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Contribution of livestock effluent management to the soil greenhouse gas emission in a Sahelian agropastoral region

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Abstract. The assessment of greenhouse gas (GHG, i.e., CO_2, CH_4 and N_2O) emissions from soils is a major component of the carbon footprint of the agro-pastoral ecosystems in the Sahelian region. For this purpose, CO_2 emissions were measured in the district of Dantchandou in Niger using a portable analyzer EMG-5 over the annual cycle at nineteen sites from three land use types: shifting crop fields, manured crop fields, and fallow, as well as from three livestock concentration spots: livestock corrals, areas near pastoral ponds and near a pastoral well. Furthermore, CH_4, and N_2O emissions were measured using a static chamber on a subsample of three land uses and in five different months. The daily and seasonal emission dynamics are defined. The CO_2 emissions measured with the EMG-5 are consistently lower at the beginning and end of the day, higher in the early afternoon in un-manured sites, and in the late morning in manured sites. Mean daily CO_2 emissions increase with the first rains in June, peak at the beginning and end of the rainy season, and fall sharply following the end of the rains in October. The average daily CO_2 emissions from livestock concentration spots reaches during the rainy season 2.64±1.35 $gCO_2\ m^{-2}\ d^{-1}$ in vicinity of the pond, 24.99±15.73 $gCO_2\ m^{-2}\ d^{-1}$ in corralling field and 75.09±28.34 $gCO_2\ m^{-2}\ d^{-1}$ close to the pastoral well, compared to respectively 1.53±1.35, 1.68±0.65 and 4.68±0.75 $gCO_2\ m^{-2}\ d^{-1}$ during the dry season. The rainy season averages from shifting, manured and fallow fields are 4.3±2.72, 13.8±5.76 and 4.7±2.62 $gCO_2\ m^{-2}\ d^{-1}$ respectively and only 1.3±0.41, 1.8±0.48 and 1.2±0.35 $gCO_2\ m^{-2}\ d^{-1}$ during the dry season. The annual mean CO_2 emissions are very high in livestock corrals and near pastoral wells (respectively 34.0±10.9 and 92.5 $MgCO_2\ ha^{-1}\ y^{-1}$) and higher in manured fields (21.2 ±3.9 $MgCO_2\ ha^{-1}\ y^{-1}$) than in shifting fields, fallow and around ponds (8.3±2.5, 8.7±1.5 and 9.9±3.7 $MgCO_2\ ha^{-1}\ y^{-1}$ respectively). To account for that spatial variability in assessing the annual emissions at the scale of the district, emissions were weighted by the areas of each land use or livestock concentration spots in the territory. As a result, annual emissions from soils in the district are estimated at 16.5 $MgCO_2\ ha^{-1}\ y^{-1}$, 175 kg $CH_4\ ha^{-1}\ y^{-1}$ and 36 kg $N_2O\ ha^{-1}\ y^{-1}$. The gap in CO_2 emissions between manured and un-manured sites is used to estimate the contribution of the livestock effluent deposit to the annual CO_2 emissions in the territory. In average over the year this contribution amounts 0.48 $gCO_2\ m^{-2}d^{-1}$ or 15.3% of total soil CO_2 emissions.

Keywords: greenhouse gases**,** CO_2, CH_4, N_2O, seasonality, spatial heterogeneity, manure, livestock.

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1. Introduction

Ruminant farming in sub-Saharan Africa is unique due to the strong seasonal nature of rainfalls, water and fodder resources, as well as the diversity of ruminant species raised, herd sizes and seasonal mobility (Gbenou et al., 2024). Most animals living in this arid to semi-arid environment (Assouma et al., 2019b; Lo et al., 2024) move along grazing circuits during the day and are kept either in enclosures, in corral or in the farm yard at night (Butterbach-Bahl et al., 2020; Leitner et al., 2024). In sub-Saharan Africa, the organic matter, nitrogen and soluble phosphorus contents of soils are major limiting factors of crop and rangeland yields (Ambouta et al., 1998; Iliasso et al., 2022; Penning de Vries, 1982) which are also affected by rainfall variability (Velluet et al., 2014). Soil fertility has been maintained or restored through fallow practices (De Rouw, 2004; Floret et al., 1993) and locally by spreading manure or corralling livestock in crop fields (Schlecht and Buerkert, 2004; Guerin and Roose, 2017). In sub-Saharan Africa, livestock and soils are significant sources of GHG emissions, directly from livestock enteric fermentation and effluent management (Assouma, 2016), from nitrogen fertilizer application, and indirectly from pastoral bush fire and land use change (Davidson, 2009). In particular, livestock are blamed for being a major contributor on the basis of GHGs emitted per kilogram of meat and milk produced (FAO, 2023; Gerber et al., 2013). Moreover livestock are often incriminated for soil and vegetation cover degradation (N'Goran et al., 2022). The total livestock GHG emissions in Sub-Saharan Africa, including enteric methane, effluent and soil emissions, is estimated to represent more than 30% of the contribution of the agriculture sector (Graham et al., 2022). At global scale, the livestock supply chain contribution to anthropogenic GHG emissions expressed in CO_2-equivalent would be 44% methane (CH_4), 29% nitrous oxide (N_2O) and 27% carbon dioxide (CO_2) (Gerber et al. 2013). The atmospheric concentrations of these three gases have increased at an unprecedented rate since the industrial revolution and have contributed to more than 90% of human-induced global warming since pre-industrial time (IPCC, 2023).

