the N₂O abatement potential of the low emissions cropping system by means of modelling and direct measurements.

3.1 Predictions of N₂O emissions

1
2 During the monitored period, the model was able to predict the occurrence of a series of peaks, even
3 after leguminous crop incorporation and mulching, albeit with a lower magnitude than observed
4 (Figures 1, 2). There was also a residual effect in the simulations after peaks in November 2009, which
5 did not appear in observed data (Figure 1), as it was discussed by Ludwig et al. (2011) with DNDC. In
6 general, CERES-EGC correctly predicted low emission rates occurring during drier periods in
7 particular in spring (Figures 1, 2). Measurements on faba beans evidenced a coupled effect of
8 leguminous residues and higher soil moisture due to no tillage, since low emissions system plot
9 involved direct drilling for the crop proceeding faba bean. This resulted in a greater soil moisture than
10 in the reference system from mid-August to mid-September 2011, in accordance with Kong et al.
11 (2009).

12
13 For the NitroEurope trial, model bias remained under 1 g N₂O-N ha⁻¹ d⁻¹, while RMSEP was
14 approximately 5 g N₂O-N ha⁻¹ d⁻¹. On the other hand, the agronomical trial plots had a slightly larger
15 bias (0.17-1.88 N₂O-N g ha⁻¹ d⁻¹). The RMSEP of the agronomical trial plots ranged from 0.81 to 13.7
16 N₂O-N g ha⁻¹ d⁻¹, dependent mostly on the agreement between observed and simulated emission spikes
17 in fall (Figures 1, 2). In the test against the NitroEurope data set, the ratio of model bias to averaged
18 measured N₂O emission rate was 31%, lying in the middle of the 1%-55% range reported with the
19 DNDC model pertaining to barley crops in Ireland (Abdalla et al. 2009). On the other hand, CERES-
20 EGC achieved larger RMSEP values (2.23 times higher) for triticale in the NitroEurope trial than
21 those estimated with DNDC by Kariyapperuma et al. (2011) for a maize-soybean (*Glycine max* (L.)
22 Merr.)-winter wheat rotation in Canada, but similar with the value obtained with CERES-EGC by
23 Lehuger et al. (2009) with winter wheat and Maize datasets (6 g N₂O-N ha⁻¹ d⁻¹ versus 5.35 in this
24 research). However the RMSEP obtained here for triticale was within the 0.93-8.75 g N₂O-N ha⁻¹ d⁻¹
25 range obtained with FASSET by Chirinda et al. (2010). Model efficiency was also within the -78.15-
26 0.11 range obtained by the latter, and greater than the values they estimated with Mobile DNDC model
27 (-10.82- -1.78 versus 0.07 in the present study). This positive value for model efficiency indicated
28 model results were better predictors than the average for N₂O emissions.

29
30 When cumulated over the triticale growing season in the NitroEurope trial, simulated N₂O emissions
31 totalled 1054 g N₂O-N ha⁻¹, 34% higher than the measured value, within 10-58% difference range
32 calculated from Ludwig et al. (2011) who used DNDC. The discrepancy found in the present study,
33 was partly due to the large spatial variability of soil nitrous oxide emissions, as discussed by
34 Li et al. (2012). Simulated emissions were also outside the 1700-2900 g N₂O-N ha⁻¹y⁻¹ range recorded
35 in previous years of this trial, but the order of magnitude was similar and this difference could be
36 expected due to inter-annual climate variability. For the agronomic trial, CERES-EGC simulated
37 annual emissions between 274-1640 g N₂O-N ha⁻¹ y⁻¹. This range was comparable with figures
38 reported by other authors, obtained either with model simulations or mathematical interpolation of
39 observed data in temperate and semi-arid zones: (2-3400 g N₂O-N ha⁻¹ y⁻¹) (Halvorson et al. 2008;
40 Abdalla et al. 2009; Ludwig et al. 2011; Pappa et al. 2011; Li et al. 2012). However, other authors
41 reported significantly larger ranges for cereals (3290-5560 g N₂O-N ha⁻¹ y⁻¹) (Jarecki et al. 2008;
42 Hastings et al. 2010).

3.2 Cropping systems effects on N₂O emissions

43
44 The average cumulative N₂O emissions from low emissions system was 28.5% lower than the
45 reference system, with a 45.0% larger confidence interval (Figure 3). These ratios are lower than the
46 50% abatement target assigned to the former system, but are likely be compensated by soil C
47 sequestration (Lehuger et al. 2011). These nitrous oxide reductions were obtained with no relevant
48 yield change (Colnenne David et al. 2012).

