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Process-based modeling of nitrous oxide emissions from wheat-cropped soils at the sub-regional scale

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1 **Abstract.** Arable soils are a large source of nitrous oxide (N₂O) emis-
2 sions, making up half of the biogenic emissions worldwide. Estimating their
3 source strength requires methods capable of capturing the spatial and tem-
4 poral variability of N₂O emissions, along with the effects of crop manage-
5 ment.

6 Here, we applied a process-based model, CERES, with geo-referenced input
7 data on soils, weather, and land use to map N₂O emissions from wheat-cropped
8 soils in three agriculturally intensive regions in France. Emissions were mostly
9 controlled by soil type and local climate conditions, and only to a minor ex-
10 tent by the doses of fertilizer nitrogen applied. As a result, the direct emis-
11 sion factors calculated at the regional level were much smaller (ranging from
12 0.0007 to 0.0033 kg kg N₂O-N kg⁻¹ N) than the value of 0.0125 kg N₂O-N kg⁻¹
13 N currently recommended in the IPCC Tier 1 methodology. Regional emis-
14 sions were far more sensitive to the soil microbiological parameters govern-
15 ing denitrification and its fraction evolved as N₂O, soil bulk density, and soil
16 initial inorganic N content. Mitigation measures should therefore target a
17 reduction in the amount of soil inorganic N upon sowing of winter crops, and
18 a decrease of the soil N₂O production potential itself. From a general per-
19 spective, taking into account the spatial variability of soils and climate thereby
20 appears necessary to improve the accuracy of national inventories, and to
21 tailor mitigation strategies to regional characteristics.

1. Introduction

1 Emissions from arable soils are a key item in the global nitrous oxide (N₂O) budget,
2 making up about half of the terrestrial biogenic emissions [*Mosier et al.*, 1998]. Since
3 agricultural activities are gradually coming into focus in the greenhouse gas (GHG) bud-
4 get calculations, precise estimates of current N₂O emissions from arable land are being
5 sought, along with possible means of abatement. However, compared to other GHG such
6 as CO₂, N₂O fluxes are of small magnitude and highly variable in space and time [*Duxbury*
7 *and Bouldin*, 1982], being tightly linked to the local climatic sequence and soil properties.
8 In national GHG inventories, the default recommended method is that defined by *IPCC*
9 [1997], currently being overhauled. It relates direct N₂O emissions to the amount of fer-
10 tilizer N applied based on a fixed emissions factor, thereafter noted EF_d. Although this
11 method is relatively easy to implement, by combination with nationwide economic statis-
12 tics, it ignores the effect of the above-mentioned characteristics. Also, it cannot be used
13 directly to define crop management strategies that would mitigate N₂O emissions, since
14 it does not account for the effect of fertilizer N application (let alone other management
15 practices) on crop growth and yield.

16 In the last ten years, the prediction of N₂O emissions within process-based agro-ecosystem
17 models has emerged as a promising route to deal with these issues, primarily at the local
18 scale to single out the effect of crop management practices [*Li et al.*, 2005]. Application
19 on larger spatial scales has also been demonstrated at the regional, country and sub-
20 continental levels [*Mummey et al.*, 1998; *Li et al.*, 2001; *Butterbach-Bahl et al.*, 2004].
21 However, it is complicated by the lack of adequate input data and the fact that models

1 may not be robust to such upscaling. In terms of spatial resolution, the above examples
2 involved 16 to 400-km²-wide elementary counties or grid squares, implying that models
3 were run on 'average' soils resulting from the combination of the possibly wide range of soil
4 types occurring in the elementary spatial unit considered. Short-range (< 1 km) variability
5 across agricultural fields was therefore likely to be smoothed out in these spatial extrap-
6 olations, which precludes a back-tracking of those zones with high emission potentials on
7 which particular measures might be taken to reduce the efflux of N₂O. Also, it makes it
8 impossible to compare the elementary cell-averaged flux with local, ground measurements,
9 the level at which these plot-scale models were generally tested [*Butterbach-Bahl et al.*,
10 2004].

11 Upscaling to small areas with a much finer grain has also been reported [*Grant and Pat-*
12 *tey, 2003*]. The latter authors simulated N₂O emissions in a 12-ha landscape by means
13 of 50 m x 50 m grid squares, and showed micro-relief to be responsible for emission 'hot-
14 spots' accounting for most of the spatial variability in N₂O efflux. They concluded that
15 aggregation of N₂O emissions at higher scales should be based on 'typical landscapes in
16 which surface topography and soil type is accurately represented'. There is therefore a
17 need for process-based inventories at an intermediate resolution between the field (1-100
18 ha) and county (10-1000 km²) levels, which would explicitly account for heterogeneities
19 between individual soil types.

20
21 Here, we report results obtained on such a grain for N₂O emissions from wheat-cropped
22 soils, at the sub-regional level. We used a crop model derived from CERES [*Jones and*
23 *Kiniry, 1986*], which incorporates a module for N₂O emissions [*Gabrielle et al., 2006*]. The

1 model was run on elementary units (vectorized contours) resulting from the combination of
2 several information layers in three agricultural sub-regions in Central France. The model
3 parameterization procedure was checked against ground measurements of N₂O emissions
4 in three test sites, and its spatial estimates compared to those obtained with the *IPCC*
5 [1997] method. We assessed the sensitivity of the modeled sub-regional estimates to un-
6 certainties in key physical and microbiological parameters, and evaluated their impacts
7 by means of an uncertainty analysis.

2. Material and Methods

2.1. The CERES-EGC model

8 CERES-EGC was adapted from the CERES suite of soil-crop models [*Jones and Kiniry,*
9 1986], with a focus on the simulation of environmental outputs such as nitrate leaching
10 and gaseous emissions of N₂O, ammonia and nitrogen oxides [*Gabrielle et al., 2006*].
11 CERES-EGC comprises sub-models for the major processes governing the cycles of wa-
12 ter, carbon and nitrogen in soil-crop systems. A physical module simulates the transfer
13 of heat, water and nitrate down the soil profile, as well as soil evaporation, plant water
14 uptake and transpiration in relation to climatic demand. A microbiological module simu-
15 lates the turnover of organic matter in the plow layer, involving both mineralization and
16 immobilization of inorganic N. Lastly, crop net photosynthesis is a linear function of in-
17 tercepted radiation according to the Monteith approach, with interception depending on
18 leaf area index based on Beer's law of diffusion in turbid media. Crop N uptake is com-
19 puted through a supply/demand scheme, with soil supply depending on soil nitrate and
20 ammonium concentrations and root length density.
21 CERES-EGC includes NOE [*Hénault et al., 2005*], a semi-empirical sub-model simulating

1 the production and reduction of N₂O in agricultural soils through both the denitrifi-
2 cation and nitrification pathways. The denitrification component of NOE is based on
3 NEMIS [*Hénault and Germon, 2000*], a model that expresses total denitrification of soil
4 NO₃⁻ as the product of a potential rate with three unitless factors related to soil water
5 content, nitrate content, and temperature. The fraction of denitrified nitrate that evolves
6 as N₂O is considered as constant for a given soil type, according to the experimental evi-
7 dence provided by *Hénault et al. [2001]*. In a similar fashion, nitrification is modeled as a
8 Michaëlis-Menten reaction, with NH₄⁺ as substrate. The corresponding rate is multiplied
9 by unitless modifiers related to soil water content and temperature. As for denitrifica-
10 tion, a soil-specific proportion of total nitrification evolves as N₂O, following the results
11 of *Garrido et al. [2002]*. The two pathways are connected in that nitrification-derived
12 N₂O may be reduced to N₂ by denitrification, should the two processes be simultaneously
13 active. Unlike other N₂O emission modules such as NGAS [*Parton et al., 2001*] or DNDC
14 [*Li et al., 2001*], NOE does not use the microbial respiration of organic C as a driver for
15 denitrification.

16 CERES-EGC runs on a daily time step, and computes the various transforma-
17 tion rates of N with the following sequence: nitrification, denitrification, mineraliza-
18 tion/immobilization, and crop uptake. This sequence reflects the priority order for possi-
19 bly competing processes, such as denitrification and crop uptake of nitrate.

