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Greenhouse gas emissions from the grassy outdoor run of organic broilers

**B. Meda^{1,2,3}, C. R. Flechard^{1,2}, K. Germain⁴, P. Robin^{1,2}, M. Hassouna^{1,2}, and
C. Walter^{2,1,5}**

¹INRA, UMR1069 Sol Agro et hydrosystème Spatialisation, 35000 Rennes, France

²Agrocampus Ouest, UMR1069 Sol Agro et hydrosystème Spatialisation, 35000 Rennes, France

³INRA, UR83 Unité de Recherches Avicoles, 37380 Nouzilly, France

⁴INRA, UE1206 Elevage Alternatif et Santé des Monogastriques, 17700 Surgères, France

⁵Université Européenne de Bretagne, France

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Correspondence to: C. R. Flechard (chris.flechard@rennes.inra.fr)

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Abstract

Nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2) fluxes over the grassy outdoor run of organically grown broilers were monitored using static chambers over two production batches in contrasted seasons. Measured N_2O and CH_4 fluxes were 5 extremely variable in time and space for both batches, with fluxes ranging from a small uptake by soil to large emissions peaks, the latter of which always occurred in the chambers located closest to the broiler house. In general, fluxes decreased with increasing distance to the broiler house, demonstrating that the foraging of broilers and the amount of excreted nutrients (carbon, nitrogen) largely control the spatial variability 10 of emissions. Spatial integration by kriging methods was carried out to provide representative fluxes on the outdoor run for each measurement day. Mechanistic relationships between plot-scale estimates and environmental conditions (soil temperature and water content) were calibrated in order to fill gaps between measurement days. Flux integration over the year 2010 showed that around $3 \pm 1 \text{ kg N}_2\text{O-N ha}^{-1}$ were emitted 15 on the outdoor run, equivalent to 0.9 % of outdoor N excretion and substantially lower than the IPCC default emission factor of 2 %. By contrast, the outdoor run was found to be a net CH_4 sink of about $-0.56 \text{ kg CH}_4\text{-C ha}^{-1}$, though this sink compensated less than 1.5 % (in CO_2 equivalents) of N_2O emissions. The net greenhouse gas (GHG) 20 budget of the outdoor run is explored, based on measured GHG fluxes and short-term (1.5 yr) variations in soil organic carbon.

1 Introduction

Carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) are among the most important greenhouse gases (GHG) responsible for climate change (IPCC, 2007b), and N_2O also contributes to stratospheric ozone depletion (Ravishankara et al., 2009). 25 Climate change is one of the most challenging environmental issues of the 21st century (UNFCCC, 2009) and solutions must be found in order to mitigate GHG emissions on

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CH_4 is also often oxidised (consumed) by agricultural soils (Smith et al., 2000; Le Mer and Roger, 2001; Castaldi et al., 2007). The interplay of all these different processes makes the prediction of net N_2O and CH_4 fluxes a difficult exercise.

In this paper, we present the results of GHG flux measurements (N_2O , CH_4 and CO_2) over a period of 1 yr over a sown grassland, which served as the run for organic broilers, as part of the French AlterAviBio project. The study was conducted on two broiler batches, reared in winter/spring 2009–2010 and in summer/autumn 2010, providing a range of climatic and environmental conditions known to control GHG emissions. The study also focuses on broiler behaviour as a factor controlling the spatial and temporal variability of GHG fluxes. The measurements are used to provide annual emission fluxes, which for N_2O are also expressed as emission factors (EF) as the percentage of emission relative to the N input to the run (Pain and Menzi, 2011), and to estimate the net GHG exchange (NGHGE) of the run.

2 Materials and methods

15 2.1 Study site characteristics

The study took place on the experimental facility of the French National Institute for Agricultural Research (INRA) at Le Magneraud (Long. $00^{\circ}41'25''$ W, Lat. $46^{\circ}09'04''$ N) at an altitude of 60 m above mean sea level. The climate in the region is temperate oceanic with an interannual mean air temperature of around 12°C and mean annual precipitation of around 780 mm. The soil is a clay loam and moderately alkaline (pH about 8.2). It is morphologically simple, consisting of an A horizon (25–35 cm thick) with about 15 % of limestone coarse elements (from a few millimetres to a few centimetres) above a C horizon (rendzic leptosol (calcaric)). The upper layer (0–15 cm) is rich in organic carbon (2.45 %), with a C/N ratio of about 9.7. Before 2008, the field was used for crop production (maize, winter wheat, sunflower and winter pea) before being converted into a grassland during spring 2008. The sown grassland mix consisted of

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41 % tall fescue, 19 % lolium, 11 % Kentucky bluegrass, 11 % birdsfoot trefoil, 11 % alsike clover, 7 % white clover. Before the start of the first broiler batch (March 2009), the canopy was cut in order to offer a short canopy to the broilers. The field has a gentle slope down to the broiler house (Fig. 1).

5 2.2 Organic broiler production system

Five broiler batches were reared consecutively on the study site between March 2009 and November 2010. The GHG flux measurements presented in this paper were carried out during two batches only (batches 3 and 5). Batch 3 was studied from December 2009 to May 2010 (winter and early spring, denoted "WS" hereafter) while batch 5 was studied from August 2011 to December 2010 (late summer and autumn, or "SA").

10 The main characteristics of the two studied batches (number of animals, important dates, weight at slaughter) are listed in Table 1. During each batch, between 750 and 800 slow-growing strain broilers were reared in a broiler house of 75 m^2 ($l = 12.5$, $L = 6 \text{ m}$) with straw bedding. After 35 days (batch WS) or 28 days (batch SA), two pop-holes of 2 m were continuously open and allowed the animals an unlimited access to the outdoor run of 2350 m^2 surface area ($l = 50 \text{ m}$, $L = 47 \text{ m}$).

15 2.3 Flux measurement technique

Greenhouse gas fluxes were measured using static chambers (Smith et al., 1995; Coen 20 and Smith, 1998). Square steel chambers ($L = 50$, $l = 50$, $H = 30 \text{ cm}$) were operated manually and fluxes were measured at (a maximum of) 16 locations on the run, and also at 3 locations just outside the fence to measure background fluxes (Fig. 1), using steel frames which were permanently inserted 10 cm into the soil. Among these frames, 9 were located within the first 15 m of the chicken house, as previous behavioural observations had shown that broilers are preferentially present in this zone 25 (Zeltner and Hirt, 2003, 2008; Hegelund et al., 2005), and we therefore expected higher emissions due to a higher amount of nutrients (carbon, nitrogen) excreted.

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Measurements were carried out routinely at regular time intervals after broilers gained first access to the run. In addition, measurements were also carried out after the last access (slaughter) to the run. At the start of each flux measurement, the chambers were placed on top of the steel frames, their lid being equipped with a septum for gas sampling using a 50 ml syringe. Four air samples of 15 ml were taken at $t = 0$, $t = 10$, $t = 20$ and $t = 30$ min and injected into 5-ml evacuated vials closed with leak free septa before being analysed using gas chromatography (Agilent 6890N, Agilent Technologies, Santa Clara, USA). The trace gas (CO_2 , N_2O and CH_4) exchange flux between soil/vegetation/atmosphere is proportional to the temporal change in head-space gas concentration (C):

$$F(t) = \frac{V}{A} \frac{\partial C}{\partial t} = H \frac{\partial C}{\partial t} \quad (1)$$

with V the head-space volume, A the surface area and H the chamber height. In practice, the slope of the linear regression of gas concentration vs. time was used.

2.4 Soil and meteorological measurements

The site was equipped with a meteorological station and datalogger (CR10X, Campbell Scientific Ltd., Loughborough, UK) providing half-hourly means of air temperature, global radiation, wind speed and rainfall. Soil temperature was measured at -5 cm , while volumetric soil water content (SWC) at -5 cm was measured using time domain reflectometry (TDR) probes (CS616, Campbell Scientific Ltd., Loughborough, UK). These measurements were made on site but outside the run, at a distance of around 150 m from the broiler house. The meteorological and soil data were downloaded periodically, but there were occasional gaps in SWC data due to data retrieval problems. To fill the SWC gaps mechanistically, a simple one-dimensional soil water budget model was used. The uppermost 10 cm of topsoil was assumed to be the most relevant layer for GHG emission and consumption processes, with most of the grass rooting system and intense microbial activity located here, and thus only this 10-cm

layer of topsoil was considered for the water budget. The soil water balance was computed every half-hour using the following equation:

$$\frac{d\phi}{dt} = \frac{1}{Z_s} (P - I - D - E) \quad (2)$$

with ϕ the mean soil water content ($\text{m}^3 \text{m}^{-3}$) of the considered topsoil layer, $Z_s = 0.1$

5 the depth of considered topsoil layer (m), P the precipitation rate ($\text{m}^3 \text{m}^{-2} 30 \text{ min}^{-1}$),
 I the rate of rainfall interception by the canopy ($\text{m}^3 \text{m}^{-2} 30 \text{ min}^{-1}$), D the gravitational
drainage rate from the top 10-cm layer down to the deeper layers ($\text{m}^3 \text{m}^{-2} 30 \text{ min}^{-1}$),
and E the evapotranspiration flux ($\text{m}^3 \text{m}^{-2} 30 \text{ min}^{-1}$). D was parameterised as a function
10 of ϕ based on rainless nighttime observations of the rate of SWC change (when
also both $E = 0$ and $P = 0$); D was found to decrease linearly with increasing ϕ (drainage
was slower when the soil was wet) for values above the permanent wilting point. I was
modelled as a function of precipitation rate and leaf area index (LAI) according to Nor-
15 man and Campbell (1983). E was modelled using the Penman-Monteith equation
(Monteith, 1965), with stomatal resistance of the grass being adjusted on a monthly
basis for the modelled SWC to fit the observations by TDR. Surface run-off and lateral
water flows were not taken into account in this 1-D approach.

2.5 Spatial integration of GHG fluxes

For each measurement day (Table 2), the spatial integration of GHG fluxes was car-
ried out using geostatistical methods with the SURFER software (Golden Software,
20 Golden, USA). A grid map was generated with its origin at the top-left corner of the
run. On each measurement day, the GHG flux values on the run were used to gener-
ate a map of fluxes with a $1 \times 1 \text{ m}$ resolution; the mean of the control chambers was
used as background flux around the fringes of the run. As datasets were small (about
25 20 observations per measurement day), kriging and radial basis function interpolation
methods were selected. Gridded fluxes were summed to provide spatial integrals for

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each GHG and each measurement day. The average of both methods was used in the rest of the study.