49
50 When taking each crop separately for the 2009-2010 season, the low emissions winter wheat emitted
51 55.6% less than the reference wheat, while barley showed a more limited decrease (19.6%). There
52 were no consistent patterns across the 2 growing seasons for a given crop type. Between the two
53 cropping systems, barley emitted 45.9% less in the low emissions system compared to the reference
54 system in 2010-2011 season. Conversely, faba bean emissions were similar between the two systems
55 (in the 1200-1300 g N₂O-N ha⁻¹ range), because most of the emissions peaks occurred after the 2011

1 harvest (Figure 2). Differences between crops were probably mitigated by unusually dry springs that
2 reduced the occurrence of denitrification after fertiliser applications. This contrasts with the commonly
3 observed pattern where emissions peak in the weeks following fertiliser application. In terms of crop
4 management effects, N₂O emissions increased as fertilizer rates increased, in accordance with previous
5 research (Stehfest and Bouwman 2006; Abdalla et al. 2009; Saggar 2010). The decomposition of
6 leguminous residues in late summer 2011 also triggered higher emissions of N₂O and caused variation
7 among crops, in both simulations and measurements.

8 For the low emissions system, N₂O abatement agronomic strategies were only partly effective. In
9 particular, introduction of cereals in the rotation had a limited effect on N₂O emissions. This situation
10 was not expected due to the high C:N ratio of cereal residues (Ruser et al. 2001) and was caused
11 mainly by the interference of soil moisture and nitrate availability, as discussed by Saggar (2010). For
12 both systems, the introduction of cover crops and mulching, obtained by limiting tillage operations,
13 should have reduced N₂O emissions by decreasing residue decomposition rate, and thus the build-up
14 of soil nitrate. However, this effect was counterbalanced by higher soil moisture content which is
15 conducive to N₂O emissions (Saggar 2010). The benefit of substituting mineral fertiliser N with N
16 fixed by leguminous crops was also not clearly detected, because of unexpected low soil moisture
17 during the fertiliser application period. On the other hand for the reference system, deep tillage should
18 have increased aeration and reduced water logged periods; nevertheless, it favoured residues
19 decomposition and mineralization, thus increasing emissions during fall-winter. These contrasting
20 effects of the N₂O abatement strategies might be due to crop management prior to trial establishment
21 or a limited differentiation among cropping systems as the trial was only recently established (2008).
22 Indeed, possible agronomic effects are hard to observe in short term trials due to interplay with
23 particular climatic conditions. Furthermore, a comprehensive evaluation of the two cropping systems
24 requires monitoring of the complete rotation, of which only 2 years were analysed here (Nassi o Di
25 Nasso et al. 2011). This was compounded by unusually dry conditions in spring which mitigated
26 fertilisation effects. The fact that model simulations were still able to reveal some degree of
27 differentiation between cropping systems is notable, and consistent with findings of Halvorson et al.
28 (2008).
29
30

31 **4. Conclusion**

32
33 Overall, CERES-EGC model was able to mimic N₂O emission patterns observed throughout the
34 growing seasons for the crops investigated here, although it generally underestimated the magnitude of
35 emission peaks. Due to dry spring conditions, measured N₂O emissions were generally low and spikes
36 occurred only during fall, winter, and after the harvest of legume crops in late summer. As a result,
37 cropping system N₂O emissions differed little during fertiliser application periods, and fertilisation
38 effects were lower than expected. Conversely, a combined effect of legume residues and no tillage
39 management was found to enhance N₂O emissions both in the simulated and observed data. Over two
40 seasons, the cropping system aiming to halve greenhouse gas emissions achieved a 29% reduction in
41 N₂O emissions compared to the reference system. Among the N₂O abatement strategies tested,
42 reduction in mineral fertiliser N application rates emerged as the most effective, while contrasting
43 results were obtained from no tillage, minimum tillage and introduction of leguminous crops. This
44 evidences potential trade-offs between N₂O emissions and strategies aiming to preserve soil C content
45 or reduce upstream greenhouse gas emissions due to the manufacturing of synthetic fertilisers.
46 However, further monitoring of these cropping systems are required to better understand the effect of
47 agricultural management and cropping systems on nitrous oxide emissions. Indeed most of these
48 results were highly affected by seasonal variability.
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7. Tables

Table 1. Main crop management practices for the two cropping systems during the growing seasons (2009-2010, 2010-2011, beginning of 2011-2012) (Low emissions system, 3 plots; Reference system: 3 plots). As stated in section 2.3, the main differences between the two systems are related to the following farming practices: fertiliser N rate, cover crops, leguminous crops, tillage.