2.2. Spatial simulations

2.2.1. Information layers

21 The study area comprised three administrative 'agricultural sub-regions' of the Beauce
22 region, lying approximately 200 km southwest of Paris, France: Beauce Chartraine (74

1 000 ha), Beauce Dunoise (61 200 ha), and Faux-Perche (48 200 ha). The sub-regions were
2 delineated by French authorities as relatively homogeneous zones from the point of view
3 of physical characteristics (climate, pedogenesis and geological substrate), and agricul-
4 tural production systems. The majority of soils in Beauce Chartraine are thick clay loams
5 (Haplic Luvisols - *Isambert* [1984]), either permeable upon limestone parent material, or
6 less material developed on a flinty clay substrate. The mean annual rainfall is 600 mm,
7 and mean air temperature is 10.6 °C. Beauce Dunoise comprises mostly thin loamy clay
8 soils (Haplic Calcisols), developed on calcareous layers. Mean annual rainfall is 636 mm,
9 and mean air temperature is 10.8 °C. Lastly, the soils in Faux-Perche are loamy Gleyic
10 Luvisols, developed on a flint clay substrate. Mean annual rainfall is 783 mm, and mean
11 air temperature is 10.3 °C. Farming systems are based on cereal crops in the first two
12 regions, and include some livestock production in Faux-Perche.

13
14 Elementary simulation units were defined by overlaying spatial information soil types,
15 climate, land use and crop management available at various geographical or administra-
16 tive levels. Only a fraction of the sub-regions was simulated, since we had chosen to focus
17 on winter wheat. Wheat is the major arable crop in the area, being grown on 30% to 40%
18 of total arable land. Each sub-region comprised 4 counties, at which level information
19 on land use was available through agricultural census data and farmers declarations for
20 European subsidies. Typical crop management practices for winter wheat were set based
21 on a survey in the three sub-regions. Soils were parameterized based on a 1:250 000 scale
22 soil map, organized into geographical units (SMU) containing a mixture of soil typological
23 units (STU), following the model of the European Union soil map [*King et al.*, 1994]. The

1 soil data base attached with the map comprised geographical information (the shape of
2 the SMUs) and quantitative data for each SMU: the occurrence of particular STUs within
3 the SMU, and various descriptors characterizing the STUs. The SMUs covered between
4 3 and 19,000 ha, with an average size of 775 ha. Daily weather data was taken for each
5 simulation unit from the closest station available, less than 20 km away from the centroid
6 of the unit.

7 **2.2.2. Soil parameterization**

8 Various methods were combined to estimate the soil parameters of CERES-EGC. Some
9 were readily-available as thematic fields in the soil data base: depth to parent material
10 (down to 2 m), which was used to set the simulation depth; maximum rooting depth
11 (with an upper limit of 1.5 m); the thickness of the various soil horizons along with
12 their particle-size distribution and bulk density. Soil water contents at wilting point and
13 field-capacity were estimated with pedo-transfer functions developed on a collection of *c.*
14 600 samples, mostly taken from the Paris basin, with contrasting textures [*Bastet et al.*,
15 1998]. The saturation water content, also required by CERES-EGC as input, was esti-
16 mated with the pedo-transfer function originally proposed by CERES [*Jones and Kiniry*,
17 1986]. Topsoil organic matter content was also included based on a nationwide survey
18 [*Arrouays et al.*, 1999], and updated in the course of this study. Surface pH and CaCO₃
19 contents were added to the data base using local references and expertise, and the same
20 went with saturated hydraulic conductivity. The latter was estimated using only three
21 classes centered on the following values: 0.02, 0.08, and 0.3 m d⁻¹, respectively.

22

23 The N₂O module of CERES-EGC involves a set of 3 microbiological parameters gov-

1 erning the processes of N₂O production and reduction in soils, as detailed in *Hénault*
2 *et al.* [2005]. They were measured in the laboratory in each test site of the sub-regions,
3 as follows: potential denitrification rates were measured by acetylene blocking of undis-
4 turbed soil cores taken from the top 20 cm of soil, saturated with water and incubated
5 with an ample supply of nitrate [*Hénault and Germon, 2000*]; the fraction of denitrified
6 nitrate that evolves as N₂O was determined as the difference between the N₂O production
7 rates of soil cores incubated with and without acetylene [*Hénault et al., 2001*]; lastly, the
8 fraction of nitrification evolved as N₂O was measured on sieved soil samples incubated
9 with increasing soil moisture content and non-limiting NH₃ supply, using the methodology
10 proposed by *Garrido et al.* [2002]. Table 1 lists the parameter values obtained in the three
11 sites.

12
13 Unfortunately, the limited size of the data base currently available for these parameters
14 precludes the definition of pedo-transfer functions for their spatial extension [*Hénault*
15 *et al., 2005*]. We thus simply applied the values obtained in the test site to the whole sub-
16 region, considering these sites representative of this area. The influence of this hypothesis
17 on the final results was tested in the uncertainty analysis.

18 **2.2.3. Model running**

19 CERES-EGC was run in each of the elementary simulation units for a reference period
20 running from mid-September, 1998, to mid-September, 1999. Initial moisture content was
21 set at 90% of the field-capacity content throughout the soil profile, based on simulations
22 of the preceding cropping season. Initial nitrate and ammonium concentrations in the soil
23 were set at 5 and 1 mg N kg⁻¹ soil, respectively, throughout the profile. It corresponds to

1 a total residual N content of 80 kg N ha⁻¹ in the top 1 m of soil, which is the average of
2 N stocks measured in the region at that time of year (B. Nicoullaud, unpublished data,
3 2003). Annual N deposition was neglected, being less than 4 kg N ha⁻¹ in the area [*Ulrich*
4 *and Willot*, 1993]. Since the focus was on wheat-cropped soils, the area of the simulation
5 units were corrected for the fraction of land cropped to wheat in these units. Aggregation
6 of elementary fluxes within each sub-region yielded the total N₂O efflux estimated from
7 winter wheat crops over this sub-region.

8 Wheat management data was set according to the recommendations made by local advi-
9 sory services [*Germon et al.*, 2003]. The mean doses of fertilizer N were 195 kg N ha⁻¹ in
10 Beauce Dunoise and 215 kg N ha⁻¹ in Faux-Perche and Beauce Chartraine, split into
11 three applications in spring. Only mineral fertilizers were considered (in the form of am-
12 monium nitrate and urea), since organic forms are applied on only 2% of the cropland area
13 in the region studied here, and make up less than 2 % of the total amounts of fertilizer N
14 applied.

15 **2.2.4. Sensitivity and uncertainty analysis**

16 Extrapolating model simulations from plot to regional scale involves two main sources
17 of uncertainty [*Butterbach-Bahl et al.*, 2004], which may be considered independent: i/
18 uncertainties in model inputs, including parameters, driving variables (climate and crop
19 management), and initial conditions, and ii/ model prediction error.

20 To address the first source, we ran a simple, local sensitivity test in which the inputs were
21 varied one-at-a-time over their plausible range while keeping the others at their nominal
22 value. We subsequently estimated a probability density functions (pdfs) for the most
23 sensitive inputs, and evaluated their combined effect on the variance of model predictions

1 using winding stairs sampling [*Jansen et al.*, 1994]. The method is a modified Latin
2 Hypercube sampling which makes it possible to estimate the contribution of individual
3 inputs (X_i) to the total variance in model output (Y) using variance ratios. For instance,
4 the 'top marginal variance' (TMV) is defined as: $TMV = Var(E(Y | X_i = x_i))/Var(Y)$,
5 where Var and E denote the variance and expectancy, respectively. The TMV indicates
6 the mean reduction of $Var(Y)$ made possible by setting input X_i at its nominal value x_i ,
7 *i.e.* imposing $Var(X_i) = 0$.

8 All analyses were done at the sub-regional scale, the output variable of interest (Y) being
9 the simulated N₂O efflux.

10

11 The second source of uncertainty (model error) was estimated as mean squared error
12 achieved by CERES-EGC in the prediction of annual N₂O fluxes in the three test sites,
13 using the regional parameterization (see below section). Ultimately, the total uncertainty
14 on the predicted sub-regional efflux was calculated as the sum of the variances related to
15 input uncertainties and to model error.