2.6 Temporal gap-filling and integration of GHG fluxes

To fill gaps between two measurement days, and to compute time-integrated fluxes over a batch or a year, three methods were used and compared. First, the temporal mean of daily spatial integrals was calculated and multiplied by the duration of the batch. Second, a simple linear dot-to-dot interpolation was carried out between daily spatial integrals obtained from Sect. 2.5. Note that the first and second methods would be equivalent if consecutive measurement days were all equidistant, which was not the case here. Third, to provide more mechanistically-based estimates of GHG fluxes, relationships between measured fluxes and assumed control variables, such as soil temperature and SWC, were investigated. These functions are detailed in Sect. 3.3. To derive estimates of batch-scale fluxes, temporal integrals were calculated by summing actual measurement-based spatial flux integrals for each measurement day and gap-filled fluxes in-between. The batch-scale integrals included data from first outdoor access of the N th batch to the first outdoor access of the following ($N + 1$)th batch, since we considered that emissions before first outdoor access of batch $N + 1$ should be attributed to batch N .

2.7 Outdoor nitrogen excretion

In order to estimate the amount of N excreted on the run during batches WS and SA, mass balances of N, P and K were computed at the house + run scale. These mass balances are presented in another study (Meda et al., 2011b) in which more methodological details are given. Total ingestion was calculated as the product of feed consumption and nutrient content of the diet, ignoring in a first approach any ingestion of non-feed material from the outdoor run. Body retention for N, P, K was calculated according to CORPEN (2006). Total excretion was calculated by difference

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between total ingestion and body retention. Straw and litter were weighed, sampled and analyzed for chemical composition in N, P and K, respectively at the beginning of the batch, and at the end of the batch. For non volatile compounds (P and K), outdoor excretion was computed according to Eq. (3). The average outdoor/total excretion ratio was then calculated for P and K, and then applied to N to estimate the outdoor N excretion.

$$X_{\text{Outdoor excretion}} = X_{\text{Total excretion}} - (X_{\text{Litter}} - X_{\text{Straw}}) \quad (3)$$

where X is the mass of either P or K.

2.8 Temporal and spatial variations in soil nutrient (P, N, C) stocks

Changes in soil organic carbon (SOC), total nitrogen (N) and total phosphorus (P) stocks in the soil of the run were estimated in order to assess the temporal and spatial impacts of broiler foraging on soil biogeochemistry. Soil samples were taken before the first broilers had access to the run (March 2009) and after the end of the last batch (December 2010). The run was divided into 25 squares of equal surface area. In each square, 5 to 6 auger samples were dug up to characterize the 0–15 cm horizon. Bulk density (g cm^{-3} soil) was measured by the cylinder method for each sample and a correction for the stone content estimated by 2 mm mesh sieving was applied. These samples were then mixed to create a composite sample for each square for chemical analysis. Total contents in C and N (g kg^{-1} soil) were measured by dry combustion (ISO, 1995, 1998) while P content was measured with spectrometry (ISO, 1994). For each sample, stocks were finally calculated according to Eq. (4).

$$S_X = A \cdot d \cdot \theta_X \cdot h \quad (4)$$

with X the considered nutrient (C, N or P); S_X the stock of X in the soil (kg); A the area of the square (m^2); d the bulk density (kg m^{-3} soil); θ_X the content in X of the soil (in kg kg^{-1} soil) and h the horizon thickness (m).

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Stock variations for each square of the run were then calculated as the difference between initial and final stocks. Data were interpolated spatially by kriging in order to provide a spatially integrated stock variation for the whole run.

2.9 Outdoor spatial distribution of broilers

5 The spatial distribution of broilers on the run was obtained by a series of behavioural observations, which were performed on days 35, 49 and 63 of each rearing period (5 and 7 scans per day for batches WS and SA, respectively), using the method described by Germain et al. (2010, 2011b). About 100 broilers were tagged with a numbered poncho placed through the back of the neck. During each observation period, the locations of the tagged broilers on the run were recorded according to 16 predefined zones. To that purpose, 4 equal stripes of 11.75 m wide and perpendicular to the broiler house were divided into 4 zones of respectively 5, 10, 15 and 20 m wide parallel to the broiler house. Data were interpolated spatially by kriging in order to derive a spatially explicit “foraging index”, which represents a percentage of total outdoor time spent in each square meter of the run.

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3 Results

3.1 Overview of measured chamber fluxes

Measured N_2O and CH_4 fluxes were extremely variable in time and space for both batches, with temporal variations shown in Fig. 2 and spatial variability shown in Fig. 3, 20 4 and 5 for the three GHG. Statistics for N_2O , CO_2 and CH_4 fluxes for each measurement day are given, for both batches, in Table 2. Measured chamber-scale N_2O fluxes ranged -32 to $+1026 \text{ ng N}_2\text{O m}^{-2} \text{ s}^{-1}$ and from -12 to $+5910 \text{ ng N}_2\text{O m}^{-2} \text{ s}^{-1}$ during batches WS and SA, respectively, with the usual atmospheric science sign convention of plus for emissions and minus for deposition. Several emission peaks were observed during the study, but they mostly occurred in chambers located closest to

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the house and the two pop-holes for outdoor access (Fig. 3). Uptake fluxes on the run represented about 21 % and 14 % of all individual chamber measurements during batches WS and SA, respectively. In comparison, control fluxes measured outside the run in the control chambers ranged from -16 to $+26$ $\text{ng N}_2\text{O m}^{-2} \text{s}^{-1}$ and from -7 to

5 $+34$ $\text{ng N}_2\text{O m}^{-2} \text{s}^{-1}$ during batches WS and SA, respectively.

CH_4 exchange was largely dominated by small uptake fluxes, observed in 64 % and 61 % of all individual flux data for batches WS and SA, respectively. Nevertheless, fluxes ranged from -50 to $+566$ $\text{ng CH}_4 \text{ m}^{-2} \text{ s}^{-1}$ and from -42 to $+169$ $\text{ng CH}_4 \text{ m}^{-2} \text{ s}^{-1}$ during batches WS and SA, respectively, suggesting that the net sink activity on the run was offset by rare emission peaks (Table 2). Once again, these peaks were observed in the chambers located closest to the broiler house (Fig. 4). In comparison, fluxes measured outside of the run in the control chambers ranged from -29 to $+40$ $\text{ng CH}_4 \text{ m}^{-2} \text{ s}^{-1}$ and from -44 to $+36$ $\text{ng CH}_4 \text{ m}^{-2} \text{ s}^{-1}$ with median values of -1 and -4 $\text{ng CH}_4 \text{ m}^{-2} \text{ s}^{-1}$ during batches WS and SA, respectively, suggesting a weak net sink activity in background conditions.

Concerning CO_2 , emission fluxes generated by the (heterotrophic and autotrophic) respiration of the soil + grass ecosystem (R_{eco}) ranged from $+0.2$ to $+5 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ and from $+0.2$ to $+24 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ for batches WS and SA, respectively. Unlike N_2O or CH_4 , the magnitudes of fluxes in control chambers (outside the fence) were not very different from chambers inside the fence, ranging from $+0.2$ to $+6 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ and from $+0.1$ to $+4 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ for batches WS and SA, respectively.

3.2 Spatially integrated GHG fluxes

Figures 3, 4 and 5 present the spatial distributions of N_2O , CH_4 and CO_2 fluxes, respectively, for each measurement day and based on kriging (the radial basis function yielded a similar picture, but data are not shown here). Table 3 summarizes, for each measurement day, the spatial N_2O , CH_4 and CO_2 flux integrals estimated by kriging and radial basis function. The discrepancy between the two interpolation methods is

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generally below 10 % (in absolute value with kriging as reference), and on average -4% , -0.9% and -1.3% for N_2O , CH_4 and CO_2 fluxes, respectively, showing that the spatial integrals are not very sensitive to the interpolation method.

Plot-scale N_2O fluxes (spatial integrals for the whole run) ranged from -2.1 to $+31.8 \text{ ng N}_2\text{O m}^{-2} \text{ s}^{-1}$ and from $+3.5$ to $+181.7 \text{ ng N}_2\text{O m}^{-2} \text{ s}^{-1}$, respectively for all measurement days of batches WS and SA. Plot-scale CH_4 fluxes were frequently negative confirming a sink activity at the scale of the run, with values for different measurement days ranging from -12.2 to $+15.1$ and from -8.3 to $+23.7 \text{ ng CH}_4 \text{ m}^{-2} \text{ s}^{-1}$, respectively for batches WS and SA. These much narrower ranges of plot-scale N_2O and CH_4 fluxes, as compared with individual chambers (see Sect. 3.1 and Table 2), highlight the large spatial variability in fluxes and the presence of emission hot spots, mostly near the broiler house. The range of spatial integrals of respiration of the ecosystem R_{eco} at the scale of the run, from $+0.8$ to $+3.1 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ and from $+0.7$ to $+3.3 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ respectively for batches WS and SA (Table 3), indicates somewhat weaker spatial patterns of R_{eco} than of N_2O , even if large CO_2 fluxes were also clearly associated with the area just outside the broiler house (Fig. 5).

3.3 Temporal gap-filling functions

To derive annual-scale estimates of N_2O fluxes based on a discrete time series of measurements, one possible method consists in an investigation of the relationships of N_2O emission fluxes to environmental variables known to control N_2O production and consumption in soils, with meteorology and soil moisture key controlling variables at any given site (Davidson, 1991; Granli and Bøckman, 1994). While the effect of soil temperature on N_2O emissions is predictably positive, with responses being linear or exponential at environmental temperatures, the effect of water-filled pore space (or WFPS, expressed as the percentage ratio of SWC to saturation SWC), is unlikely to be monotonous from 0 to 100 % WFPS, since in wet saturated soils total denitrification is expected to proceed all the way to N_2 , with less or no potential for N_2O to evolve. At

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lower WFPS, nitrification is expected to be the dominant mechanism for N_2O emission (Davidson, 1991). As a result, the overall effect of WFPS on the N_2O emission potential can be thought of as bell-shaped, with maximum likelihood of emission somewhere in the range 60–90 % WFPS, and minimum flux in either very dry or waterlogged conditions. The optimum range depends on the soil texture, pH, substrate C/N ratio and the composition of microbial communities.