However, it has been shown that soils can also act as sinks of atmospheric GHGs, particularly for CH_4 (Oertel et al., 2016). Indeed, in Sahelian rangelands are potential sinks for atmospheric CH_4 because of their coarse sandy texture, low pH and organic carbon content, that all support low permanently soil moisture status and subsequent CH_4 oxidation by methanotrophic microorganisms (Fiedler et al., 2005; Liu et al., 2022). Globally, the soil respiration, i.e. soil CO_2 emission, includes root respiration, and anaerobic and aerobic microbial respiration (Oertel et al., 2016). In Sahel, the soil texture, the short period of soil moisture increase, and the yearly high temperatures favor active aerobic respiration. Moreover, the strong seasonality of rainfall, and the large domination of therophytes among the rangeland and crop plants limit the root respiration during the dry season to the scattered woody plants among which some deciduous species have reduced activity during the dry season (Hiernaux et al., 1994). At the first rains of the monsoonal rainy season, following the long dry season, a surge of soil respiration is observed as often in arid and semi-arid ecosystems (Nguyen et al., 2025), the so-called Birch effect (Birch, 1958). This surge result from both a physical gas displacement by the soil wetting front (Singh et al., 2023), and a biological emission of CO_2 due to the microbial reactivation (Schimel, 2018). As a matter of consequences, CO_2 emissions from soil in

Sahel are expected to be mostly driven by wet season aerobic microbial respiration. N_2O emissions from soil result either from nitrification (i.e., oxidation of ammonium to nitrate) or from denitrification (reduction of nitrates to N_2O and possibly N_2) (Xiong et al., 2025). Once again, specificity of Sahelian soil and environmental conditions should favor aerobic nitrification (Bigaignon et al., 2020). Denitrification may also occur following large rain events triggering a surge of high microbial activity with ephemeral anaerobic condition (Zaady et al., 2013). In both cases, N_2O soil emissions in Sahel are closely linked to nitrogen inputs from livestock manure deposited in croplands and rangelands (Xu et al., 2019).

The quantification of GHG budgets in agropastoral ecosystems faces diverse challenges (Rosenstock et al., 2016). On the one hand, precipitations, which are highly seasonal in the Sahel, trigger the growth of herbaceous vegetation and crops, and therefore the storage of atmospheric carbon (Tagesson et al., 2015). On the other hand, it stimulates the biological activity of the soil responsible for the decomposition and mineralization of organic matter, which ensures the recycling of nitrogen, phosphorus, and other nutrients at the cost of GHG emissions from the soil (Delon et al., 2015). Moreover, the GHG emissions from soil and water surfaces receiving livestock effluents are poorly documented in semi-arid ecosystems, particularly in sub-Saharan agro-pastoral lands (Assouma et al., 2017; Butterbach-Bahl et al., 2020). The emissions stimulated by the deposition of faecal and urinary excretions from livestock have been assessed in a Sahelian sylvo-pastoral system in the Ferlo region of northern Senegal (Assouma et al., 2017; Assouma et al., 2019a; Assouma et al., 2019b). Yet, in mixed crop-livestock systems and intensive fattening and dairy farms (Vall et al., 2014), there is a diversity of livestock effluent management practices to fertilize crop fields. Few studies have attempted to assess the GHG emissions resulting from these managements and the resulting soil amendments, to parametrize the processes involved, and to finally improve the accuracy of GHG inventories at different scales, from local to global (Macharia et al., 2020).

This study is part of the CaSSECS research project, «Carbon Sequestration and greenhouse gas emissions in (agro) Sylvo-pastoral Ecosystems in the sahelian CILSS (Comité Inter Etat de Lutte contre la sécheresse au Sahel) States» (https://www.cassecs.org), which overall aim was to assess the role of livestock in the carbon balance in the Sahel.