2.3. Local test sites

16 One test site was set up in each sub-region to check the simulations of N₂O emissions
17 obtained with the regional parameterization procedure detailed in section 2.2.2. The sites
18 were selected as representative of the sub-region, and involved a Haplic Luvisol in Beauce
19 Chartraine (site name: La Saussaye; 4824'N, 134'E), a Haplic Calcisol in Beauce Dunoise
20 (at Villamblain; 4798'N, 134'E), and a Gleyic Luvisol in Faux-Perche (at Arrou; 4808'N,
21 106'E) - FAO classification [*ISSS/ISRIC/FAO*, 1998].

22 N₂O emissions were monitored by the static chamber method using circular chambers (0.5

1 m in diameter and 0.15 m in height), with 8 replicates [Hénault *et al.*, 2005]. Other out-
2 puts were also monitored to test the simulation of intermediate variables. Topsoil water
3 content was continuously recorded using TDR probes, soil nitrogen content was measured
4 every two weeks in the topsoil and every month in the subsoil, and plants were regularly
5 sampled and analyzed for aerial dry matter, leaf area and nitrogen content. Lastly, a
6 weather station was set up to record the data required by CERES-EGC (rainfall, air tem-
7 perature and solar radiation), along with soil temperature.

8 Detailed information was also collected to supply the soil parameters of CERES-EGC.
9 Hydrodynamic parameters (water retention and hydraulic conductivity curves) were mea-
10 sured on intact cores taken to the laboratory. Site-specific parameters required by the
11 N₂O module were also measured in the laboratory, following the procedures given in sec-
12 tion 2.2.3.

13 These data sets were used to test the implementation of the N₂O modules within CERES-
14 EGC in a previous paper *Gabrielle et al.* [2006]. Here, they served to test the 'regional'
15 parameterization method described in section 2.2.2, against the baseline, more detailed
16 'local' parameterization resulting from the above measurements. In the test sites, model fit
17 to observed data was evaluated by calculating the mean deviation (MD) and the root mean
18 squared error (RMSE), defined as: $MD = E(O_i - S_i)$ and $RMSE = (E[(O_i - S_i)^2])^{1/2}$,
19 where S_i and O_i are the time series of the simulated and observed data. Model error in
20 the prediction of yearly cumulative (as opposed to daily instantaneous) N₂O fluxes was
21 assumed proportional to the simulated flux, and estimated as [Smith *et al.*, 1996]:

$$22 \quad RMSE_{yr} = 100/E(O_{i,s}) \times [E(MD_s^2)]^{1/2},$$

1 where MD_s are the mean deviations in the test sites, and $O_{i,s}$ the daily observations in
2 these sites.

3. Results

3.1. Simulations in the three test sites

3 Figure 1 compares the simulations obtained with the regional parameterization proce-
4 dure in the three test sites with those resulting from the detailed soil characterization,
5 which was used to implement the N₂O module of CERES-EGC [Gabrielle *et al.*, 2006].
6 In one of the sites (Villamblain), the potential denitrification rate had to be reduced by a
7 factor of 5 in order to obtain an acceptable fit to observed emission rates. Thus, this pa-
8 rameter was set at 3.4 kg N₂O-N ha⁻¹ yr⁻¹ in the surrounding sub-region, namely Beauce
9 Dunoise.

10 The local and regional parameterization scenarios yielded similar temporal dynamics in
11 all sites. However, closer examination revealed some differences in the magnitude of the
12 emission peaks simulated. Compared to the local parameterization, the regional one re-
13 sulted in lower fluxes after spring fertilization at Arrou and Villamblain, and higher fluxes
14 in La Saussaye. As a result, the N₂O emissions predicted by the regional parameteri-
15 zation scenarios differed by -40% to +130% relative to the local parameterization, when
16 accumulated over the simulation period (Table 2).

17 These discrepancies were mostly due to differences regarding soil water retention prop-
18 erties and bulk density, to which the model proved very sensitive. At La Saussaye, for
19 instance, topsoil bulk density differed by only 0.08 g cm⁻³ between the two parameteri-
20 zations, but this was enough to create a 30% deviation in terms of simulated N₂O efflux.

1 Despite these discrepancies, the mean deviations (MD) and root mean squared errors
2 (RMSE) achieved by the two parameterization scenarios were generally close, the only
3 notable difference being that the RMSE was significantly higher with the regional param-
4 eterization than with the local one at Arrou. The mean deviation was also relatively high
5 for this site (amounting to 8 g N₂O-N ha⁻¹ d⁻¹), compared to the other two sites in which
6 it was negligible. As a result, the estimated relative error for the annual simulated flux
7 (RMSE_{yr}) amounted to 64%.

3.2. Regional simulations

8 Table 3 summarizes the simulation outputs for the three sub-regions, while Figure 2
9 provides a geographical mapping of the emissions. In terms of spatial distribution, there
10 were no marked differences between the sub-regions, which all presented a wide range of
11 emission rates. Beauce Chartraine exhibited a longitudinal gradient with lower N₂O fluxes
12 to the East and higher fluxes to the West, whereas in Faux-Perche the emission levels were
13 vertically stratified from North to South. Conversely, Beauce Dunoise was rather homo-
14 geneous and centered in the mid-range values of N₂O fluxes. When expressed per unit
15 area, the mean N₂O fluxes varied markedly across the regions, from 0.63 kg N₂O-N ha⁻¹
16 yr⁻¹ in Beauce Dunoise to 2.23 kg N₂O-N ha⁻¹ yr⁻¹ in Faux-Perche. This range was
17 much lower than the 3.85 - 5.45 kg N₂O-N ha⁻¹ yr⁻¹ simulated in the test sites with the
18 regional parameterization.

19
20 Within the sub-regions, the western half of Beauce Chartraine appeared particularly sen-
21 sitive in the regional balance of N₂O emissions. Other zones prone to N₂O emissions zones
22 could also be delineated, such as the northernmost and southernmost tips of Faux-Perche.

1 Spatial structures in the other parts of the map were mostly determined by the spatial
2 resolution of the soil map units (SMU), some of which were rather large with sizes ranging
3 up to 19,000 ha. In addition, SMUs were made up of two to five different soil type units
4 (STUs), with possibly contrasting potentials for N₂O emission. On the other hand, emis-
5 sions were much less variable within a given STU when it occurred across several map
6 units and thereby climatic conditions. Figure 3 shows the distribution of fluxes across the
7 various STUs to be strongly skewed, with an extended tail in the higher range of emissions
8 ($> 5 \text{ kg N ha}^{-1} \text{ yr}^{-1}$). However, the weight of this upper-tail was very limited, comprising
9 only 11 STUs out of a total of 230, and making up 0.7% of the total area simulated.

3.3. Sensitivity analysis

10 Table 4 lists the parameters included in the sensitivity analysis, along with their stan-
11 dard deviations or variation ranges. Model response to changes in these inputs is given
12 only in the case of Beauce Chartraine, but similar patterns were noted in the other two
13 sub-regions (not shown).

14 Overall, the two microbiological parameters governing N₂O emissions (PDR and r_D) were
15 among the the three most sensitive inputs. When varied across their inter-regional range,
16 they introduced a one- to three-fold variation in the predicted N₂O efflux. This could
17 be expected since there was a factor of 5 between the minimum and maximum values of
18 PDR, and a factor of 3 for r_D . Also, given the nature of the denitrification equations, the
19 model responded linearly to changes in these parameters. Soil bulk density (BD) was the
20 next most influential parameter, as already noted in the local test sites. A 10% relative
21 variation of BD entailed more than much higher relative changes in model output, ranging
22 from -80% to 320%. This is due to the markedly convex power function used in the model

1 to relate the water-filled pore space (WFPS) to denitrification [*Hénault and Germon,*
2 2000]. Increasing bulk density decreases soil porosity and thereby the threshold moisture
3 content above which denitrification is activated, which corresponds to 62% WFPS. It
4 therefore increases the probability of moisture conditions conducive to denitrification and
5 N₂O emissions. For the same reason, the field-capacity water content (θ_{fc}) also proved
6 sensitive, but to a lesser extent. Surprisingly, the saturated hydraulic conductivity had
7 very little effect, despite being varied over a wide range ($\pm 50\%$). It is probably because
8 the dynamics of topsoil water were mostly governed by the field-capacity content, at least
9 for water contents close to saturation, as previously reported with the CERES water bal-
10 ance routine [*Gabrielle and Kengni, 1996*].