To interpret the temporal variations in N_2O flux measurements reported in this paper, and to derive a mechanistically grounded gap-filling algorithm for the time intervals between measurements, we therefore adapted the empirical model used by Flechard et al. (2007a), in which a bell membership function (BMF, ranging from 0 to 1), characterizing the optimum WFPS range for N_2O emission, was parameterized on the basis of the observed N_2O fluxes. The N_2O flux dataset used here consisted of the spatial integrals (Table 3) obtained for all measurement days using spatial interpolation methods, as described previously. The model responds exponentially to soil temperature, and the WFPS and temperature effects are multiplicative. Datasets for soil temperature and WFPS are also given in Table 3. The N_2O flux was modelled as:

$$F_{\text{N}_2\text{O}} = e^{(c_0 + c_1 T_s + c_2 B(\text{WFPS}))} \quad (5)$$

with $F_{\text{N}_2\text{O}}$ expressed in $\text{ng N}_2\text{O m}^{-2} \text{s}^{-1}$, T_s the soil temperature at –5 cm ($^{\circ}\text{C}$), WFPS at –5 cm expressed as a percentage of pore saturation (0–100), and c_0 , c_1 and c_2 the parameters of a multiple linear regression between $\ln(F_{\text{N}_2\text{O}})$ and the independent variables T_s and $B(\text{WFPS})$. The bell membership function was given as:

$$B(\text{WFPS}) = \frac{1}{1 + \left(\frac{\text{WFPS} - c}{a}\right)^{(2b)}} \quad (6)$$

The three parameters of the bell function (a , width; b , taper coefficient; c , center) were adjusted to maximize the goodness of fit between the observed data and the fluxes predicted by the multiple regression of Eq. (5). With the bell function parameters

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$a = 20.1$ (% WFPS), $b = 6$ and $c = 82.1$ (% WFPS), the resulting regression parameters were $c_0 = 0.57 \pm 0.77$, $c_1 = 0.05 \pm 0.03$ and $c_2 = 1.87 \pm 0.61$, and the multiple R^2 was 0.41. The observation-based model thus predicts a maximum likelihood of N_2O emission at 82 % WFPS, suggesting that denitrification was the dominant mechanism of N_2O production at this site.

Note that two measurement days excluded from the data set used to derive these equations. First, 11 December 2009 (before the start of batch WS) was removed because the negative (uptake) N_2O fluxes were considered to reflect background conditions and were not representative of batches WS and SA. Second, 27 September 2010 was removed because the low apparent value of WFPS (38 %) measured at -5 cm depth could not be considered representative of soil moisture at the surface (1–2 cm depth), which was certainly influenced by rainfall a few days earlier (24 September) after a long period without rain and triggered the highest N_2O flux of all our measurements (Table 3). Also, SWC was not measured directly in situ inside the run, but a few tens of metres away (see Sect. 2.4), and the slope of the terrain may have led to a strong spatial gradient in SWC, which a single point TDR measurement cannot address. This highlights the challenge of interpreting GHG fluxes mechanistically on the basis of low resolution environmental data.

Results of temporal N_2O gap-filling using Eq. (5) are presented in Fig. 2b. Measured fluxes indicate a steady increase over the course of batch WS (cool, wet), which is reasonably well simulated by the gap-filling algorithm. By contrast, measured emissions during batch SA (warm and dry with wet episodes) were much more heterogeneous, being much more dependent on recent rainfall. Here, the gap-filling algorithm does reproduce some of the small-scale temporal variability, but the peak on 27 September is not simulated since the model is driven by SWC at -5 cm depth, which did not respond much to the rainfall of 24 September. Thus, for the special case of the September 27 peak, for the temporal integration we used a linear interpolation between 24 September up to 27 September, and again from 27 September down to the next measurement day on 7 October.

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For the temporal gap-filling of the (spatially integrated) R_{eco} (CO_2) fluxes, an empirical algorithm based on functional relationships to T_g and WFPS was also derived. We started by determining the temperature response of R_{eco} for optimal (non water-limiting) conditions (set arbitrarily by WFPS > 75 %), by fitting the parameters of the Lloyd and Taylor (1994) Arrhenius-type function, such that:

$$R_{\text{eco}}(\text{opt}) = R_{\text{ref}} \times e^{\left(E_0 \left(\frac{1}{T_{\text{ref}} - T_0} - \frac{1}{T_g - T_0} \right) \right)} \quad (7)$$

in which R_{eco} is expressed in $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, temperatures are expressed in K, R_{ref} is ecosystem respiration at the reference temperature T_{ref} (= 283.15 K), T_0 determines the growth characteristic of the exponential function, and E_0 is an activation energy analogue representing the ecosystem respiration sensitivity to temperature (set to 309 K). For the subset of CO_2 fluxes measured at WFPS > 75 %, the fitted parameters were $R_{\text{ref}} = 1.60 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ and $T_0 = 234 \text{ K}$, and the R^2 of the regression was 0.87. For drier periods (June to August 2010), however, ecosystem respiration was assumed to be limited by the lack of moisture, and R_{eco} no longer responded to the high summer temperature as predicted on the basis of the Arrhenius model (Eq. 8) as demonstrated e.g. by Balogh et al. (2011) and Longdoz et al. (2008). We therefore introduced a soil moisture multiplicative term to modulate the temperature response, which took the shape of a sigmoidal function $S(\text{WFPS})$, ranging from 0 to 1:

$$R_{\text{eco}} = R_{\text{eco}}(\text{opt}) \cdot S(\text{WFPS}) \quad (8)$$

$$\text{with } S(\text{WFPS}) = S_2 + \frac{(S_1 - S_2)}{1 + e^{\left(\frac{\text{WFPS} - S_3}{d} \right)}} \quad (9)$$

Here, S_2 was set to 1 (maximum value for S , i.e. no water limitation for R_{eco}), and the parameters S_1 , S_3 and d were adjusted to maximise the goodness of fit between the observed data and the fluxes predicted by the overall temperature/moisture respiration algorithm (Eq. 8). The resulting values were $S_1 = 0.125$, $S_3 = 65$ (% WFPS) and $d = 9$

(% WFPS), with an R^2 for the whole dataset of 0.86. These numbers suggest 50 % and 80 % reductions of R_{eco} at WFPS levels of 62 % and 44 %, respectively, as compared to the non water-limited case (Eq. 7).

5 Note that for the same reason as for N_2O (see above), the 27th September 2010 data point was removed from the data set used to fit parameters of the CO_2 algorithm. Also, due to a lack of data points measured in or near waterlogged conditions (100 % WFPS), we could not identify whether a reduction in R_{eco} would actually occur at saturation, due to a potential limitation imposed on CO_2 efflux through a reduced coefficient of molecular diffusion (Flechard et al., 2007b). This would require a modification of the 10 S function toward 95–100 % WFPS, or possibly the use of a bell-type function as for N_2O . However, since waterlogged conditions tend to occur predominantly in the winter half year at this site, when temperatures are low and therefore R_{eco} is small, the overall (annual) error would likely be small.

15 Results of temporal CO_2 gap-filling using Eq. (8) are presented in Fig. 2c. The semi-empirical model of R_{eco} reproduces satisfactorily the short-term as well as the seasonal fluctuations observed in system respiration, with summer values severely limited by the lack of moisture, despite the higher temperatures.

20 Concerning CH_4 emissions no significant relationship between fluxes and environmental conditions was found. Therefore, temporal gap-filling was carried out either with a simple linear interpolation between measurement days (Fig. 2d), or with an average flux multiplied by the duration of the batch as presented in Sect. 2.6.

3.4 Batch-scale and annual-scale GHG fluxes

25 Results of temporal integration for batches WS and SA obtained from the different gap-filling methods described previously are given in Table 4. Emission estimates for N_2O ranged from 0.86 to 1.01 $\text{kg N}_2\text{O-N ha}^{-1}$ and from 1.45 to 2.44 $\text{kg N}_2\text{O-N ha}^{-1}$ for batches WS and SA, respectively. The run was found to be a net CH_4 sink during batch WS (-0.39 to $-0.34 \text{ kg CH}_4\text{-C ha}^{-1}$) but the flux was probably not significantly different

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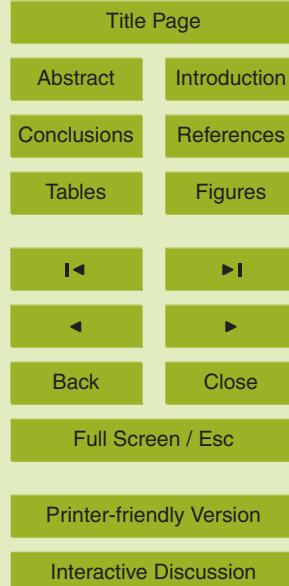
from zero during batch SA (+0.03 to +0.07 kg CH₄-C ha⁻¹). Cumulative estimates of R_{eco} ranged from +1284 to +1819 kg CO₂-C ha⁻¹ during batch WS and from +1560 to +2312 kg CO₂-C ha⁻¹ during batch SA, depending on the temporal integration method. For both N₂O and CO₂, the estimates based on the upscaled mean flux and from linear interpolation were systematically higher than estimates using the T- and WFPS-based functions. This is logical since, i) the distributions of fluxes were not normal but skewed or log-normal, with few elevated (peak) values leading to a bias in average-based estimates, and ii) fluxes were always measured in the afternoon, when soil temperatures and microbial activity were highest.

Although flux measurements focused on batches WS and SA, and only two flux data points are available for batch 4 (Fig. 2), we present tentative estimates of GHG fluxes for batch 4 from 6 May 2010 to 31 August 2010 (Table 4), based either on the mean of these two fluxes, or on functional relationships derived from batches WS and SA. Although these values are highly uncertain, we speculate that N₂O fluxes were rather low due to dry soil conditions and low rainfall during these summer months. These estimates are also needed to provide annual-scale GHG flux estimates, corresponding approximately to the sum of the three batches, and ranging from 2.7 to 4.8 kg N₂O-N ha⁻¹ yr⁻¹, -0.5 to -0.6 kg CH₄-C ha⁻¹ yr⁻¹, and 4.4 to 6.1 t CO₂-C ha⁻¹ yr⁻¹ (R_{eco} only).

20 4 Discussion

4.1 Emission factors for the outdoor run

There are no measurement-based GHG emission factors (EF) for poultry with outdoor access in the literature. Our flux measurements indicate substantial annual N₂O emissions and a weak net CH₄ sink on the run. For N₂O, the calculation of an EF requires the knowledge of total N inputs to the grassland, as well as background N₂O emissions



outside the run, which were provided in our case by three control chambers (Table 2). The only way to quantify N inputs to the run by broiler droppings is by a calculation of the mass balance of chemical elements in animal feed through the production system (ingestion, retention, excretion), whereby the fraction of outdoor excretion is estimated as the difference between total and indoor excretion.

Based on P and K data, Meda et al. (2011) showed that the ratios of outdoor/total excretion were 6 % and 47 % for batches WS and SA, respectively, and that excretion of N on the run was estimated as 5.4 and 42.2 kg N (equivalent to 23 and 180 kg N ha⁻¹) for batches WS and SA, respectively. For batch 4, a similar calculation yielded an outdoor excretion rate of 33.2 kg N (equivalent to 141 kg N ha⁻¹), and the annual N input by outdoor excretion (3 batches) to the run was thus estimated at 344 kg N ha⁻¹ yr⁻¹. This value is high, but according to CORPEN French references (2006), a large part of this N input is lost through volatilization (60 %), certainly albeit with considerable variability and uncertainty (Sintermann et al., 2011).