The general objective of the present study conducted in 2022 is to estimate the annual GHG emissions (CO_2, CH_4, and N_2O) from soils across the Sahelian agro-pastoral territory of the Dantchandou district in Niger. More specifically, the objective is to estimate the contribution of livestock effluent deposition and management to the GHG emissions from soils. This exercise is conducted by considering the different land uses and livestock concentration spots of the territory. The sampling protocol of the emission measurements is designed to quantify the emissions variations at the day and year scale. The surface areas of each land use type and livestock concentration spots in the district is used to weight these emissions in order to estimate the daily, seasonal, and annual emissions for the whole Dantchandou district territory. Finally, the contribution of the livestock fecal and urinary excretions to the annual GHG emissions from soils is estimated through the differences in GHG emissions depending on the amount of livestock effluents deposited in each land use and livestock concentration spots.

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2. Material and methods

2.1 Site description

The climate of the Dantchandou district (919 km²) is typical of monsoonal semi-arid tropics with 499.4± 95.4mm mean annual rainfall between 1990 and 2025, only falling in a single rainy season from June to September. Mean minimum temperature of 24°C in observed January, and mean maximum of 40°C in April. Rainfall in 2022 was below average (419.9mm), and unevenly distributed with two short dry spells in June and July, and a long interruption in September followed by a few rain events. Set on the tertiary sandstone of a wide sedimentary basin, the district landscape consists in a plateau (14% of the area) topped by a thick hard pan and dissected by a web of shallow valleys, with gentle sandy slopes (62% of district) and narrow alluvial plain (24%). Overall, thick sandy soils (94.3±2.8 % sand) dominate in the land cropped with low $pH_{(H2O)}$ (5.5±0.4) and poor organic matter (0.18±0.07%), nitrogen (0.15±0.06 g kg^{-1}) and phosphorus $_{(Bray\ P1)}$ (5.1±3.7 mg kg^{-1}) concentrations (Turner and Hiernaux, 2015). The land use map (Figure 1) of the Dantchandou district was compiled from supervised classification of 2022 Sentinel2 images using the iota 2 processing chain (Inglada et al., 2017). The resulting map (Figure 1) distinguishes nine types of land use/cover: old fallow (22.4% of the district area), young fallow (18.4%), manured crop fields (14.0%), shifting crop fields (19.9%), range plain (5.8%), and range plateau (13.0%), thicket and isolated trees (2.6%), built areas (3.6%) and surface water (0.3%).

The district harbor the AMMA-CATCH (African Monsoon Multidisciplinary Analysis – Coupling Tropical Atmosphere and the Water Cycle) long-term environmental observatory, which equipment includes meteorological and hydrological censors (Cappelaere et al., 2009). Since 2005 the observatory also records energy, water and CO_2 fluxes by eddy covariance from two towers, one set over a millet crop field, the other over a bushy fallow (Boulain et al., 2009).

2.2. GHG emission equipment and flux calculation

Soil CO_2 emissions were measured in situ using static chamber connected with a portable infrared gas analyzer (EMG-5, version 1.01, PP-Systems, Amesbury, USA). Measurements were taken directly at the soil surface with the chamber covering a circular area of 78cm², and fluxes were calculated from the change in CO_2 concentration monitored over 90 seconds. These measurements were carried out at 19 sites representative of land use and livestock concentration of the district. Additionally, the soil emissions of CH_4 and N_2O were measured in situ using a rectangular stainless steel static chamber (40 x 20 x 20 cm). Measurements were taken directly at the soil surface, covering a rectangular area of 800cm², with chamber headspace sampled every 20 minutes over one hour (e.g. Serça et al., 1994). Given the labor-intensive and time-consuming nature of this method, its deployment was limited to a single site per category of land use/cover (shifting field, manured field and cattle corral), and only on five occasions (5 different months).

2.3. Sampling strategy to cover spatial variability

The sampling strategy of the soil emission measurements was designed to include the main land use/cover types: shifting crop fields (n=3), manured crop fields (n=5), and fallow fields (n=3). All these sites are part of the AMMA-CATCH observatory, which has conducted the monitoring of vegetation dynamics and soil properties in the district area since 1994