11
12 The model was unsensitive to topsoil organic C content and pH, because unlike other
13 models [*Parton et al., 2001; Li et al., 2001*], it does not explicitly include these factors as
14 controls in the production and reduction of N₂O. Their influence is only indirect, via the
15 processes of ammonia volatilization (for soil pH) and the mineralization/immobilization
16 of soil N (for soil organic C). Initial soil water and N content appeared little to mod-
17 erately sensitive, respectively. There was a -21% to +31% change in the sub-regional
18 N₂O flux over the range of initial N contents. The influence of initial water content was
19 more marginal, probably because the simulations started two months ahead of the wetter
20 winter season. On the other hand, changes in annual rainfall affected soil water content
21 throughout the simulation period, and rainfall appeared as sensitive as initial N content
22 as a result.

3.4. Uncertainty analysis

1 Based on the above results, 5 parameters were selected for the uncertainty analysis:
2 PDR, r_D , BD, θ_{fc} , and initial soil N content (I_N). We used truncated Gaussian pdfs
3 ($0.025 \leq p \leq 0.975$) for the last 3 inputs, considered site-specific, and uniform pdfs for
4 the first two, considered as constant within each sub-region. A correlation coefficient of
5 -0.52 between the field-capacity water content and bulk density was introduced, according
6 to the finding of *Bastet et al.* [1998].

7 The distributions of N₂O fluxes generated with the winding stairs sampling (WSS) of these
8 inputs were log-normal, with an extended tail in the higher range of values and a large
9 variance (Figure 4). Table 5 shows the median and 95% confidence intervals calculated
10 in the three sub-regions. In all of them, the median fluxes were larger than the baseline
11 values of Table 3. This was expected in Beauce-Chartraine and Beauce Dunoise, given
12 that in the baseline parameterization they were ascribed the lowest values for r_D and/or
13 PDR. Since the pdfs of these two parameters were centered on the mid-range estimates
14 of these parameters, the fluxes generated by sampling in these pdfs could only be higher
15 than with the baseline parameterization. However, this is not true of Faux-Perche, and
16 in fact the opposite since the baseline value of r_D in Faux-Perche was the higher bound of
17 its sampling range (64%). The fact that the WSS-generated median flux was still higher
18 than its baseline value evidences the influence of the site-specific parameters (θ_{cf} , I_N and
19 BD), and also strong non-linearity with the model.

20
21 There was ample variation around the median: the lower and upper 95% confidence
22 limits corresponded to 18-20% and 420-450% of the median, respectively, and the coeffi-

1 cients of variations ranged from 109% to 123%. Compounding this variability with the
2 estimated model prediction error (assuming both variates to be log-normal), the lower
3 and upper limits of the 95% confidence were estimated as 33% and 300% of the predicted
4 flux, respectively. Lastly, the calculation of top marginal variances (TMV) made it pos-
5 sible to estimate the contribution of individual inputs to the total variance. Soil physical
6 parameters (BD and θ_{fc}) explained 62% to 75% of the total variance, while the microbi-
7 ological parameters (PDR and r_D) had a contribution ranging from 12% to 30%, and the
8 initial nitrate content only had a marginal role. This ranking differs from that output by
9 the one-at-a-time sensitivity test (Table 4), evidencing interactions between inputs that
10 amplified model response to physical parameters while drastically reducing the influence
11 of initial conditions.

3.5. Sensitivity to fertilizer N

12 At the sub-regional level, the model-based estimates of direct N₂O emissions from wheat-
13 cropped fields were 10% to 70% lower than the IPCC ones. The deviation was strongest
14 in Beauce Dunoise and smallest in Faux-Perche, reflecting the ranking of the sub-regions
15 respective to N₂O emissions on a per hectare basis. The background emissions simulated
16 by CERES-EGC were also lower than the IPCC default value of 1 kg N₂O-N ha⁻¹, but to
17 a lesser extent than the total emissions, and ranged from 0.52 to 1.02 kg N₂O-N ha⁻¹. As
18 a result, model-based EF_d estimates were extremely low compared to the IPCC default
19 (0.0125 ± 0.01 kg N₂O-N kg⁻¹ N), ranging from 0.0007 to 0.0033 kg N₂O-N kg⁻¹ N. This
20 low sensitivity of model results to fertilizer N essentially arose from the fact that a major
21 fraction of the emissions happened outside the spring season during which fertilizer was
22 applied. Some emissions occurred prior to wheat planting in the fall of 1998, as may be

1 seen on Figure 1, or in the late summer and fall of 1999. Because wheat crops actively
2 took up soil N during their growing season, fertilization actually had little influence on
3 the soil inorganic content upon harvest in summer, and on the subsequent emissions of
4 N₂O.

5
6 Secondly, N₂O emissions were generally proportional to the amount of fertilizer N ap-
7 plied to crops, whatever the range of fertilizer doses (Figure 5). As a result, the average
8 EF_{dS} estimated by fitting a straight line to the response curve provided estimates nearly
9 identical to those obtained by using emissions data only for the nominal and zero doses
10 of fertilizer N, as is usually done in the IPCC method.

4. Discussion

4.1. Uncertainty and validity of regional estimates

11 Extrapolating model simulations from plot to regional scale involves some degree of
12 uncertainty in spatialized inputs as well as model robustness to spatial extension. The
13 uncertainties of a range of inputs could be quantified prior to extrapolation, and their
14 effects approached via sensitivity and uncertainty analyses (UA).

15 The setting of microbiological parameters (PDR and r_D) proved most crucial in the re-
16 gional extension, being both sensitive and highly uncertain. Unfortunately, they could not
17 be spatialized based on the available soil information because they do not yet appear to
18 be related to particular physico-chemical properties, such as soil texture or organic mat-
19 ter content [Hénault *et al.*, 2005]. For lack of an alternative method, we assumed in the
20 baseline parameterization that the values of PDR and r_D measured in each test site could
21 apply to the entire surrounding sub-region. This hypothesis of a strong spatial structure

1 in the distribution of soil microbiological properties was based on the pedoclimatic zoning
2 of the sub-regions. However, it may appear somewhat arbitrary, and was actually tested
3 against a null hypothesis by which microbiological properties were randomly distributed
4 across the sub-regions within their overall variation ranges. The difference between the
5 two parameterizations turned out to be extremely large: the median N₂O effluxes cal-
6 culated in the UA were 1.2- to 8-fold higher than with the baseline parameterization.
7 Better knowledge of the spatial determinants of those parameters is therefore paramount
8 to reducing the uncertainty of such model-based estimates.

9
10 Topsoil bulk density was also very sensitive, but its contribution to the total variance
11 was somewhat reduced because of its correlation with the field-capacity water content.
12 Although the wide body of literature currently available on the estimation of these param-
13 eters makes it possible to narrow down their range of uncertainty, it is notable that they
14 contributed nearly as much variance to the N₂O fluxes as the microbiological parameters.
15 This contribution of water content was also noted by *Mummey et al.* [1998], who reported
16 a 1.3- to 2-fold increase in N₂O emissions from arable crops when increasing soil water
17 content by 40%. In addition, because the variation ranges chosen for these parameters
18 fall within their spatial variations at the field-scale [*Yanai et al.*, 2003], it is likely that
19 this source of error will remain as a background noise in the predictions of N₂O.

20 Lastly, the fact that the model was sensitive to the initial soil N content points at a pos-
21 sible strategy for reducing N₂O emissions. A target initial content of 40 kg N ha⁻¹ (down
22 to 1 m) would indeed make it possible to reduce the emissions by 25%, which is more than
23 what could be achieved by a drastic reduction of fertiliser N application to the following

1 crop. Best management practices may in principle make it possible to reach such a target
2 [*Loyce et al.*, 2002].