Our estimates of annual N₂O emission range from +2.71 to +4.76 kg N₂O-N ha⁻¹ yr⁻¹ for the run (Table 4). The background annual emission for the experimental site, outside the run, calculated as the mean of all control chamber fluxes, was +1.25 kg N₂O-N ha⁻¹ yr⁻¹. This background emission is relatively high but can possibly be explained by a high atmospheric N (NH₃ dry deposition from the surrounding experimental farm buildings (poultry, pigs). The EF for N₂O is calculated as the run emission minus the background flux, and divided by the excretion N input. This yields a range of EF of 0.4 % to 1.0 % for outdoor N excretion. These values are substantially lower than the IPCC default value of 2 % (IPCC, 2006b). However, our N input estimate of 344 kg N ha⁻¹ yr⁻¹ obtained by mass balance calculations was rather high and is also subject to considerable uncertainty.

Concerning CH₄, no study on outdoor CH₄ emissions by free range poultry was found in the literature. However, based on IPCC references (IPCC, 2006a) and on our estimation of droppings partitioning between the house and the run, we were able to calculate a theoretical CH₄ EF of 0.03 kg CH₄ ha⁻¹ yr⁻¹ due to the

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by droppings. However, soil water was limiting throughout the summer and certainly affected ecosystem respiration as reflected by the need to modulate the temperature response of R_{eco} by a SWC factor (Eqs. 7 to 9). The mechanism certainly involved a reduction of both autotrophic and heterotrophic components in dry conditions, with limited plant CO_2 assimilation rates reducing the supply of root exudates to soil microorganisms.

4.2 Spatial and temporal controls of GHG fluxes

The initial distribution of the static chambers on the run was determined under the assumption that broilers would spend more time in the first half of the run, close to the broiler house, where emissions should be higher than in the rest of the run due to a larger amount of nutrients (carbon, nitrogen) excreted. Behavioural observations (Fig. 6a) confirmed indeed that, when they were outdoors, broilers spent most of their time in the first 15 m of the run (75 % of the total time spent outdoors), which led to a higher soil accumulation of phosphorus here (65 % of the total stock increment for the whole run) (Fig. 6b). Similar nutrient accumulation was also reported by Aarnink et al. (2006) and Kratz et al. (2004) who concluded that the phosphorus load in the first meters close to the broiler house was several times higher than Dutch and German standards, respectively, and indicates a enhanced risk of P run-off, especially in a zone where the plant cover has been suppressed by broilers. Variations in phosphorus soil stock were positively correlated (spatially) with the foraging index ($R^2 = 0.74$), but no relationship between foraging index and variations in total nitrogen or total carbon soil stocks was found ($R^2 < 0.1$). This is due to a faster turnover of carbon and nitrogen than for phosphorus, partly due to the uptake by plants, soil fauna and microorganisms, but more importantly here by mineralisation and gaseous emissions (NH_3 , NO , N_2O , N_2 , CO_2) in the soil, and possibly leaching (NO_3^- , dissolved inorganic or organic C and N). Further, we may hypothesize that variations in C and N soil stocks were of the same magnitude close to the house and at the back of the run because of two distinct phenomena. In the first part of the run, the vegetation was very sparse and the

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increase in C and N in soil was explained by the concentration of nutrients excreted in this zone, whereas at the back of the run, the increase in C and N was mostly due to C sequestration and N fixation by the soil and the vegetation.

The spatial interpolation of N_2O , CH_4 and CO_2 fluxes, summarized in Figs. 3 to 5, respectively, confirmed the dominance of near-house emissions. The highest emissions peaks were generally measured in the two chambers placed only one meter away from the pop-holes. Relationships between average measured N_2O and CH_4 fluxes and variations in phosphorus stock soil, foraging index and distance to the broiler house, for all chamber sampling points on the field, are given in Fig. 7. As expected, N_2O and CH_4 fluxes were positively correlated with the animals presence and their cumulative droppings (as shown by the increase in soil P), and negatively correlated with distance to the broiler house. Good correlation between CO_2 fluxes and these variables (not shown in this paper) was also found ($R^2 > 0.50$).

The ratio between the lowest and highest flux magnitudes in space was similar for N_2O and CH_4 (around 1 : 100), while for CO_2 this ratio was only of the order of 1 : 5. This indicates that different microbial processes and communities were involved for the different gases, constrained by different limiting factors. The spatial variability of fluxes and the higher emissions measured in the first 15 m of the run could be explained by the amount of carbon and nitrogen available for soil microorganisms. We may assume that the high amount of nutrients excreted close to the house generated a non-limiting situation for soil microbial activity (Flechard et al., 2005), which, coupled with the disappearance of the plant cover in the first meters in front of the broiler house, because of broiler consumption, stalling and compaction, led to the absence of competition for resources for soil microorganisms. This indicates that R_{eco} was dominated by soil heterotrophic respiration. Furthermore, the surface compaction of the soil in the first meters of the run (Fig. 1), coupled with high input of reactive C, may have generated local anaerobic conditions and thus enhanced the production of N_2O through denitrification and CH_4 production. By the same token, this compaction certainly reduced oxygen availability in the soil and thus limited methane oxidation. The large

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area index) and soil characteristics. The slope of the run (Fig. 1) probably also induced a higher SWC close to the broiler house (Fig. 1) than upslope, due to surface run-off, especially during high intensity precipitation events. Therefore, local predictions of T and SWC would reduce uncertainty of annual averages of GHG fluxes from the run.

4.3 Net annual GHG budget of the outdoor run

Emission factors are needed from an inventory viewpoint (IPCC), but to assess the whole climate change impact of a production system, a total net GHG exchange (NGHGE), taking into account all global warming potential (GWP) contributions by CO_2 , N_2O and CH_4 fluxes should be calculated, e.g. in CO_2 equivalents (Soussana et al., 2007). The NGHGE is calculated according to Eq. (10) adapted from Soussana et al. (2007):

$$\text{NGHGE} = \frac{44}{28} F_{\text{N}_2\text{O}} \cdot \text{GWP}_{\text{N}_2\text{O}} + \frac{16}{12} F_{\text{CH}_4} \cdot \text{GWP}_{\text{CH}_4} + \frac{44}{12} \text{NEE}_{\text{G+B}} \quad (10)$$

where $F_{\text{N}_2\text{O}}$ and F_{CH_4} are respectively the annual N_2O and CH_4 fluxes from the run (in $\text{kg N}_2\text{O-N ha}^{-1} \text{yr}^{-1}$ and $\text{kg CH}_4-\text{C ha}^{-1} \text{yr}^{-1}$, respectively); $\text{GWP}_{\text{N}_2\text{O}}$ and GWP_{CH_4} the respective GWPs of CH_4 (25 CO_2 eq.) and N_2O (298 CO_2 eq.) (IPCC, 2007a); $\text{NEE}_{\text{G+B}}$ is the net ecosystem exchange ($\text{kg CO}_2\text{-C ha}^{-1} \text{yr}^{-1}$) defined as the sum of NEE_G ($\text{kg CO}_2\text{-C ha}^{-1} \text{yr}^{-1}$), the net ecosystem exchange of grassland (vegetation + soil), and R_{broilers} the respiration of broilers on the run. CH_4 emissions from enteric fermentation of broilers is neglected given the lack of knowledge (IPCC, 2006a), but is certainly very small.

Usually, NEE_G is measured by eddy covariance (Soussana et al., 2007) or by chambers, and Gross Primary Production (GPP) is calculated by difference between NEE and R_{eco} , which is derived from night-time measurements (Woodwell and Whittaker, 1968; Reichstein et al., 2005). By convention, a negative value of NEE_G indicates a net sink. In this study we only measured R_{eco} but not NEE , and thus no GPP estimates could be made either. However, a tentative estimate of NEE_G may be made according

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to Eq. (11) adapted from Ammann et al. (2007) and Loubet et al. (2011), based on the measured changes in soil organic carbon over the time scale of the experiment and assumptions regarding other C fluxes into and out of the ecosystem:

$$\text{NEE}_G = C_{\text{import}} - \frac{\Delta \text{SOC}}{\Delta t} - C_{\text{export}} - C_{\text{leaching}} - F_{\text{CH}_4} \quad (11)$$

5 where C_{import} is the import of C on the outdoor by broiler excretion; $\frac{\Delta \text{SOC}}{\Delta t}$ the measured change in SOC with time (a positive value corresponding to a carbon sequestration in the grassland); C_{export} the export of C out of the run; C_{leaching} the organic carbon leached out of the soil and F_{CH_4} , the methane flux measured in our study.

In this study, C_{export} is only due to the consumption of vegetation, soil or soil fauna by the broilers, as the grassland was not cut, and was estimated according to Eq. (12) in which the total C export for each batch is calculated as the difference between total C ingestion on the run and the part of this C excreted on the run.

$$C_{\text{export}} = n_{\text{out}} \cdot n_{\text{broilers}} \cdot [I_{\text{soil}} \cdot C_{\text{soil}} \cdot (1 - E I_{\text{soil}} \cdot r_{\text{out}}) + I_{\text{veg}} \cdot C_{\text{veg}} \cdot (1 - E I_{\text{veg}} \cdot r_{\text{out}}) + I_{\text{fauna}} \cdot DM_{\text{fauna}} \cdot C_{\text{fauna}} \cdot (1 - E I_{\text{fauna}} \cdot r_{\text{out}})] \quad (12)$$

15 with n_{out} the number of days with outdoor access; n_{broilers} the number of broilers; I_{soil} ,
 I_{veg} and I_{fauna} are the daily intake of soil, vegetation and soil fauna per broiler (in kg
dry matter (DM) for soil and vegetation, in kg fresh matter for fauna); C_{soil} , C_{veg} , C_{fauna}
20 are the carbon content of soil, vegetation and fauna (in kg C per kg DM); DM_{fauna} the
DM content of soil fauna (in %); EI_{soil} , EI_{veg} , EI_{fauna} are the Excretion/Intake ratio (in
%) for soil, vegetation and fauna, respectively; r_{out} is the ratio of outdoor excretion to
total excretion used previously to estimate N outdoor excretion. Values and references
25 used for the estimation of C_{export} are given in Table 5.

Total ingestion of carbon from vegetation, soil and soil fauna was estimated about 2541 kg C ha⁻¹ yr⁻¹, which was equivalent to less than 10% of C ingested from feed in the house. This value is consistent with the values given by Rivera-Ferre et al. (2007) who estimated that consumption of vegetation by broilers represented

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less than 10 % of energy and protein daily requirements. C_{export} was estimated at about $2111 \text{ kg C ha}^{-1} \text{ yr}^{-1}$ for the year 2010 as shown in Table 6, with about 65 % due to vegetation C, 34 % to fauna C and less than 1 % to soil C. C_{export} represented about 83 % of total C ingestion from the run.