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(Hiernaux et al., 2009). The site selection was based on the diversity of livestock grazing pressure and the intensity of livestock manure application. Among the crop sites, three of them have not been manured and have alternated between cropping and fallowing periods (shifting crop fields). Manured crop fields include fields that have a history of manure application but did not receive manure from livestock corralled or penned in the year prior to the measurement. However, they may have received some fecal excretions from livestock passing through the site while grazing. Similarly, the three fallow sites were selected to reflect a gradient in fallow durations: one short, (≤3 years), one medium (4 to 8 years) and one long (>10 years), based on the assumption that extended fallow duration enhances soil organic matter supply, thereby leading to higher GHG emissions. In addition to the eleven sites selected in the main land use/cover types, seven sites were selected in three types of livestock concentration spots: livestock corrals (n=4), including two used for cattle and two others for mixes of sheep and goats, the vicinity of a pastoral well (n=1) and the vicinity of seasonal pastoral ponds (n=2). Furthermore, to investigate the possible emission from surface water contaminated by livestock effluents, GHG fluxes were measured from pastoral ponds and ponds fed by borehole leaks (n=14) in November, during the onset of the low-water period following the intensive use by livestock watered from these ponds during the rainy season. Moreover, GHG fluxes were regularly measured, on a sandy loam bare soil (n=1), with crusted topsoil, close to one of the monitored shifting crop fields in order to test the influence of herbaceous vegetation on the CO_2 fluxes (Figure 1). In addition, considering the heterogeneity of the rangeland vegetation cover with large extends of bare soils, patches of grasslands and thickets of the tiger bush (Hiernaux and Gérard, 1999), the GHG emissions from rangeland soils were estimated by the average of the emission measured in the bare soil, fallows, and on the pond bank located within the rangeland.

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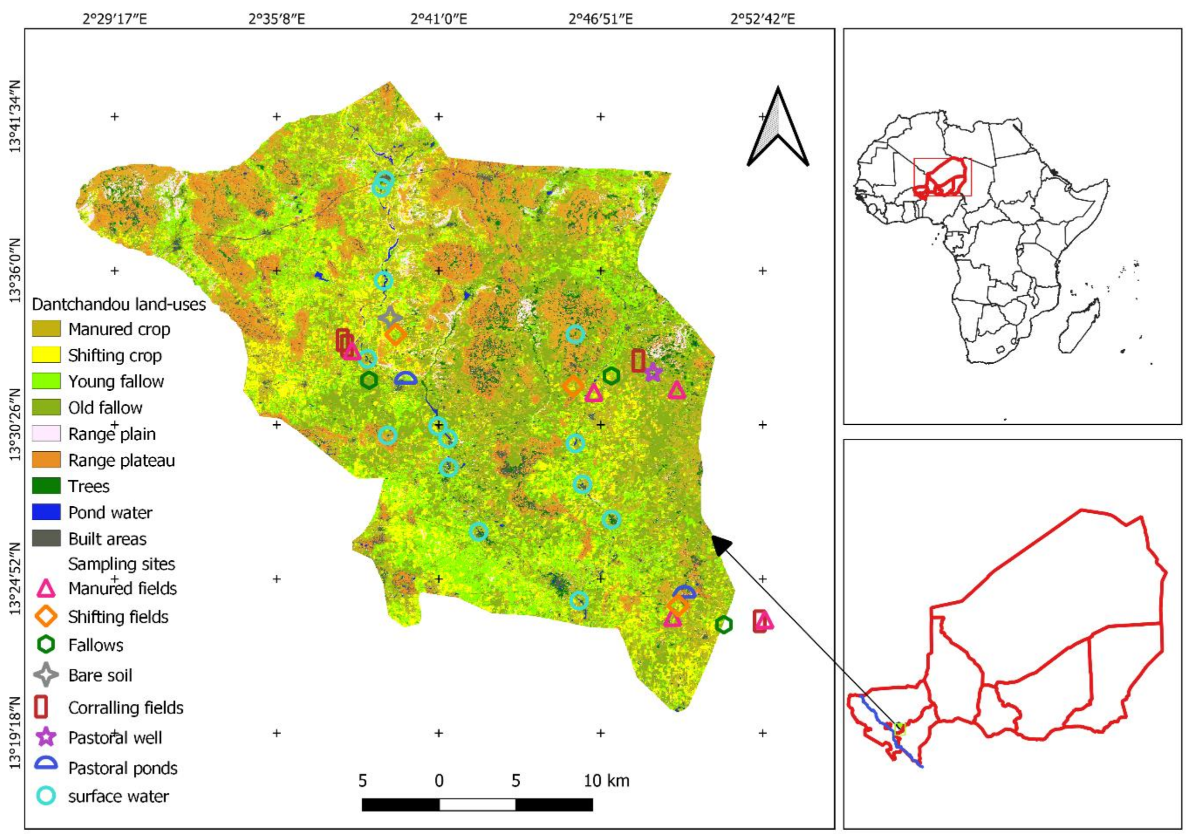

Figure 1: Land use/cover map of the Dantchandou district, Niger, with the location of the GHG emission measurement sites