3
4
5 The second major source of uncertainty (model robustness to spatial extension) could
6 be judged from the mean deviations achieved by CERES-EGC in the test sites with the
7 regional parameterization. These errors ranged from 0.5 to 8.4 g N₂O-N ha⁻¹ d⁻¹, which
8 represents 7% to 50% of the mean observed fluxes (Table 2). This range may be taken as
9 the error margin associated with the simulation of the annual N₂O efflux by the model.
10 When compounded over the three sites, the average relative prediction error was esti-
11 mated at 64%, because one of the test sites (Arrou) had much higher fluxes than the
12 other two. From a more qualitative viewpoint, the extent to which CERES-EGC could
13 be extrapolated to new field situations may be judged based on its N₂O sub-model, NOE.
14 The latter was successfully tested in 3 field sites in France, other the 3 test sites involved
15 here, along with 3 field sites in Central America [*Hénault et al.*, 2005]. In these sites the
16 mean daily emission rates varied between 2 to 50 g N₂O-N ha⁻¹ d⁻¹, thus encompassing
17 the 6-7 g N₂O-N ha⁻¹ d⁻¹ range that could be expected in the sub-regions based on the
18 IPCC approach (Table 3).

19
20 Regional estimates based on bottom-up aggregation of plot-scale fluxes generally involve
21 model testing in a few test sites, and direct extrapolation to the area of interest [*Li et al.*,
22 2001; *Mummey et al.*, 1998]. Because testing usually involves site-specific calibration of
23 some model parameters [*Frolking et al.*, 1998; *Gabrielle et al.*, 2002], we included here

1 an intermediate phase in which the default parameterization procedure applied at the re-
2 gional scale was compared with a more detailed, site-specific parameterization. Of course,
3 this comparison also involves a scaling issue, since the soil typological units (STUs) used
4 in the regional parameterization were much larger than the area covered by the measure-
5 ments in the test sites. As a result, the discrepancies between the model outputs using
6 whether the site-specific or the regional parameterization should not be taken as a failure
7 of the model, but rather as an indication of the degree of uncertainty associated when
8 downscaling from the mapping unit (SMU) to the plot-scale. It is also noticeable that
9 they produced an acceptable fit to the measurements (Table 2).

10 Overall, combining the unknowns mentioned above resulted in 95% confidence limits rep-
11 resenting 33% and 300% of the mean simulated estimates, respectively. This is much
12 larger than the $\pm 80\%$ confidence interval of the IPCC methodology, and the $\pm 50\%$ in-
13 terval reported by *Li et al.* [2001] in their inventory based on the DNDC model, but
14 it encompasses more sources of uncertainty - including, most notably, model prediction
15 error.

4.2. Empirical and model-based emission factors

16 There is a growing body of literature on the determination of direct emission factors
17 (EF_ds) from field measurements at the plot-scale. These factors have been shown to be
18 extremely variable from one field to the other, ranging from 0.0003 to 0.068 kg N₂O-
19 N kg⁻¹ N [*Flessa et al.*, 2002; *Velthof et al.*, 2003; *Kaiser et al.*, 1998; *Zheng et al.*, 2004].
20 There are many sources of uncertainty behind these empirical estimates: quantification
21 of background emissions, spatial and temporal coverage, and time-frame on which the
22 measurements are carried out, which all warrant corrections [*Zheng et al.*, 2004]. Ac-

1 cording to the latter, the absence of background emissions data is expected to lead to
2 an over-estimation of EF_{ds} , by 15% to 110% under Chinese conditions. Conversely, a
3 shortage of temporal coverage (insufficient frequency of measurements) would lead to an
4 under-estimation by 19% to 30%.

5 Process-based models should not require any such corrections since they simulate
6 N₂O emissions continuously over time, and can predict fertilized as well as unfertilized
7 crops. Thus, they may be expected to supply EF_d values up to 80% lower than the empir-
8 ical estimates listed above, among which the IPCC methodology. Such was the case with
9 the EF_{ds} simulated with CERES-EGC, which fell in the lower range of the IPCC val-
10 ues. Similarly, another modeling study reported an average EF_d of 0.008 kg N₂O-N kg⁻¹
11 N with a 0.0025-0.04 kg N₂O-N kg⁻¹ N range for cropland in China [Zheng *et al.*, 2004].
12 The same tendency was reported in another modeling study: Li *et al.* [2001] estimated
13 Calculation of EF_{ds} without the control term (ie assuming zero emissions for unfertilized
14 crops), as was done in a number of studies for lack of background emissions data [Zheng
15 *et al.*, 2004], resulted in EF_{ds} ranging between 0.0033 and 0.0104 kg N₂O-N kg⁻¹ N. This
16 falls within the lower half of the IPCC range (0.0025 to 0.0225 kg N₂O-N kg⁻¹ N).

17 Fertilizer type is also mentioned to affect the values of EF_d , although there is a lack of
18 sufficient data to derive generic, fertilizer-specific figures [Bowman, 1996; Mosier *et al.*,
19 1996]. Bowman [1996] reported EF_d values of 0.003 ± 0.003 kg N₂O-N kg⁻¹ N for am-
20 monium nitrate and urea, the two types of fertilizers used in the sub-regions simulated
21 here.

22

23 Lastly, EF_{ds} should capture some range of inter-annual variability. It is in principle

1 possible with a model like CERES-EGC, but we considered it beyond scope here since we
2 focused on spatial extension from plot-scale to regional scale. However, our results are to a
3 large extent conditioned by the growing season in which the experiments and simulations
4 were run. Investigating the effect of inter-annual climate variability is therefore a major
5 prospect for future work on N₂O simulations.

4.3. Factors controlling N₂O emissions at the regional scale

6 Two major differences occurred between the model-based and IPCC estimates of
7 N₂O emissions at the sub-regional scale: the magnitude of the emissions, and the re-
8 sponse to fertiliser N. Both appeared much weaker with the model, and are discussed
9 below. The lack of response to fertilization essentially occurred because the simulated
10 N₂O emissions were not concentrated in the spring season when fertilizer was applied.
11 However, it may also be a result of the upscaling from field- to regional-scale. The lit-
12 erature on spatial extension of N₂O fluxes, whether using process-based models or more
13 empirical methods, shows the 'fertilizer dose' factor to lose some influence in favor of envi-
14 ronmental characteristics, as the spatial area increases. At the European scale, *Freibauer*
15 [2003] modeled N₂O emissions based on pedological and agronomic factors, and found a
16 coefficient of only 0.4% in the correlation between these emissions and fertilizer doses. In
17 a review of emission data covering a wide range of crop management and geographical
18 locations, *Kaiser et al.* [1998] report a similar coefficient with a value of 0.6%. These
19 figures could be interpreted as an average EF_d of 0.004 to 0.006 kg N₂O-N kg⁻¹ N for
20 Europe. The apparent discrepancy between the ranges of EF_ds obtained at the plot and
21 regional scales may be due to an uneven sampling of field sites biased towards the more
22 N₂O-productive sites, when establishing empirical EF_ds, and these sites might turn out

1 to represent only a small proportion of total arable land. Such was the case in our study
2 since the test sites were actually above average in terms of N₂O emissions. The frequent
3 lack of background data in these experiments is also a source of bias since a significant
4 part of the emissions attributed to fertilizer use might actually be related to the soil
5 potential per se, as happened in our simulations. For urea and ammonium-nitrate type
6 fertilizers, *Bouwman* [1996] reported relative differences as high as 100% between EF_d
7 estimates including or not an unfertilized control.

8
9 Regarding the magnitude of the simulated fluxes, the study by *Li et al.* [2001] at the
10 country level revealed a clustered spatial pattern for N₂O emissions, with contrasting ef-
11 flux rates between groups of counties (equivalent to our sub-regions). It is thus probable
12 that some sub-regions would contribute significantly less N₂O than others, which seems
13 to be the case with those we had selected here. On the other hand, the IPCC EF_d are
14 representative at a global or continental scale, as they were obtained from observations
15 worldwide, rather than at the sub-regional level. Overall, in our sub-regions, N₂O emission
16 levels primarily depend on a local potential set by climatic conditions combined with soil
17 microbiological and physical properties, with the influence of crop management appearing
18 somewhat minor in the expression of this potential. As a consequence, reducing fertilizer
19 N would seemingly have little effect on abating N₂O fluxes. However, the fertilizer dose
20 also influences the residual N content upon sowing of the proceeding crop, which signifi-
21 cantly affected the sub-regional N₂O efflux.