5 The other terms of Eq. (11) were more straightforward, and probably less uncertain. $\frac{\Delta \text{SOC}}{\Delta t}$ can be viewed as a short-term C sequestration and was estimated from measurements at $3765 \text{ kg C ha}^{-1} \text{ yr}^{-1}$ (Table 6). C_{import} was estimated from calculated N outdoor excretion assuming a C:N ratio in fresh droppings of 10 (Sasáková et al., 2010) and estimated to $3440 \text{ kg C ha}^{-1} \text{ yr}^{-1}$ for the year 2010 (Table 6), which is of a comparable magnitude to $\frac{\Delta \text{SOC}}{\Delta t}$. C_{leaching} was estimated at $294 \text{ kg C ha}^{-1} \text{ yr}^{-1}$ according to the average value for a range of grazed grasslands given by Kindler et al. (2011). By difference between all these terms (Eq. 11), NEE_G would be a C sink of about $-2730 \text{ kg CO}_2\text{-C ha}^{-1} \text{ yr}^{-1}$ (Table 6).

15 R_{broilers} is an additional term needed for the calculation of the NGHGE, and can be estimated using the heat production of broilers, which is a function of live weight and air temperature (CIGR, 2002). However, heat production of broilers (in W) has been studied with fast-growing strains in claustrophobia conditions (metabolic chambers) and this equation is probably not well adapted to slow-growing strains such as the one reared in our study because of differences in animal metabolism (slower growth rate). In order to take into account these differences of growth rate, heat production was weighted for each batch by the ratio between average daily gain (ADG in kg d^{-1}) of a fast-growing strain (0.05 kg d^{-1} i.e. about 2 kg in 42 d) and the ADG of the batch (about 0.02 kg d^{-1}). R_{broilers} was then calculated assuming that 0.185 m^3 of CO_2 are produced per hour per kW of total heat produced (CIGR, 2002). For 2010, R_{broilers} was estimated to about $1567 \text{ kg CO}_2\text{-C ha}^{-1} \text{ yr}^{-1}$ as shown in Table 6, roughly one third of R_{eco} .

20 The estimate of NEE_{G+B} thus obtained ($-1163 \text{ kg C ha}^{-1} \text{ yr}^{-1}$, i.e. $-4264 \text{ kg CO}_2 \text{ eq. ha}^{-1} \text{ yr}^{-1}$) implies that the whole (soil + vegetation + broilers)

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ecosystem would still have been a net sink of CO_2 . This sink was offset by roughly one third by N_2O emissions, which represented a net emission of $+1722 \text{ kg CO}_2 \text{ eq. ha}^{-1} \text{ yr}^{-1}$ (Table 6). The impact of CH_4 (about $-19 \text{ kg CO}_2 \text{ eq. ha}^{-1} \text{ yr}^{-1}$, mean of the values estimated with two different interpolation methods) could be neglected, as CH_4 oxidation compensated only 1.1 % of the N_2O forcing effect.

Overall, the NGHGE of $-2561 \text{ kg CO}_2 \text{ eq. ha}^{-1} \text{ yr}^{-1}$ would suggest that the outdoor part of the rearing system behaves as a net sink of greenhouse gases, though uncertainties are very large and this would have to be confirmed by plot-scale measurements of all component terms of Eq. (11), including NEE by eddy covariance (which should include R_{broilers}) as well as DOC leaching. Furthermore, an estimate of CO_2 eq. emissions from the house should also be estimated in order to propose a full GHG budget of the rearing system (broiler house + run) (Meda et al., 2011b).

No published data concerning GHG outdoor emissions from “grazing poultry” were found in the literature, but studies concerning grassland grazed by cattle (Allard et al., 2007; Gilmanov et al., 2007; Soussana et al., 2007) can serve as reference points. In these studies, grassland management practices concerns cutting, grazing and fertilization. In our study, the grassland was “grazed” but not cut and we consider that it was fertilized because nutrients excreted on the run are mainly due to droppings enriched by feed consumption, which is not part of the ecosystem. In grazed grassland studies, the measurement of NEE by eddy covariance is assumed to include both soil/vegetation as well as animal respiration, and constitutes therefore a reference for our estimated $\text{NEE}_{\text{G+B}}$. The average value of NEE in the afore-mentioned studies from the GREENGRASS project (2002–2004) is about $-8260 \text{ kg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ whereas our estimate of $\text{NEE}_{\text{G+B}}$ ($-4263 \text{ kg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$) was 48 % lower. This may be partly explained by a combined effect of lower GPP (lower leaf area index, drier conditions at Le Magneraud) and lower respiration values in our study (Table 6), compared to average values of 48 220 and 39 960 $\text{kg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ respectively for GPP and respiration calculated from Allard et al. (2007) and Gilmanov et al. (2007). Stocking density in

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our study was equivalent to 5.5 Livestock Unit (LU) $\text{ha}^{-1} \text{yr}^{-1}$ whereas for cattle studies stocking density was closer to 1 LU $\text{ha}^{-1} \text{yr}^{-1}$ (Allard et al., 2007). The high stocking density was responsible for vegetation destruction in the first part of the run where broilers were frequently observed, and for trampling and soil compaction in that area.

5 This may have led to a decrease in the capacity of the grassland to assimilate carbon and could explain the lower GPP value that we estimated. However, our estimation of $\text{NEE}_{\text{G}+\text{B}}$ mostly relies on estimates of R_{broilers} and C_{export} with strong hypotheses, and this estimate should be treated with caution. In future experiments, $\text{NEE}_{\text{G}+\text{B}}$ should be measured directly using eddy-covariance technique such as in the pasture studies

10 (Allard et al., 2007; Gilmanov et al., 2007; Soussana et al., 2007), and ensuring that the flux footprint of the EC tower includes the flock of broilers.

5 Conclusions

Annual GHG flux estimates suggest that the run of organic, free-range broilers emitted between 2.7 and 4.7 $\text{kg N}_2\text{O ha}^{-1} \text{yr}^{-1}$ and acted as a very weak sink of CH_4 , which compensated less than 1.5 % of the N_2O forcing effect. Spatial variability of fluxes was high. As expected, GHG fluxes were higher close to the broiler house where large amounts of organic matter are excreted by the broilers. The temporal variability of fluxes is related to soil moisture and temperature, which regulate soil microbial processes. The uncertainty associated with our estimates can be reduced by an improved understanding and modelling of processes controlling GHG fluxes. This study provides the first measurement-based assessment of outdoor N_2O emissions factors for “grazing” poultry. However, this value is site-specific and more measurements are needed in different climatic conditions and over different soil and vegetation types, in order to derive a comprehensive and representative set of values to be used in emission inventories and in Life Cycle Assessment approaches. Based on measured GHG fluxes and on the change of soil organic carbon during the time frame of the experiment, we calculated a short-term net GHG budget for the run, equivalent to a net sink of -2600 kg CO_2

equivalent $\text{ha}^{-1} \text{yr}^{-1}$. However, more data over the lifetime of a production system (e.g. 10 yr) would be required to assess the long term soil carbon sequestration potential. This study focused on GHG fluxes, and outdoor ammonia emissions should be also quantified, given the potential impacts associated to ammonia deposition downwind from the source (eutrophication, acidification, secondary N_2O emissions).

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Table 1. Main characteristics of the two broiler batches during which GHG fluxes were measured.

Batch	Number of animals at start	Number of animals at slaughter	Weight at slaughter (kg/broiler)	Chicks arrival	Dates	
					First outdoor access	Slaughter
WS	758	678	2.21	8 Dec 09	13 Jan 10	8 Mar 10
SA	788	711	2.23	3 Aug 10	1 Sep 10	10 Nov 10

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Table 2. Summary of N_2O , CO_2 and CH_4 chamber flux statistics for each measurement date.