2. 4. Sampling strategy to cover temporal variability

To capture the daily dynamics of GHG emissions, flux measurements were performed in five different times during the day (24h): 5-6 a.m., 10-11 a.m., 1-2 p.m., 4-5 p.m., and 7-8 p.m. Measurements from the EMG-5 provide sets of five measures, each made during 90 seconds. By contrast, measurements from the static chamber require one hour for gas sampling carried out at 20-minutes intervals, resulting in a total of four samples respectively at t0 min, t20 min, t40 min and t60 min. Samples were taken using a 20-cc syringe and then transferred into 10 ml vacuum flasks. Per day, 20 gas sample flasks were taken at each site allowing for the calculation of 5 fluxes. In both cases (EGM-5 or static chamber), daily average fluxes were calculated from the 5 measurements performed daily (see later distinction between daytime and nighttime calculation).

To capture the seasonal dynamics, daily measurements were carried out at ten dates between December 2021 and November 2022. Knowing that soil GHG emissions in semi-arid context are highest during the rainy season (Ago et al., 2016; Brümmer et al., 2008; Tagesson et al., 2015), measurements were set every two weeks from June to September, while they were only carried out once a month during the dry season in November, December, February and May. The seasonal dynamics of GHG emissions has also been covered with the static chamber measurements in the three subsampled sites with

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only five measurements during the year, three in the rainy season (June, July, and September) and two in the dry season (November and January).

2.5. Analysis of gas samples from the static chamber measurements

A total of 300 10ml-vials taken from the static chamber were stored along the sampling year and subsequently analyzed at the Laboratoire d'Aérologie (Toulouse) after the campaign. A gas chromatograph (SRI 8610C, SRI Instruments, USA) equipped with a 63Ni electron capture detector (ECD) for N_2O and a flame ionization detector (FID) for CH_4 was used. 500 µl were injected in duplicate in each detector with an error tolerance between repetitions lower than 5%. Calibrations were performed every 10 samples with commercial Air Liquid® "crystal" gas standards (100 and 200 ppm for CH_4, and 325 ppb for N_2O).

2.6. Flux calculation

GHG fluxes F_{gas} were calculated from the slope of the linear regression of gas concentration over time (both for EMG-5 and the static chamber) from the equation 1 (Duthoit et al., 2020):

$$\mathrm{Fgaz} = \mathrm{P}/(R.T.K).(\mathrm{V}/\mathrm{A}).(\Delta\mathrm{G}/\Delta\mathrm{t}) \qquad \mathrm{Eq.\,1.}$$

Where:

F_{gas} is the gas flux (µmolgas.m^{-2} s^{-1})

P is atmospheric pressure (101 325 N m^2)

R is the ideal gas constant (8.31 N m mol^{-1} K^{-1}),

T_k is air temperature inside the chamber in Kelvin

V (m^3) is the total system volume (chamber, tubing, analyzer cavity, internal pump)

A (m^2) is the chamber area

The slope ΔG/Δt was obtained via linear regression (Duthoit et al., 2020).

The linear regression slope calculations and data analyses were performed using R software. A quality criterion was applied when performing the calculation of the linear regression slope: regression with a $R^2 < 0.8$ were discarded and no fluxes were calculated. The minimum detectable flux (MDF) corresponds to the flux calculated with the lowest difference of mixing ratio detected by the gas chromatograph SRI along the course of the chamber application (60 min) onto the soil. These lowest differences in mixing ratio are equal to 0.4 ppmv for CH_4 and 0.6 ppbv for N_2O. To ensure a correct value of R^2 for the increase of the concentration during one hour, these lowest differences are doubled. According to Nickerson, (2016), the MDF are 0.42 µgN_2O m^{-2} h^{-1} and 0.10 mgCH_4 m^{-2} h^{-1}. Similarly, the MDF of the CO_2 fluxes measured with the EGM-5 during 90 seconds equals 2.20 µgCO_2 m^{-2} h^{-1}. All the measured fluxes stand largely over these MDF.

Daytime emissions are estimated by averaging the five measurements and attribute it to the 12-hour time between 7 a.m. and 7 p.m. period, while nighttime emissions are estimated by averaging the values measured at 5-6 a.m. and 7-8 p.m. and attribute it to the 12 hours period between 7 p.m. and 7 a.m. the following day. Daily emissions are estimated by the sum of daytime and nighttime emissions. Monthly emissions for June and July were estimated by averaging the results from the

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fortnightly measurements. The single monthly set of measurements carried out in November, December, February and May were attributed to the whole month, while the monthly emissions in October, January, March, and April were estimated by averaging the emissions measured in the previous and following of each of those months. Annual emissions are estimated by summing the monthly emissions.