Replicate	Low emissions system			Reference system		
	1	2	3	1	2	3
2009-2010 crop	barley	winter wheat	triticale	faba bean	barley	Winter wheat
Residues (dry matter Mg ha⁻¹)	8.36	8.13	8.25	8.31	6.91	7.91
Cover crop species	fodder pea	fodder pea			white mustard	
Principal Tillage Date					04/02/2010	
Sowing date	07/10/2009	12/10/2009	22/10/2009	19/11/2009	11/03/2010	19/10/2009
Fertiliser application rate (kg ha⁻¹) and date	N 40 09/03/2010 N 40 13/04/2010	N 80 13/04/2010		P 44 K 48 04/09/2009	N 70 20/04/2010	N 120 13/04/2010
2010-2011 crop	maize	barley	faba bean	winter wheat	faba bean	barley
Cover crop species	Egyptian clover and oat	fodder pea	oat			white mustard
Principal Tillage Date						17/01/2011
Sowing date	04/05/2011 24/05/2011	11/10/2010	11/03/2011	18/10/2010	05/11/2010	08/03/2011
Fertiliser application rate (kg ha⁻¹) and date	N 80 09/05/2011	N 50 18/02/2011 N 30 05/04/2010		N 90 05/04/2011		N 60 11/04/2011
2011-2012 crop	triticale	maize	Rapeseed	rapeseed	winter wheat	faba bean
Cover crop species		Egyptian clover and oat				buckwheat
Sowing date	14/10/2011		22/08/2011	22/08/2011	26/10/2011	07/11/2011

8. Figures

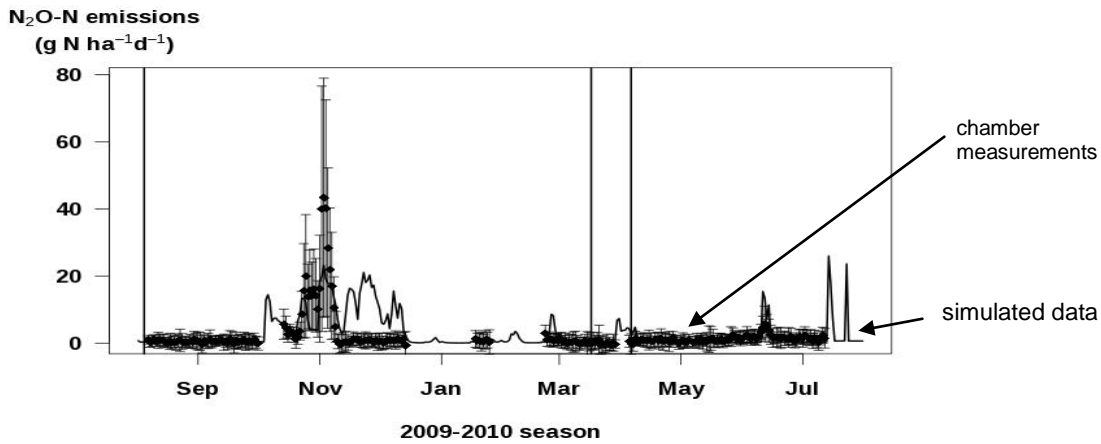
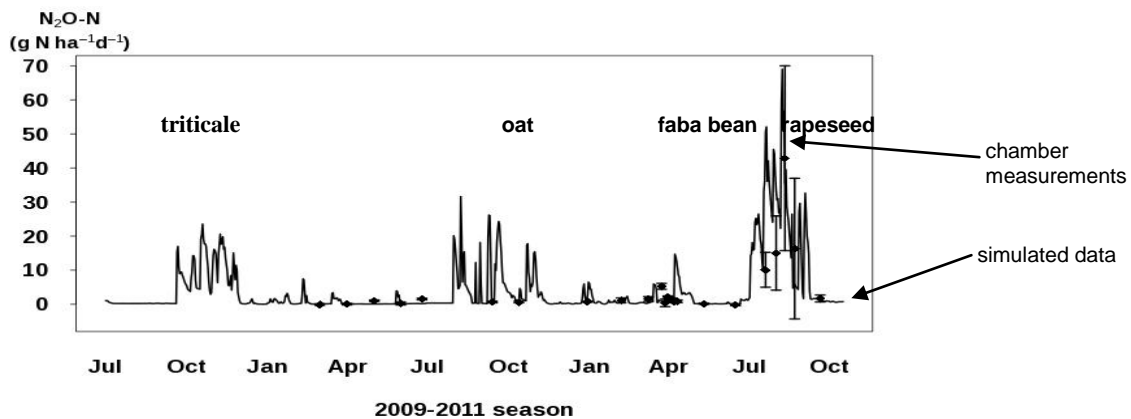


Figure 1: Simulated and observed N_2O emissions for the NitroEurope cropping system during the 2009-2010 season (Vertical lines: date of fertiliser application, error bars: 95% confidence interval for observed data). Most of simulated data fell within the confidence intervals of the observations, except from November 2009 to January 2010, during which the model predicted emission peaks which were not observed.