N_2O fluxes ($\text{ng m}^{-2} \text{s}^{-1}$)	WS batch										Intermediate										SA batch																					
	11.12.09	19.01.10	28.01.10	09.02.10	19.02.10	02.03.10	09.03.10	06.04.10	04.05.10	29.07.10	27.08.10	02.09.10	16.09.10	27.09.10	07.10.10	18.10.10	04.11.10	24.11.10	13.12.10	11.12.09	19.01.10	28.01.10	09.02.10	19.02.10	02.03.10	09.03.10	06.04.10	04.05.10	29.07.10	27.08.10	02.09.10	16.09.10	27.09.10	07.10.10	18.10.10	04.11.10	24.11.10	13.12.10				
Outdoor run (within fence)	N	16	8	6	5	15	14	10	12	13	16	16	8	8	16	16	16	16	16	16	N	16	8	6	5	15	14	10	12	13	16	16	8	8	16	16	16	16	16			
	Mean	-4	9	20	31	25	19	56	181	1	12	63	12	42	41	49	70	48	55	15	12	3	5	14	39	13	11	15	0	3	16	7	14	30	10	45	12	6				
	Median	-5	5	14	39	13	13	11	15	0	4	16	7	14	30	10	45	12	6	11	4	1	4	1	4	1	4	1	4	1	4	1	4	1	4	1	4					
	Min	-32	1	6	5	-6	6	-2	2	-5	-4	4	1	-3	16	0	-12	14	0	-11	1	1	5	3	-2	4	4	-4	0	-3	1	-7	1	-7	1	-7	1	-7				
	Max	21	28	45	60	80	63	323	1026	8	162	476	39	219	5910	159	597	96	53	1871	26	10	15	15	16	11	6	5	4	20	9	12	6	9	8	34	8	5				
Control (outside fence)	N	3	1	1	2	2	2	0	2	3	3	3	2	2	2	3	2	3	2	2	N	3	1	1	2	2	2	0	2	3	3	3	2	3	2	3	2	2	2			
	Mean	10	10	15	0	10	11	2	2	3	3	13	6	5	5	5	5	4	11	4	1	1	10	15	0	10	11	2	3	2	3	2	3	2	3	2	3					
	Median	15	10	15	0	10	11	2	2	2	2	15	6	5	5	5	9	4	1	4	1	1	10	15	0	10	11	2	3	2	3	2	3	2	3	2	3					
	Min	-10	10	15	-16	4	10	-2	1	1	5	3	-2	4	4	-4	0	-3	1	-7	1	1	5	3	-2	4	4	-4	0	-3	1	-7	1	-7	1	-7						
	Max	26	10	15	15	16	11	6	5	4	20	9	12	6	9	8	34	8	5	2	2	2	2	2	2	0	2	3	2	3	2	3	2	3	2	3						
R_{CO_2} fluxes ($\text{μmol m}^{-2} \text{s}^{-1}$)	11.12.09	19.01.10	28.01.10	09.02.10	19.02.10	02.03.10	09.03.10	06.04.10	04.05.10	29.07.10	27.08.10	02.09.10	16.09.10	27.09.10	07.10.10	18.10.10	04.11.10	24.11.10	13.12.10	11.12.09	19.01.10	28.01.10	09.02.10	19.02.10	02.03.10	09.03.10	06.04.10	04.05.10	29.07.10	27.08.10	02.09.10	16.09.10	27.09.10	07.10.10	18.10.10	04.11.10	24.11.10	13.12.10				
Outdoor run (within fence)	N	16	7	5	14	16	6	16	14	16	16	8	8	8	16	15	16	16	16	N	16	7	5	14	16	6	16	14	16	16	8	8	8	16	15	16	16	16				
	Mean	0.9	1.3	1.6	1.8	1.3	2.3	1.3	2.8	1.0	1.3	3.0	1.5	1.6	6.3	3.2	1.1	4.0	1.5	0.9	0.9	1.1	0.9	1.1	0.9	1.1	0.9	1.1	0.9	1.1	0.9	1.1	0.9	1.1	0.9	1.1	0.9					
	Median	0.9	1.1	1.6	1.6	1.0	2.1	0.7	2.5	1.0	1.1	2.7	1.5	1.5	3.7	2.8	0.8	3.6	1.4	0.8	0.8	1.1	0.9	1.1	0.9	1.1	0.9	1.1	0.9	1.1	0.9	1.1	0.9	1.1	0.9	1.1	0.9	1.1				
	Min	0.2	0.7	0.6	1.0	0.3	0.9	0.2	0.9	0.2	0.3	1.7	0.5	0.7	2.8	1.2	0.4	1.5	1.0	0.2	0.2	1.1	0.9	1.1	0.9	1.1	0.9	1.1	0.9	1.1	0.9	1.1	0.9	1.1	0.9	1.1	0.9	1.1				
	Max	1.9	2.5	2.5	2.7	3.9	5.0	3.1	5.3	2.1	2.5	5.7	2.6	3.1	24.2	5.8	3.4	10.6	2.2	3.7	3	2.5	3.1	5.7	2.6	3.1	2.5	3.1	2.5	3.1	2.5	3.1	2.5	3.1	2.5	3.1	2.5	3.1				
Control (outside fence)	N	3	1	1	3	3	1	3	2	3	3	2	2	2	2	3	2	3	2	2	N	3	1	1	3	3	1	3	2	3	2	3	2	3	2	3	2	3	2			
	Mean	0.9	0.7	0.9	0.4	0.7	1.5	0.9	4.0	1.3	1.3	2.8	1.2	1.2	2.0	2.4	1.2	2.2	1.0	0.6	0.6	1.1	0.7	1.2	0.9	3.0	1.3	1.4	2.3	1.2	1.2	2.0	2.6	1.2	2.0	1.0	0.6	0.6				
	Median	1.1	0.7	0.9	0.4	0.7	1.2	0.9	3.0	1.3	1.4	2.3	1.2	1.2	2.0	2.6	1.2	2.0	1.0	0.6	0.6	1.1	0.7	1.2	0.9	3.0	1.3	1.4	2.3	1.2	1.2	2.0	2.6	1.2	2.0	1.0	0.6	0.6				
	Min	0.2	0.7	0.9	0.4	0.5	0.9	0.9	2.6	1.1	0.9	2.1	0.5	1.0	1.8	1.3	0.5	0.5	1.0	0.1	0.1	1.1	0.7	1.2	0.9	2.6	1.1	1.4	2.1	1.2	1.2	2.0	2.6	1.2	2.0	1.0	0.6	0.6				
	Max	1.4	0.7	0.9	0.4	0.9	2.5	0.9	6.5	1.4	1.7	4.0	1.9	1.5	2.1	3.4	2.0	4.2	1.0	1.1	1.1	1.7	1.2	1.5	0.9	6.5	1.4	1.7	4.0	1.9	1.5	2.1	3.4	2.0	4.2	1.0	1.1	1.1				
CH_4 fluxes ($\text{ng m}^{-2} \text{s}^{-1}$)	11.12.09	19.01.10	28.01.10	09.02.10	19.02.10	02.03.10	09.03.10	06.04.10	04.05.10	29.07.10	27.08.10	02.09.10	16.09.10	27.09.10	07.10.10	18.10.10	04.11.10	24.11.10	13.12.10	11.12.09	19.01.10	28.01.10	09.02.10	19.02.10	02.03.10	09.03.10	06.04.10	04.05.10	29.07.10	27.08.10	02.09.10	16.09.10	27.09.10	07.10.10	18.10.10	04.11.10	24.11.10	13.12.10				
Outdoor run (within fence)	N	16	7	5	10	8	9	6	16	16	8	8	16	15	16	16	16	16	16	16	N	16	7	5	10	8	9	6	16	16	8	8	16	15	16	16	16	16	16	16		
	Mean	-10	-8	3	-3	1	114	-1	-6	-2	-6	-4	-4	-4	-3	-3	-4	-2	-3	-2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		
	Median	-6	-3	0	-2	-5	-17	9	-17	-1	-6	-4	-4	-4	-3	-3	-4	-2	-3	-2	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1			
	Min	-47	-18	50	-23	-39	-13	-27	-30	-22	-27	-11	-9	-17	-6	-42	-18	-16	-21	-19	-5	-5	-29	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
	Max	17	6	41	28	44	566	22	56	14	17	9	-1	15	86	115	27	169	35	9	9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1			
Control (outside fence)	N	3	2	2	2	1	3	0	1	2	3	3	2	3	2	3	2	3	2	3	N	3	2	2	2	1	3	0	1	2	3	3	2	3	2	3	2	3	2	3		
	Mean	-3	-7	4	-12	-15	-5	-9	-2	0	-2	-8	-6	-4	-4	-9	-1	-2	-9	-1	-2	1	-2	-9	-6	-4	-21	-1	-1	-9	-6	-4	-21	-1	-1	-9	-6					
	Median	2	-7	4	-12	-15	-5	-9	-2	0	-2	-8	-6	-4	-4	-9	-1	-2	-9	-1	-2	1	-2	-9	-6	-4	-21	-1	-1	-9	-6	-4	-21	-1	-1	-9	-6					
	Min	-12	-9	-8	-21	-15	-29	-9	-4	-3	-8	-8	-7	-11	-11	-44	-4	-5	-4	-5	-10	-11	-44	-4	-5	-10	-11	-44	-4	-5	-10	-11	-44	-4	-5							
	Max	3	-5	16	-2	-15	40	-9	0	4	3	-7	-6	3	36	1	1	1	1	1	-7	0	4	3	-7	-6	3	36	1	1	1	1	1	-7	0	4	3	-7				

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Table 3. Summary of spatially integrated GHG fluxes for each measurement day, computed using (an average of) kriging and radial basis functions to interpolate between all available individual chamber measurements. Soil temperature and water-filled pore space (WFPS) are values observed at the same time as GHG fluxes, i.e. generally around mid afternoon.

Soil T 5 cm (°C)	WFPS 5 cm (%)	N ₂ O flux (ng N ₂ O m ⁻² s ⁻¹)			CH ₄ flux (ng CH ₄ m ⁻² s ⁻¹)			R _{eco} CO ₂ (μmol m ⁻² s ⁻¹)			
		Kriging	Radial basis function	Average	Kriging	Radial basis function	Average	Kriging	Radial basis function	Average	
WS batch											
11 Dec 2009	8.6	87 %	-2.2	-1.9	-13.5 %	-2.1	-5.9	-6.0	0.3 %	-5.9	0.9
19 Jan 2010	5.1	100 %	6.9	7.0	0.7 %	7.0	-9.1	-9.0	-0.3 %	-9.1	0.9
28 Jan 2010	4.6	94 %	16.8	16.9	0.4 %	16.9	-3.0	-3.1	2.0 %	-3.1	1.2
9 Feb 2010	4.8	93 %	9.6	9.0	-6.9 %	9.3	-12.1	-12.2	1.4 %	-12.1	0.8
19 Feb 2010	5.6	91 %	14.5	14.5	-0.1 %	14.5	-5.3	-6.4	19.5 %	-5.8	0.9
2 Mar 2010	11.4	99 %	14.2	14.2	0.0 %	14.2	14.5	15.1	3.9 %	14.8	1.9
9 Mar 2010	4.6	91 %	18.2	16.9	-7.4 %	17.5	2.0	2.5	23.1 %	2.2	0.9
6 Apr 2010	13.9	100 %	33.2	30.3	-8.8 %	31.8	-11.8	-11.7	-0.7 %	-11.8	3.1
Intermediate measurements											
4 May 2010	14.5	53 %	0.6	0.7	13.1 %	0.6	-2.5	-2.5	0.8 %	-2.5	1.0
29 Jul 2010	25.3	41 %	3.6	3.4	-5.5 %	3.5	-5.9	-5.9	0.8 %	-5.9	1.3
SA batch											
27 Aug 2010	23.6	64 %	22.8	22.2	-2.4 %	22.5	-4.4	-4.4	-0.6 %	-4.4	2.8
2 Sep 2010	25.7	50 %	8.8	8.5	-3.5 %	8.7	-5.2	-5.3	3.1 %	-5.3	1.4
16 Sep 2010	20.5	50 %	11.1	9.9	-10.2 %	10.5	-4.6	-4.6	1.9 %	-4.6	1.7
27 Sep 2010	16.5	38 %	186.9	176.6	-5.5 %	181.7	0.9	0.7	-28.0 %	0.8	3.4
7 Oct 2010	20.7	64 %	28.9	27.8	-3.9 %	28.4	0.3	0.3	-19.2 %	0.3	2.8
18 Oct 2010	13.6	42 %	19.9	19.2	-3.7 %	19.6	1.3	1.3	0.6 %	1.3	1.1
4 Nov 2010	16.6	77 %	36.5	35.8	-1.9 %	36.1	24.1	23.7	-1.9 %	23.9	2.9
24 Nov 2010	7.9	99 %	8.8	8.5	-3.5 %	8.6	-1.1	-1.4	20.0 %	-1.2	1.3
13 Dec 2010	2.1	98 %	22.6	19.7	-12.7 %	21.1	-8.4	-8.3	-1.5 %	-8.3	0.8

^a Between kriging and radial basis function.

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Table 4. GHG fluxes at the batch and annual time scales, using alternative temporal integration methods.

Integration period	Time interval	Temporal gap-filling method	kg N ₂ O-N ha ⁻¹	kg CH ₄ -C ha ⁻¹	R _{eco} (kg CO ₂ -C ha ⁻¹)
Batch 3 (measured and gap-filled)	13.01.2010 to 05.05.2010	Mean Flux * Ndays ^a	0.87	-0.39	1569
		Linear (dot to dot)	1.01	-0.34	1819
		Flux = f (T _s , WFPS) ^b	0.86	na	1284
Batch 4 (simulation)	06.05.2010 to 31.08.2010	Mean Flux * Ndays ^{a,c}	0.84	-0.61	2546
		Flux = f (T _s , WFPS) ^b	0.44	na	1469
		Mean Flux * Ndays ^a	2.44	0.03	2312
Batch 5 (measured and gap-filled)	01.09.2010 to 05.01.2011	Linear (dot to dot)	2.18	0.07	2210
		Flux = f (T _s , WFPS) ^{b,d}	1.45	na	1560
		Mean Flux * Ndays ^e	4.76	-0.46	6147
Year (measured and gap-filled)	01.01.2010 to 31.12.2010	Linear (dot to dot)	3.56	-0.65	5883
		Flux = f (T _s , WFPS) ^b	2.71	na	4351

R_{eco} = Respiration of the (grassland + soil) ecosystem.