In four of the corralling sites where CO_2 emissions were measured with EMG-5, the amounts of livestock feces deposited have been monitored and measured allowing to test the interrelation between the amount of feces deposited, and CO_2 emission.

As the static chamber measurements were taken at only five dates (January, June, July, September et November) during the annual cycle, estimating annual CH_4 and N_2O emissions required further extrapolations. The measurements taken in January were extrapolated to the following four dry season months, and emissions for August, October, and December were estimated using the averages of the measurements taken in the previous and following months.

2.7. Fluxes spatialization

The emissions at the scale of the Dantchandou territory were assessed by summing the emissions from the soils in each land uses and livestock concentration spots after weighing them by the relative area occupied in the territory (Table 1). To estimate the CH_4 and N_2O emissions at the district level, we assumed that emissions from shifting crop field are also representative of emissions in fallows, rangelands and pond banks. Similarly, the emissions from the livestock corral represent the emissions at the vicinity of pastoral wells.

Table 1: Area covered by the four main types of land use/cover and the three livestock concentration spots within the district of Dantchandou (2022).

Land-uses and livestock concentration spots		area (ha)	area (%)
land use types	manured fields	9938	10.7
	shifting fields	16577	18.1
	fallows	43822	47.9
	rangeland	20646	22.6
livestock concentration spots	corrals	167.9	0.3
	wells	25	0.03
	ponds	267	0.3
Total area		91442.9	100

3. Results

3.1. Daily dynamics of GHG emissions

The daily dynamics of CO_2 emissions is presented by plots of the ten monthly sets of five emission measures along the day in separate graphs for the different land use and livestock concentration sites (Figure 2). In the dry season, CO_2 emissions change little over the daytime. By contrast, during the rainy season, CO_2 emissions show a pronounced daily pattern with a minimum observed early in the morning (between 5 and 6 am), followed by an increase during the daytime reaching a peak

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in the late morning at manured sites (1.15±0.76 gCO_2 m^{-2}h^{-1} in corralling fields and 0.60±0.20 gCO_2 m^{-2}h^{-1} in manured fields), and in the early afternoon at un-manured sites (0.23±0.13 gCO_2 m^{-2}h^{-1} in fallows and 0.19±0.19 g CO_2 m^{-2}h^{-1} in shifting fields). CO_2 emissions then decrease in the evening and early night down to 1.03±0.66 and 0.46±0.20 gCO_2 m^{-2}h^{-1} in corralling fields and manured crop field and to 0.17±0.09 and 0.16±0.07 gCO_2 m^{-2}h^{-1} in fallows and shifting crop fields.