22
23 As a conclusion, under such mild temperate climatic conditions as investigated here,

1 mitigation measures should target a reduction in the amount of soil mineral N in autumn,
2 and a decrease of the soil N₂O production potential itself. While there is a range of
3 best management packages available to address the first point, there is a need for future
4 research on the microbial and physical determinants of soil emission potentials, and how
5 they may be affected by crop management.

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References

- 9 Arrouays, D., W. Deslais, J. Daroussin, J. Balesdent, J. Gaillard, J. L. Dupouey, C. Nys,
10 V. Badeau, and S. Belkacem (1999), Stocks de carbone dans les sols de France. Quelles
11 estimations?, *CR. Acad. Agric. F.*, 85, 278–292.
- 12 Bastet, G., A. Bruand, P. Quéting, and I. Cousin (1998), Estimation des propriétés de
13 rétention en eau des sols à l'aide de fonctions de pédo-transfert (FPT), *Et. Ges. Sols*,
14 5, 7–28.
- 15 Bouwman, A. (1996), Direct emissions of nitrous oxide from agricultural soils, *Nutr. Cycl.*
16 *Agroecos.*, 46, 53–70.
- 17 Butterbach-Bahl, K., M. Kesik, P. Miehe, H. Papen, and C. Li (2004), Quantifying the
18 regional source strength of N-trace gases across agricultural and forest ecosystems with
19 process based models, *Plant Soil*, 260, 311–329.
- 20 Duxbury, J. M., and D. R. Bouldin (1982), Emission of nitrous oxide from soils, *Nature*,
21 298, 462–464.

- 1 Flessa, H., R. Ruser, P. Dorsch, T. Kamp, M. Jimenez, and J. C. Munch (2002), Integrated
2 evaluation of greenhouse gas emissions (CO₂, CH₄, N₂O) from two farming systems in
3 southern Germany, *Agric. Ecosys. Environ.*, *91*, 175–189.
- 4 Freibauer, A. (2003), Regionalised inventory of biogenic greenhouse gas emissions from
5 European agriculture, *Eur. J. Agron.*, *19*, 135–160.
- 6 Frohling, S. E., A. R. Mosier, D. S. Ojima, C. Li, W. J. Parton, C. S. Potter, E. Priesack,
7 R. Stenger, C. Haberbosch, P. Dörsch, H. Flessa, and K. A. Smith (1998), Comparison
8 of N₂O emissions from soils at three temperate agricultural sites: simulations of year-
9 round measurements by four models, *Nutr. Cycl. Agroecos.*, *52*, 77–105.
- 10 Gabrielle, B., and L. Kengni (1996), Analysis and field-evaluation of the CERES models'
11 soil components: Nitrogen transfer and transformation, *Soil Sci. Soc. Am. J.* *60*:142-
12 *149*.
- 13 Gabrielle, B., R. Roche, P. Angas, C. Cantero-Martinez, L. Cosentino, M. Mantineo, M. L.
14 an C. Hénault, P. Laville, B. Nicoullaud, and G. Gosse (2002), A priori parameterisation
15 of the ceres soil-crop models and tests against several european data sets, *Agronomie*
16 *22*: 119-132.
- 17 Gabrielle, B., P. Laville, C. Hénault, B. Nicoullaud, and J. C. Germon (2006), Simulation
18 of nitrous oxide emissions from wheat-cropped soils using CERES, *Nutr. Cycl. Agroecos.*,
19 *74*, 133 – 146, doi:10.1007/s10705-005-5771-5.
- 20 Garrido, F., C. Henault, H. Gaillard, S. Perez, and J. C. Germon (2002), N₂O and NO
21 emissions by agricultural soils with low hydraulic potentials, *Soil Biol. Biochem.*, *34*,
22 559–575.

- 1 Germon, J. C., C. Hénault, P. Cellier, D. Chèneby, O. Duval, B. Gabrielle, P. Laville,
2 B. Nicoullaud, and L. Philippot (2003), Les émissions de protoxyde d'azote (N₂O)
3 d'origine agricole. Evaluation au niveau du territoire français., *Et. Ges. Sols*, 10, 315–
4 328.
- 5 Grant, R. F., and E. Pattey (2003), Modelling variability in N₂O emissions from fertilized
6 agricultural fields, *Soil Biol. Biochem.*, 35, 225–243.
- 7 Hénault, C., and J. C. Germon (2000), NEMIS, a predictive model of denitrification on
8 the field scale, *Eur. J. Soil Sci.*, 51, 257–270.
- 9 Hénault, C., D. Chèneby, K. Heurlier, F. Garrido, S. Perez, and J. Germon (2001), Lab-
10 oratory kinetics of soil denitrification are useful to discriminate soils with potentially
11 high levels of N₂O emission on the field scale, *Agronomie*, 21, 713–723.
- 12 Hénault, C., F. Bizouard, P. Laville, B. Gabrielle, B. Nicoullaud, J. C. Germon, and
13 P. Cellier (2005), Predicting *in situ* soil N₂O emissions using NOE algorithm and soil
14 data base, *Global Change Biol.*, 11, 115–127.
- 15 IPCC (1997), *Guidelines for national greenhouse gas inventories: greenhouse gas inven-*
16 *tory reference manual, revised 1996*, IPCC/OECD/IGES, Bracknell, UK.
- 17 Isambert, M. (1984), Carte pédologique 1/100 000 de Châteaudun. Notice explicative,
18 *Tech. rep.*, INRA Edition, Paris.
- 19 ISSS/ISRIC/FAO (1998), *World Reference Base for soil resources, World Soil Resources*
20 *Rep.*, vol. 84, FAO, Rome.
- 21 Jansen, M. J. W., W. A. H. Rossing, and R. A. Daamen (1994), Monte Carlo estimation of
22 uncertainty contributions from several independent multivariate sources, in *Predictabil-*
23 *ity and nonlinear modelling in natural sciences and economics*, edited by J. Grasman

- 1 and G. van Straten, pp. 335–343, Kluwer Academic Publ., Dordrecht, N.L.
- 2 Jones, C. A., and J. R. Kiniry (1986), *Ceres-N Maize: a simulation model of maize growth*
3 *and development*, Texas A&M University Press, College Station, Temple, TX.
- 4 Kaiser, E. A., K. Kohrs, M. Kucke, E. Schnug, O. Heinemeyer, and C. Munch (1998),
5 Nitrous oxide release from arable soil: importance of N fertilization, crops and temporal
6 variation, *Soil Biol. Biochem.*, *30*, 1553–1563.
- 7 King, D., J. Daroussin, and M. Jamagne (1994), Proposal for a spatial organization model
8 in soil science (the example of the European Communities soil map), *J. Am. Soc. Inform.*
9 *Sci.*, *45*, 705–717.
- 10 Li, C., Y. Zhuang, M. Cao, P. Crill, Z. Dai, S. Frolking, B. M. III, W. Salas, W. Song,
11 and X. Wang (2001), Comparing a process-based agro-ecosystem model to the IPCC
12 methodology for developing a national inventory of N₂O emissions from arable lands in
13 China, *Nutr. Cycl. Agroecos.*, *60*, 159–175.
- 14 Li, C. S., S. Frolking, X. M. Xiao, B. Moore, S. Boles, J. J. Qiu, Y. Huang, W. Salas, and
15 R. Sass (2005), Modeling impacts of farming management alternatives on CO₂, CH₄,
16 and N₂O emissions: A case study for water management of rice agriculture of China,
17 *Global Biogeochem. Cycles*, *19*, GB3010, doi:10.1029/2004GB002341.
- 18 Loyce, C., J. P. Rellier, and J. M. Meynard (2002), Management planning for winter
19 wheat with multiple objectives (2): ethanol-wheat production, *Agric. Syst.*, *72*, 33–57.
- 20 Mosier, A. R., J. M. Duxbury, J. R. Freney, O. Heinemeyer, and K. Minami (1996), Ni-
21 trous oxide emissions from agricultural fields: Assessment, measurement and mitigation,
22 *Plant Soil*, *181*, 95–108.