^a Calculated from the average of all daily fluxes obtained from measurements between the date of first outdoor access of animals (and that of the next batch).

^b Measured fluxes + mechanistic gap-filling function (Eq. 5 for N₂O-N and Eq. 8 for CO₂-C; not available for CH₄-C).

^c Based on only two days measurements made after the slaughter of Batch 4.

^d For N₂O and CO₂, emission peaks measured on 27.09.10 added on top of base emission (see text for details).

^e Calculated from the average of all daily fluxes obtained from measurements from year start to year end.

Table 5. Parameters used in the estimation of carbon export out of the outdoor run (C_{export}). See text for details.

	Value	Source
Daily soil intake I_{soil} (g DM d^{-1} broiler $^{-1}$)	0–1.6 ^a	Jurjanz et al. (2011)
Daily vegetation intake I_{veg} (g DM d^{-1} broiler $^{-1}$)	1.3–15.4 ^a	Jurjanz et al. (2011)
Daily soil fauna intake I_{fauna} (g d^{-1} broiler $^{-1}$)	20.0	de Vries et al. (2006)
Soil organic C content C_{soil} (g C kg $^{-1}$ DM)	31.0	measured in this study
Vegetation C content C_{veg} (kg C kg $^{-1}$ DM)	0.4	Dutton et al. (1988)
Soil fauna C content C_{fauna} (kg C kg $^{-1}$ DM)	0.5	IPCC (2003)
Soil fauna DM content DM_{fauna} (%)	19 %	Devliegher and Verstraete (1995)
Soil Excretion:Ingestion ratio EI_{soil} (%)	100 % ^b	Germain et al. (2011a)
Vegetation Excretion:Ingestion ratio EI_{veg} (%)	50 % ^c	Germain et al. (2011a)
Soil fauna Excretion:Ingestion ratio EI_{fauna} (%)	25 % ^d	–

DM = Dry matter.

^a Values were determined for different seasons.

^b Assuming that soil is not digestible (in agreement with Germain et al., 2011).

^c Assuming that vegetation is rich in non digestible fibers (in agreement with Germain et al., 2011).

^d Assuming that fauna is highly digestible.

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Table 6. An assessment of annual carbon budget, greenhouse gases fluxes and their net budget (NGHGE) in CO_2 equivalents (CO_2 eq.) for the outdoor run in 2010.

C fluxes ($\text{kg C ha}^{-1} \text{yr}^{-1}$) ^a				CO ₂ fluxes ($\text{kg CO}_2\text{-C ha}^{-1} \text{yr}^{-1}$) ^d				GHG fluxes ($\text{kg CO}_2 \text{ eq. ha}^{-1} \text{yr}^{-1}$) ^h			
$\Delta\text{SOC}/\Delta t^b$	C_{import}^c	C_{export}^c	C_{leaching}^c	NEE _G ^e	R_{eco}^f	GPP _G ^g	R_{broilers}^c	$F_{\text{N}_2\text{O}}^i$	$F_{\text{CH}_4}^j$	NEE _{G+B}	NGHGE ^k
3765	3440	2111	294	-2730	4351 ^c	-7081 ^f	1567	1722	-19	-4264	-2561

^a $\Delta\text{SOC}/\Delta t$, change in soil organic carbon with time; C_{import} , C imported on the outdoor by droppings; C_{export} , C exported by the consumption by broilers of soil, vegetation and soil fauna; C_{leaching} , C losses by leaching.

^b Measured.

^c Estimated (see Sect. 4.3.).

^d NEE_G, net ecosystem exchange (includes soil and vegetation but not the broilers); R_{eco} , respiration of the soil + vegetation ecosystem; GPP_G, Gross Primary Production of the grassland; R_{broilers} , respiration of broilers on the outdoor run.

^e Calculated according to Eq. (11) (see Sect. 4.3.).

^f Mean of the 3 estimates given in Table 4.

^g Calculated as the difference between NEE_G and R_{eco} .

^h $F_{\text{N}_2\text{O}}$, F_{CH_4} , N_2O and CH_4 fluxes; NEE_{G+B}, net ecosystem exchange (defined as the sum of NEE_G and R_{broilers}); NGHGE, net greenhouse gas exchange.

ⁱ Calculated as the mean of the 3 N_2O estimated fluxes (Table 4) multiplied by its Global Warming Potential (298 kg CO_2 eq. per kg of N_2O).

^j Calculated as the mean of the 2 CH_4 estimated fluxes (Table 4) multiplied by its Global Warming Potential (25 kg CO_2 eq. per kg of CH_4).

^k Calculated as the sum of $F_{\text{N}_2\text{O}}$, F_{CH_4} and NEE_{G+B} in CO_2 equivalents (Eq. 10).

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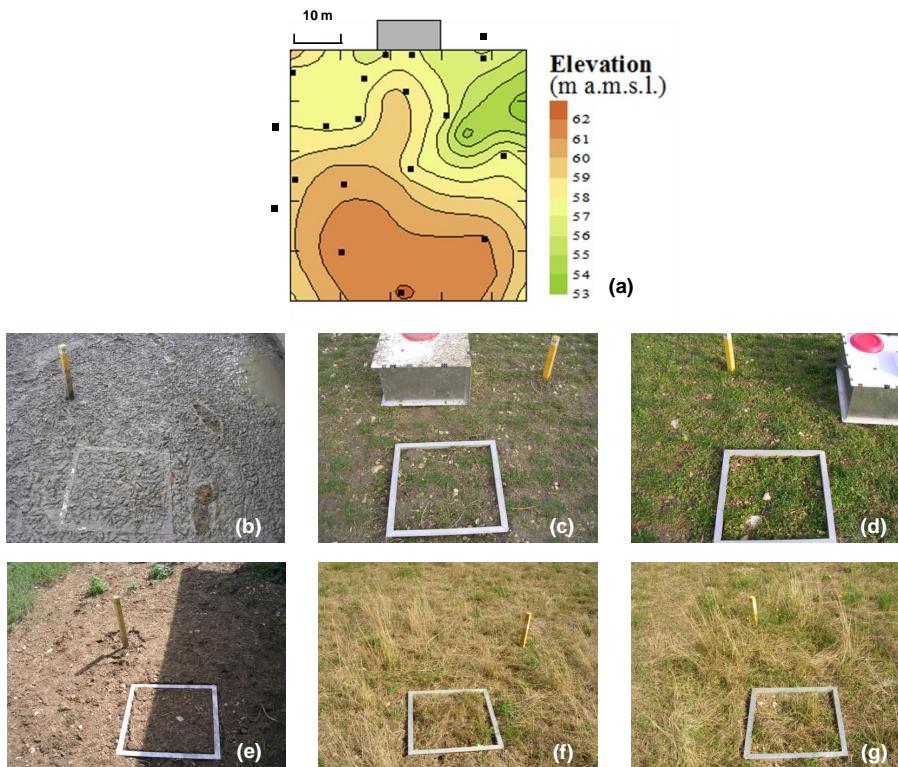


Fig. 1. (a) Site map showing the approximately square-shaped fenced-in outdoor run (50 m × 47 m), the broiler house (grey rectangle at the top), the topography of the outdoor run and the distribution of the static chambers (black square). (b to g) Photographic records of the state of soil and vegetation, showing differences in soil moisture, vegetation density and soil compaction for chamber frames located at 5 m (b, e), 24 m (c, f) and 41 m (d, g) from the broiler house. Pictures were taken on 2 March 2010 (b to d) and on 27 July 2010 (e to g), (a.m.s.l = above mean sea level).

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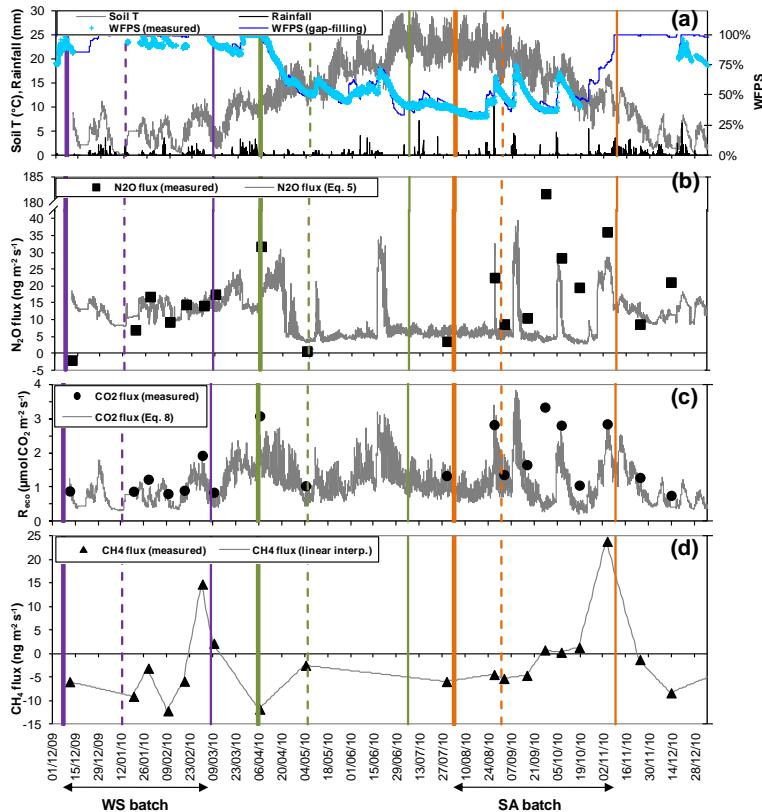


Fig. 2. Overview of soil conditions, meteorology, measured (black symbols) and gap-filled (grey lines) GHG fluxes at the outdoor run scale. **(a)** Soil temperature at -5 cm depth (Soil T), rainfall and water-filled pore space (WFPS). **(b)** N_2O fluxes. **(c)** Ecosystem respiration (R_{eco}). **(d)** CH_4 fluxes. GHG fluxes for each measurement day are spatial integrals computed from individual measurements using geostatistical methods. Vertical lines indicate batch start (thick, continuous), broilers first outdoor access (dotted) and slaughter (thin, continuous).