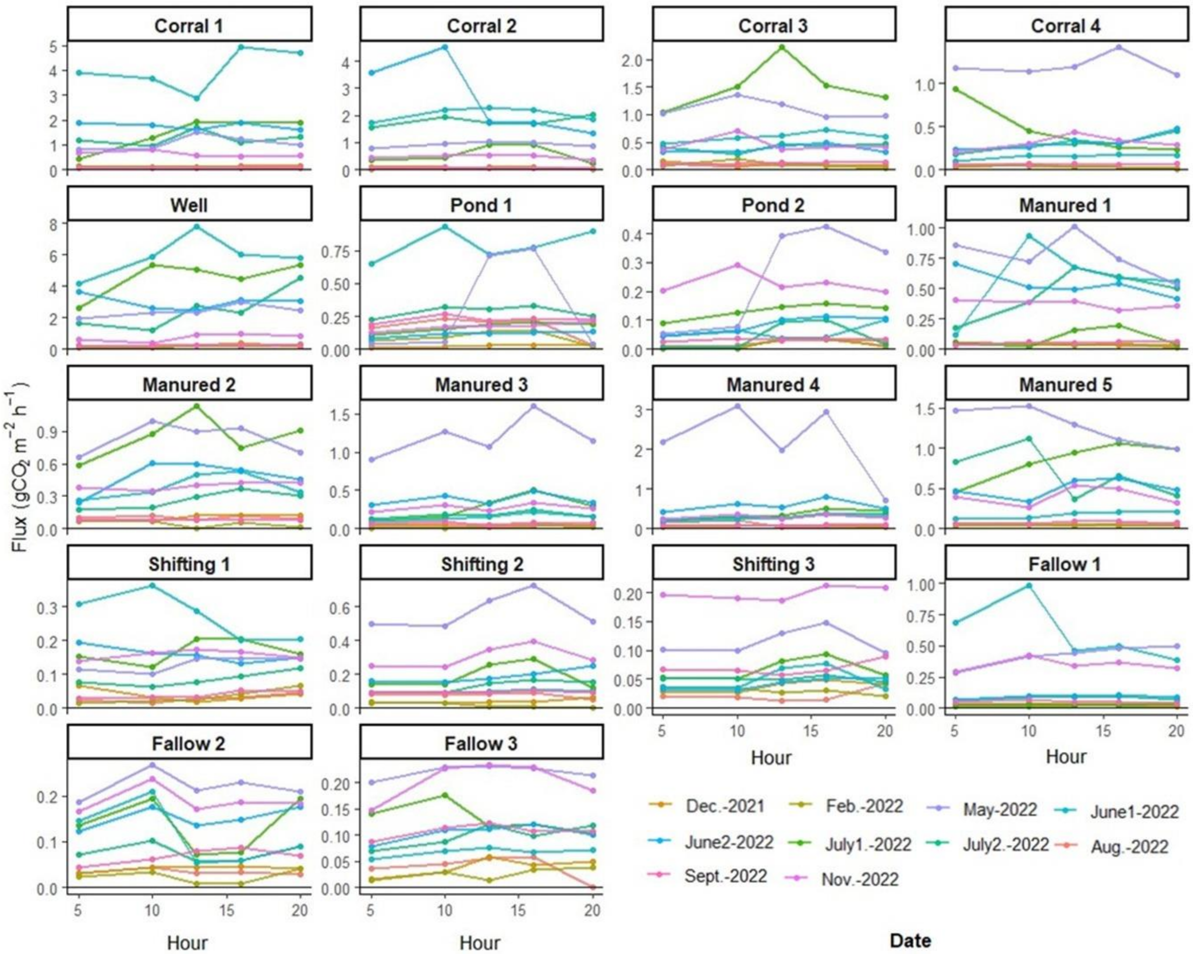

Figure 2: Daily dynamics of CO_2 emissions in gCO_2 m^{-2} h^{-1} as measured by the EMG-5 in the manured fields (n=5), the shifting fields (n=3), the fallows (n=3), the corrals (n=4), the site at the vicinity of the pastoral well, and the pastoral ponds (n=2).

N_2O and CH_4 fluxes can be negative or positive, and do not show any regular trend in their daily dynamics (figure 3). CH_4 fluxes tend to show higher uptake in shifting field and less in manured field. On the contrary N_2O fluxes tend to show higher uptake in manured field than in shifting field, and more often in the evening and early morning (figure 3).

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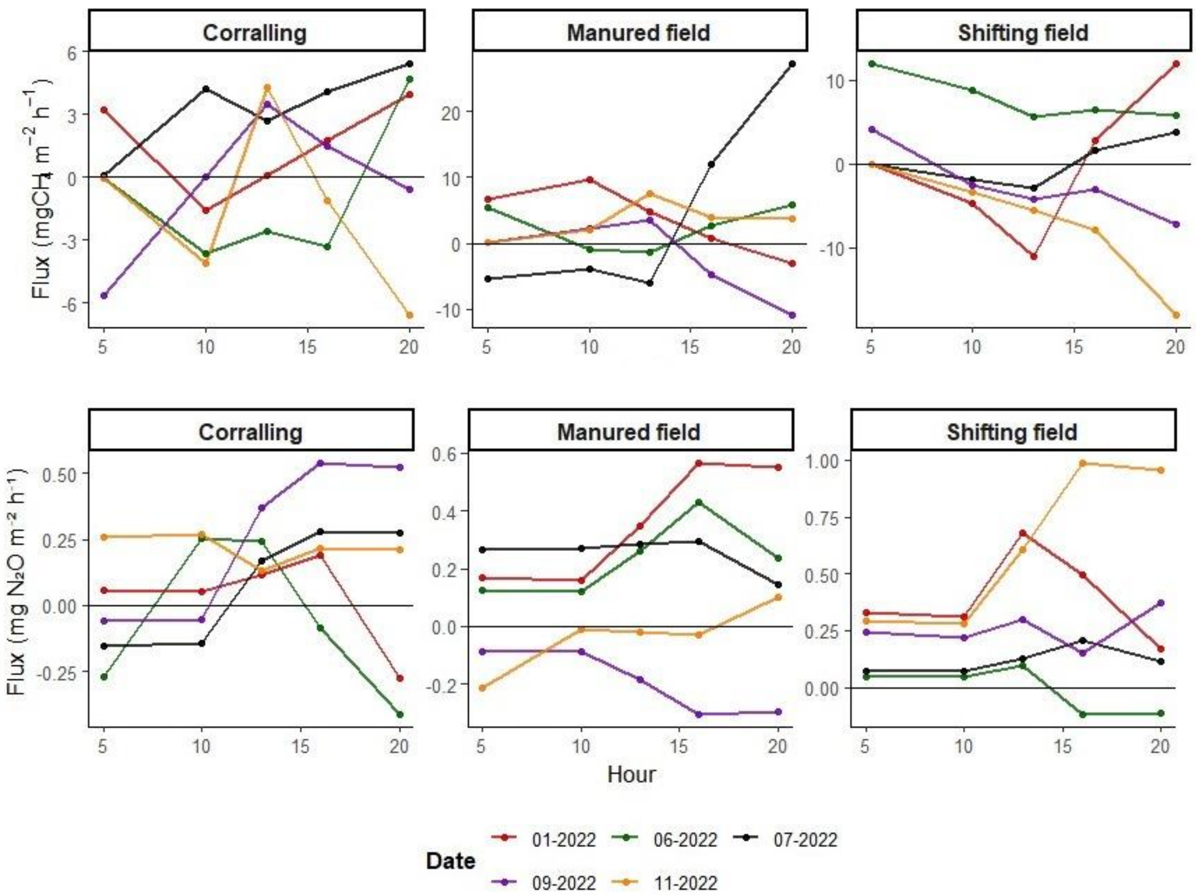