- 1 Mosier, A. R., C. Kroeze, C. Nevison, O. Oenema, S. Seitzinger, and O. V. Cleemput
2 (1998), Closing the global N₂O budget: nitrous oxide emissions through the agricultural
3 nitrogen cycle, *Nutr. Cycl. Agroecos.*, *52*, 225–248.
- 4 Mummey, D. L., J. L. Smith, and G. Bluhm (1998), Assessment of alternative soil man-
5 agement practices on N₂O emissions from US agriculture, *Agric. Ecosys. Environ.*, *70*,
6 79–97.
- 7 Parton, W. J., E. A. Holland, S. J. D. Grosso, M. D. Hartman, R. E. Martin, A. R. Mosier,
8 D. S. Ojima, and D. S. Schimel (2001), General model for NO_x and N₂O emissions from
9 soils, *J. Geophys. Res.*, *106*, 17,403–17,419.
- 10 Smith, J. U., P. Smith, and T. M. Addiscott (1996), Quantitative methods to evaluate
11 and compare Soil Organic Matter (SOM) models, in *Evaluation of Soil Organic Matter*
12 *Models*, edited by D. S. Powlson, J. U. Smith, and P. Smith, pp. 181–199, Springer-
13 Verlag, Berlin Heidelberg.
- 14 Ulrich, E., and B. Willot (1993), Les dépôts atmosphériques en France de 1850 à 1990,
15 *Synthèse*, A.D.E.M.E./O.N.F./I.N.R.A., Office National des Forêts, Paris.
- 16 Velthof, G. L., P. J. Kuikman, and O. Oenema (2003), Nitrous oxide emission from animal
17 manures applied to soil under controlled conditions, *Biol. Fert. Soils*, *37*, 221–230.
- 18 Yanai, J., T. Sawamoto, T. Oe, K. Kusa, K. Yamakawa, K. Sakamoto, T. Naganawa,
19 K. Inubushi, R. Hatano, and T. Kosaki (2003), Spatial variability of nitrous oxide
20 emissions and their soil-related determining factors in an agricultural field, *J. Environ.*
21 *Qual.*, *32*, 1965–1977.
- 22 Zheng, X., S. Han, Y. Huang, Y. Wang, and M. Wang (2004), Re-quantifying the emission
23 factors based on field measurements and estimating the direct N₂O emission from Chi-

1 nese croplands, *Global Biogeochem. Cycles*, 18(GB2018), doi:10.1029/2003GB002167.

Table 1. Soil microbiological parameters of NOE measured at the three test sites.

Symbol	Description (Unit)	Parameter value		
		La Saussaye	Villamblain	Arrou
PDR	Potential denitrification rate (kg N ha ⁻¹ yr ⁻¹)	15.7	16.9	9.4
r_D	Fraction of denitrification evolved as N ₂ O(%)	20	20	64
r_N	Fraction of nitrification evolved as N ₂ O(%)	0.06	0.06	0.06

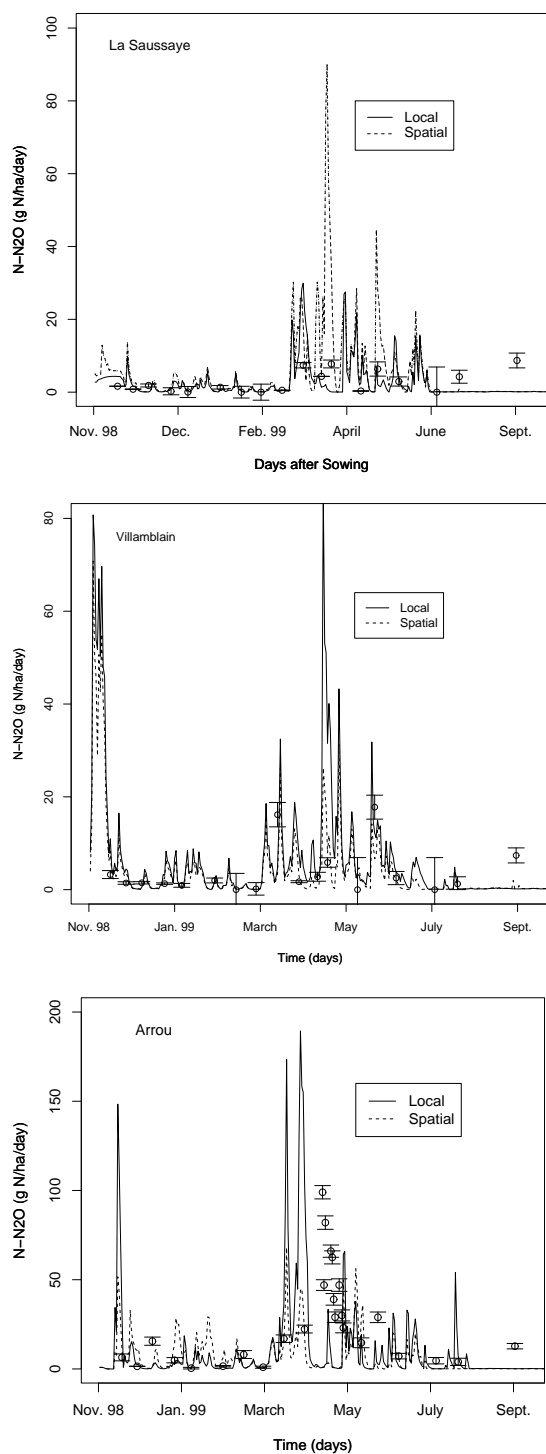


Figure 1. Simulated (lines) and observed (symbols) emissions of N₂O in the three test sites. In the local parameterization scenario, detailed, site-specific information on soil properties was used, whereas the regional scenario involved only information derived from the soil map.

Table 2. Cumulative annual N₂O emissions (kg N₂O-N ha⁻¹ yr⁻¹) simulated with the local and regional regional parameterization procedures, along with statistical indicators of model fit to observed data. The hypothesis that the mean deviation is zero was tested using a two-tailed t-Test, and the root mean squared error is compared to mean experimental error using an F variance test [Smith *et al.*, 1996].

Parameterization scenario	La Saussaye		Villamblain		Arrou	
	Regional	Local	Regional	Local	Regional	Local
Annual N ₂ O flux (kg N ₂ O-N ha ⁻¹ yr ⁻¹)	5.08	3.29	5.45	2.39	3.85	6.64
Mean deviation (g N ₂ O-N ha ⁻¹ d ⁻¹)	0.61 ^a	-0.95 ^a	0.56 ^a	-1.24 ^a	8.84 ^a	5.57 ^a
Root mean squared error (g N ₂ O-N ha ⁻¹ d ⁻¹)	4.99 ^b	8.04	6.43 ^b	9.00 ^b	34.1	38.4

^a not significantly different from zero (p=0.05)

^b not significantly greater than experimental error (p=0.05)