Low emissions system 3



Reference system 2

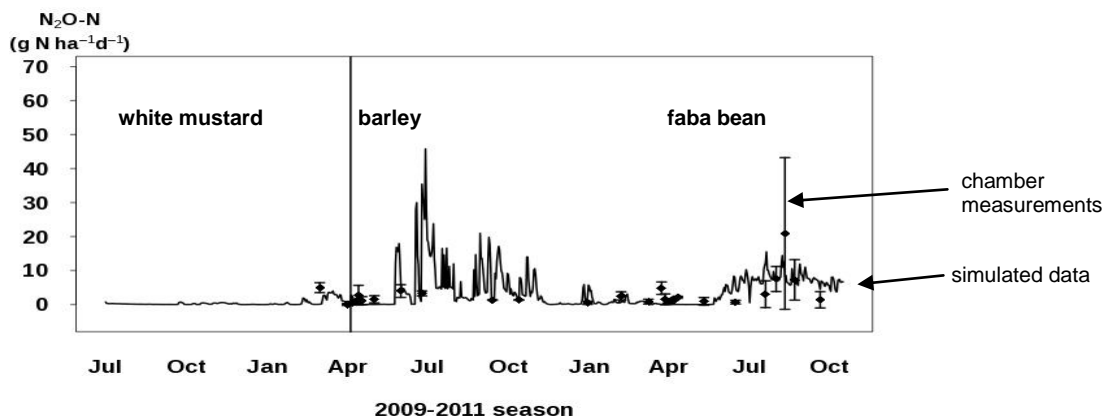


Figure 2: Simulated and observed N_2O emissions for the low emissions 3 and the reference 2 cropping systems of the innovative cropping systems under constraints trial from 15th July 2009 and 31st October 2011 (Vertical lines: date of fertiliser application, error bars: 95% confidence interval for observed data). There was a limited effect of fertiliser application on N_2O emissions, in contrast with the influence of residues decomposition in fall-winter and late summer. Also, in the low emissions system, the combination of no tillage and the presence of legume residues on the soil surface resulted in emission peaks in late summer 2011.

Mean annual N₂O emissions

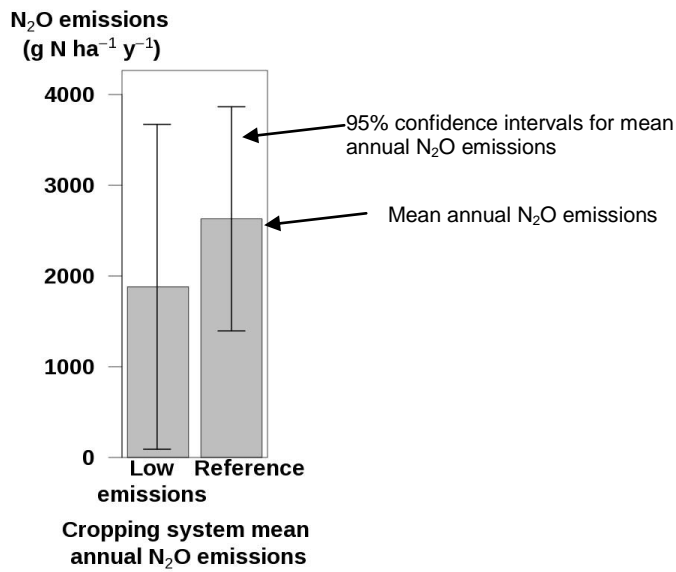


Figure 3 Annual means for 2009-2011 simulated nitrous oxide emissions of the 2 cropping systems (low emissions, reference, 3 plot each) from the innovative cropping systems under constraints trial (error bars: confidence interval ($p > 0.95$)). The main achievement of the present study: the low emissions system achieved a 29% reduction in mean annual N₂O emissions compared to the reference system. The large confidence intervals around this mean reduction were due to the interplay between climatic conditions and crop management.