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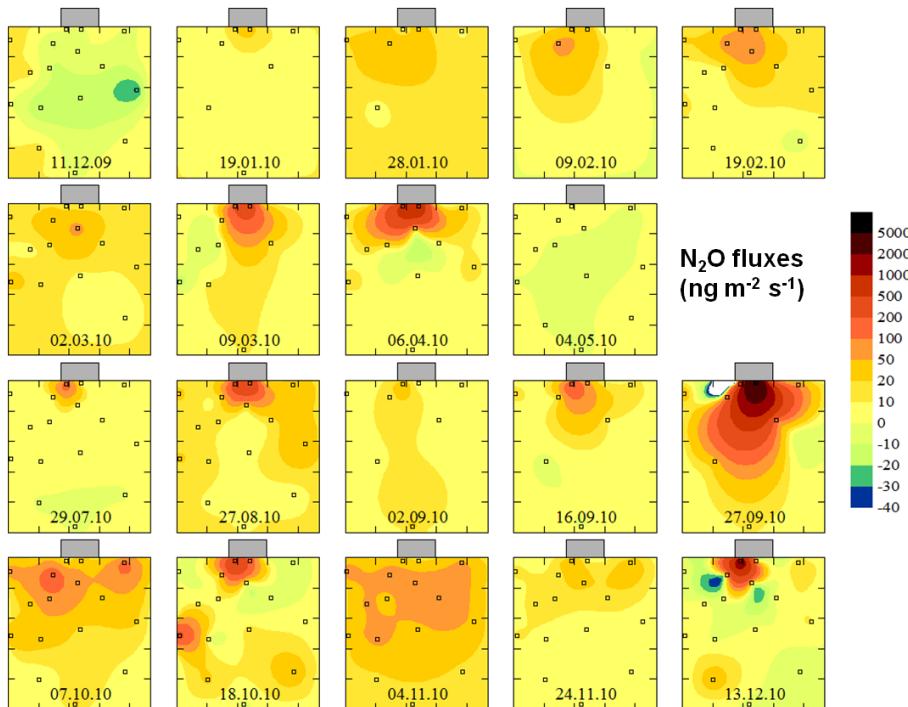


Fig. 3. Spatially interpolated (kriging method) maps of N₂O fluxes. For each measurement day, the kriging was done on the basis of the available chamber measurements as shown by the number of chambers displayed in each map.

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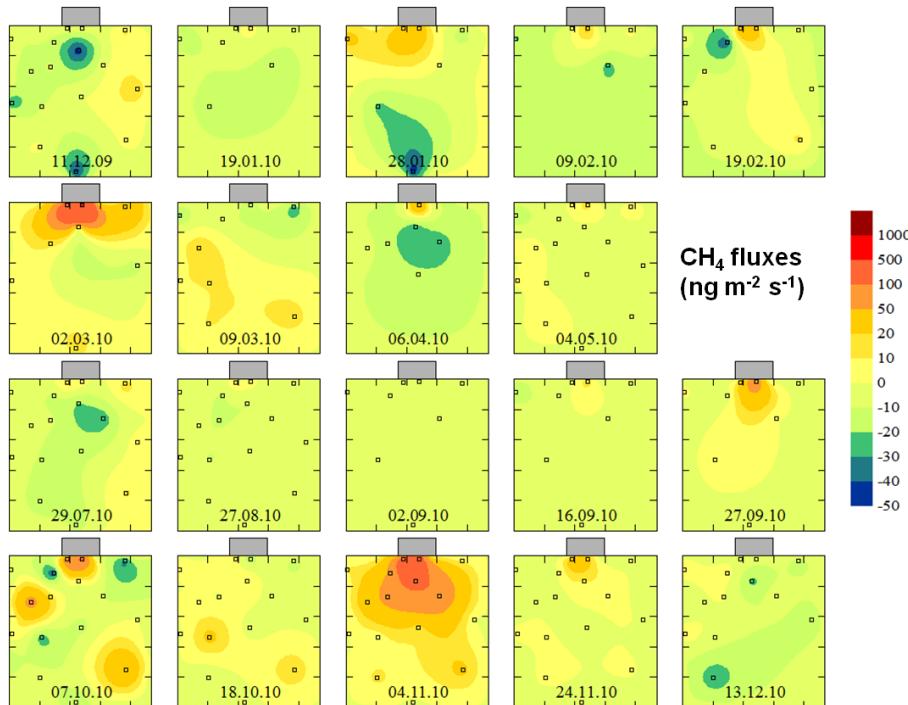


Fig. 4. Spatially interpolated (kriging method) maps of CH₄ fluxes. Comments as in Fig. 3.

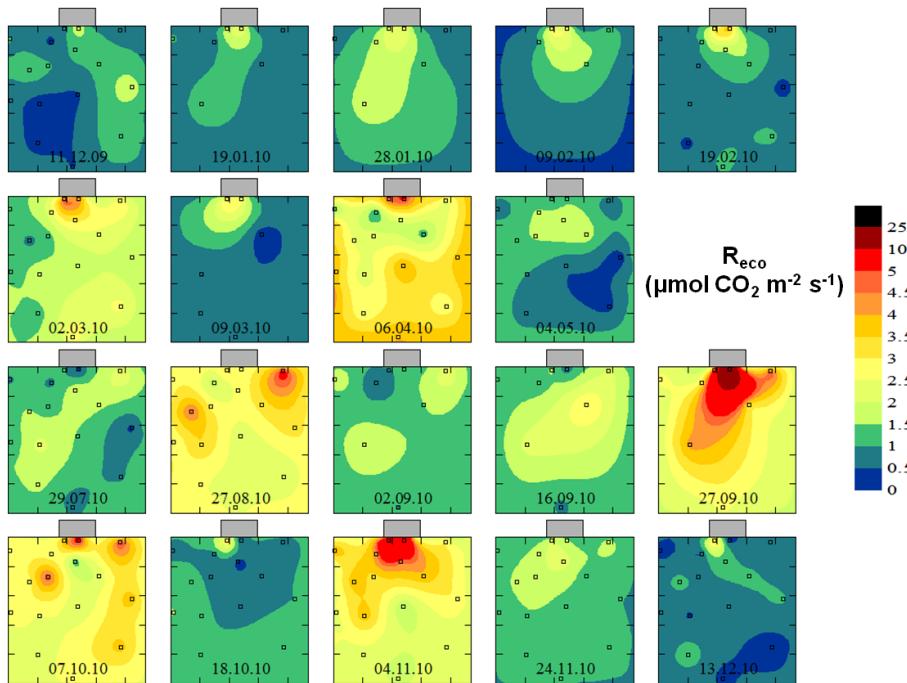


Fig. 5. Spatially interpolated (kriging method) maps of ecosystem respiration R_{eco} (not including broiler respiration). Comments as in Fig. 3.

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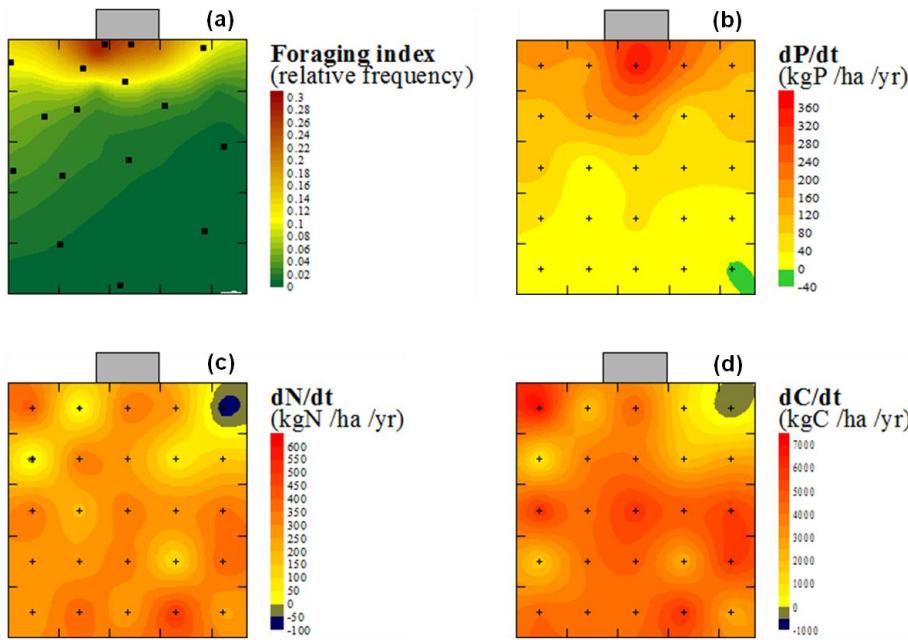


Fig. 6. Kriged maps of (a) broiler foraging index (collective probability of broilers being present on a surface area of 1 m² at a given location) and annual variations of (b) phosphorus, (c) total nitrogen and (d) total carbon soil stocks. Black squares (a) indicate locations for chamber measurements, while crosses (b, c, d) indicate soil sampling sites.

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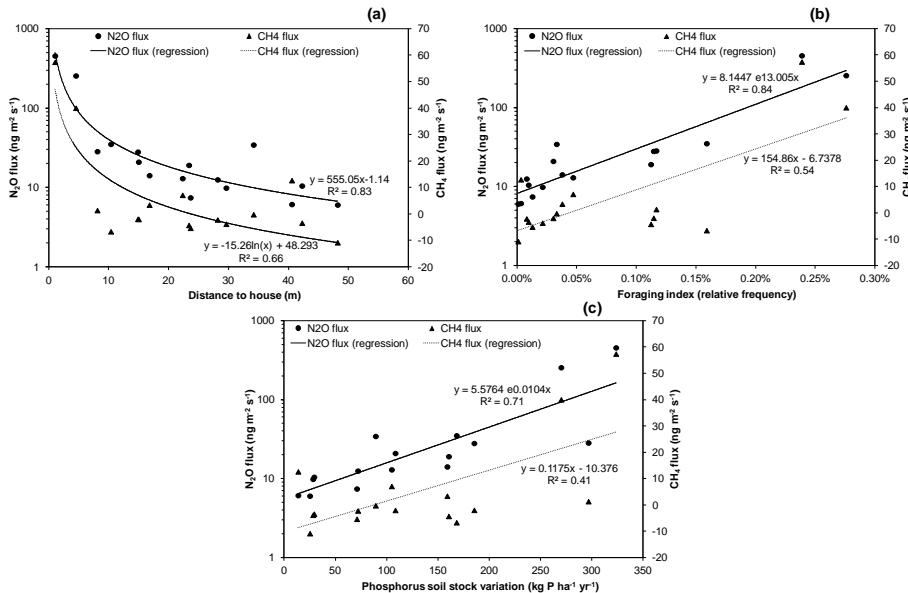


Fig. 7. Relationships between average measured N_2O and CH_4 chamber fluxes and control variables: **(a)** Distance to broiler house. **(b)** Foraging index. **(c)** Annual variation of phosphorus soil stock. Each datapoint represents the mean measured flux at one chamber location on the plot.

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