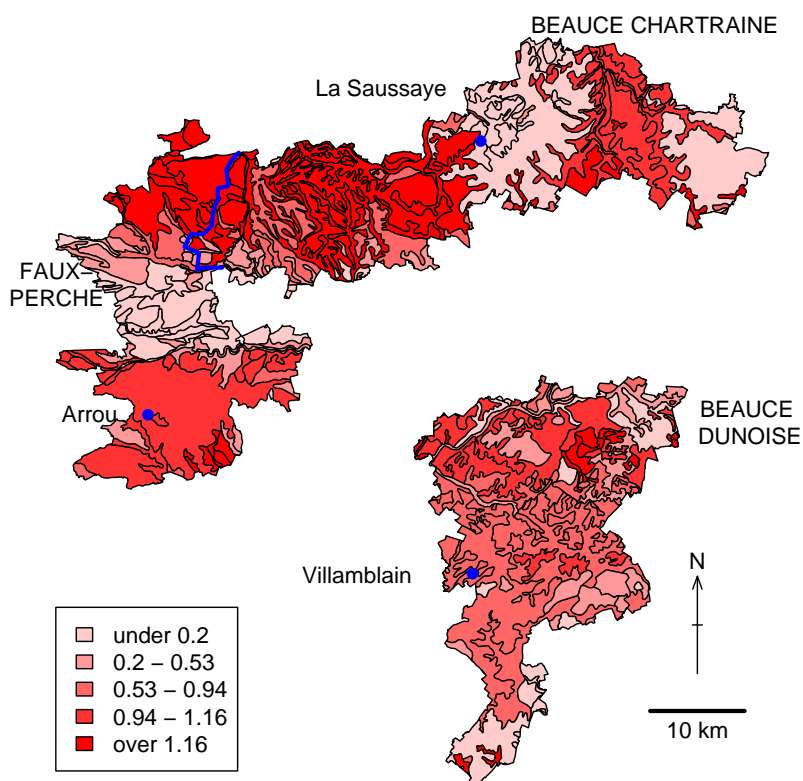


Figure 2. Simulation of N₂O emissions from wheat-cropped land in three agricultural sub-regions of the Beauce region. The fluxes are expressed in kg N₂O-N ha⁻¹.

Table 3. Emissions of N₂O simulated within each sub-region (total and average per hectare), with a standard or zero dose of fertilizer N. Regional estimates obtained with the IPCC methodology are also reported (corresponding to the emissions due to fertilizer application).

Sub-region	Total area simulated	Fertilizer N dose	Mean annual N ₂ O flux	Regional flux	Regional Emission Factor
	ha	kg N ha ⁻¹	kg N ₂ O-N ha ⁻¹	kg N ₂ O-N	kg N ₂ O-N kg ⁻¹ N
Beauce	31,927	215	1.37	42,887	0.0016
Chartraine		0	1.02	31,868	
IPCC	31,927	215	2.42	85,804	0.0125
Beauce	23,474	195	0.65	15,384	0.0007
Dunoise		0	0.52	12,165	
IPCC	23,474	195	2.13	57,218	0.0125
Faux-	16,578	215	2.23	37,010	0.0033
-Perche		0	1.51	25,062	
IPCC	16,578	215	2.42	44,553	0.0125

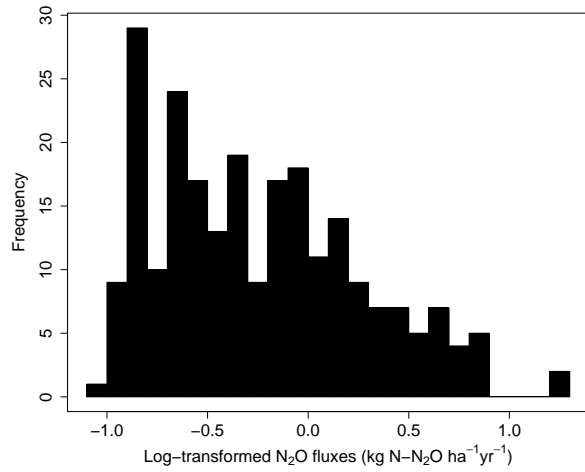


Figure 3. Histogram of log-transformed simulated fluxes across the various soil type units in the three sub-regions.

Table 4. Sensitivity of model-predicted N₂O efflux in the Beauce Dunoise sub-region to selected inputs. Soil parameters pertain to the top layer (0-30 cm). Site-specific inputs were assigned a fixed coefficient of variation (CV, in %), and varied within their 95% confidence interval, while inputs considered constant at the sub-regional level were given an overall variation range. Model response is expressed as changes in model output relative to the baseline input setting.

Symbol	Description (Unit)	Variation range / CV	Source	Model response (change relative to baseline)
SOIL PARAMETERS				
OC	organic carbon content (g g ⁻¹ soil)	15%	1	-1.7% to +2.2%
pH	pH in water	8%	1	-0.3% to +2.1%
BD	Topsoil bulk density (g cm ⁻³)	5%	2	-80% to +321%
K _{sat}	Saturated hydraulic conductivity (m d ⁻¹)	50%	3	-1.3% to +1.9%
θ _{fc}	Soil water content at field-capacity (g g ⁻¹ soil)	10%	4	-72.5% to +250%
PDR	Potential denitrification rate (kg N ₂ O-N ha ⁻¹ yr ⁻¹)	3.4 – 15.7	5	-71% to 0%
r _D	Fraction of denitrification evolved as N ₂ O (%)	20 – 64	5	0% to +290%
DRIVING VARIABLES				
R	Annual rainfall (mm yr ⁻¹)	10%	6	-22.3% to +27.2%
INITIAL CONDITIONS				
I _N	Mineral N in soil profile (top 1 m; kg N ha ⁻¹)	40 – 125	6	-24.1% to +31.4%
I _w	Moisture content in soil profile (top 1 m; mm)	50 – 150	6	-6.7% to +1.8%

1: Variability within soil type units; 2: Measurement error; 3: Range covered by each K_{sat} class; 4: Prediction error of pedo-transfer function [Bastet *et al.*, 1998]; 5: Range across the 3 test sites; 6: Intra-regional variability [Nicoullaud, B. (unpublished data, 2003)].

Table 5. Statistics of the sub-regional N₂O fluxes generated by winding stairs sampling of 5 parameters. The coefficient of variation (CV) was estimated on the truncated distribution ($0.025 \leq p \leq 0.975$).

Sub-region	Median	95% confidence interval	CV
Beauce Chartraine	118.1	21.2 – 497.2	109%
Beauce Dunoise	125.0	15.0 – 561.2	123%
Faux-Perche	49.4	9.8 – 213.0	113%

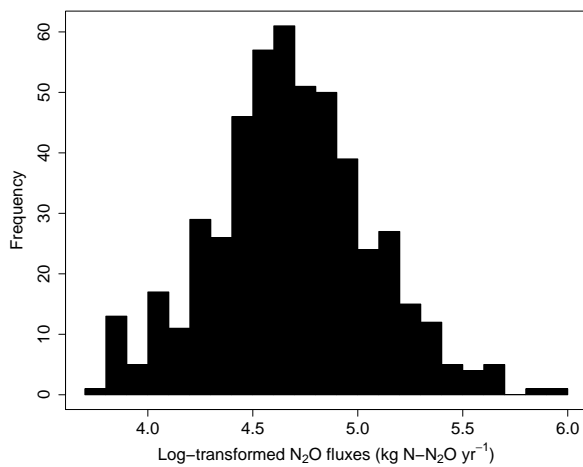


Figure 4. Log-transformed frequency distribution of the total N₂O efflux in Faux-Perche obtained by winding stairs sampling of model inputs.

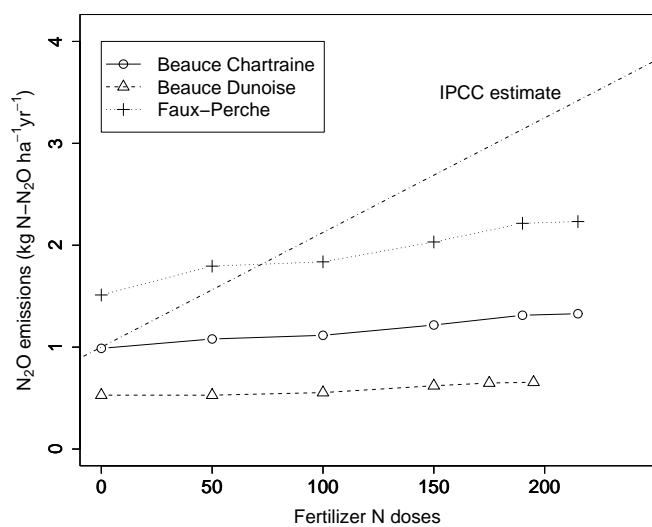


Figure 5. Simulated relationships between fertilizer N dose and year-round N₂O emissions at the sub-regional level. The straight line corresponds to the *IPCC* [1997] relationship.