Figure 3: Daily dynamics of CH_4 and N_2O respectively in mgCH_4 m^{-2} h^{-1} and mgN_2O m^{-2} h^{-1} in the corralling field site (n=1), the manured field (n=1), and the shifting field (n=1).

3.2. Seasonal dynamics of GHG emissions

During the dry season from October to May, the average CO_2 emissions remain low regardless of the measurement site, including fallows (0.95±0.38 gCO_2 m^{-2}d^{-1}), shifting fields (1.06±0.42 gCO_2 m^{-2}d^{-1}), manured fields (1.38±0.47 gCO_2 m^{-2}d^{-1}), pastoral ponds (0.95±0.42 gCO_2 m^{-2}d^{-1}) and corralling fields (1.70±0.0.67 gCO_2 m^{-2}d^{-1}), with the exception of the areas around the pastoral well where heavy effluent deposition occur during the dry season, and where the average emissions is 4.67±0.71 gCO_2 m^{-2}d^{-1}. CO_2 emissions increase sharply with the onset of the first rains between late May and June, peaking in late August-September in fallow fields, shifting crop fields and around ponds, and from July onwards in manured crop fields, livestock corralling sites and around pastoral wells (Figure 4). During the wet season, CO_2 emissions reach a peak of 3.85±0.42 gCO_2 m^{-2}d^{-1} in the shifting crop fields, 4.25±2.36 gCO_2 m^{-2}d^{-1} in the fallows, and 4.60±1.39 gCO_2 m^{-2}d^{-1} in the pastoral ponds. In the livestock concentration spots receiving more livestock effluents, these averages are 12.29±6.55 gCO_2 m^{-2}d^{-1} in the manured crop fields, 25.18±15.76 gCO_2 m^{-2}d^{-1} in the corralling fields, and up to 74.82±29.10 gCO_2 m^{-2}d^{-1} in the

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vicinity of the pastoral well. The Kruskal-Wallis test performed on the temporal variation of CO_2 emissions between land use types and livestock concentration spots shows significant differences for both the dry season (p-value = 0.001) and the rainy season (p-value < 0.0001).

The small number of measurement dates (five) performed with the static chamber limits the study of seasonal dynamics. Seasonal trends show CH_4 uptake during the dry season in corralling fields (-0.002±0.029 mgCH$_4$ m^{-2}d^{-1}) and shifting fields (-0.090±0.061 mgCH$_4$ m^{-2}d^{-1}), and emission during the rainy season of 0.014±0.043 and 0.041±0.097 mgCH$_4$ m^{-2}d^{-1}, respectively. In the manured field the mean daily CH_4 remains positive in both seasons with 0.094±0.011 mgCH$_4$ m^{-2}d^{-1}in the dry season and 0.032±0.041 mgCH$_4$ m^{-2}d^{-1} in the rainy season. Despite the N_2O uptake observed on a few dates during the dry season, the average seasonal fluxes remain positive during the dry season in corralling fields (0.003±0.003 mgN$_2$O m^{-2}d^{-1}), manured fields (0.004±0.005 mgN$_2$O m^{-2}d^{-1}), and shifting fields (0.011±0.003 mgN$_2$O m^{-2}d^{-1}), with relatively lower average fluxes during the rainy season of 0.001±0.003, 0.002±0.004 and 0.003±0.002 mgN$_2$O m^{-2}d^{-1}, respectively.

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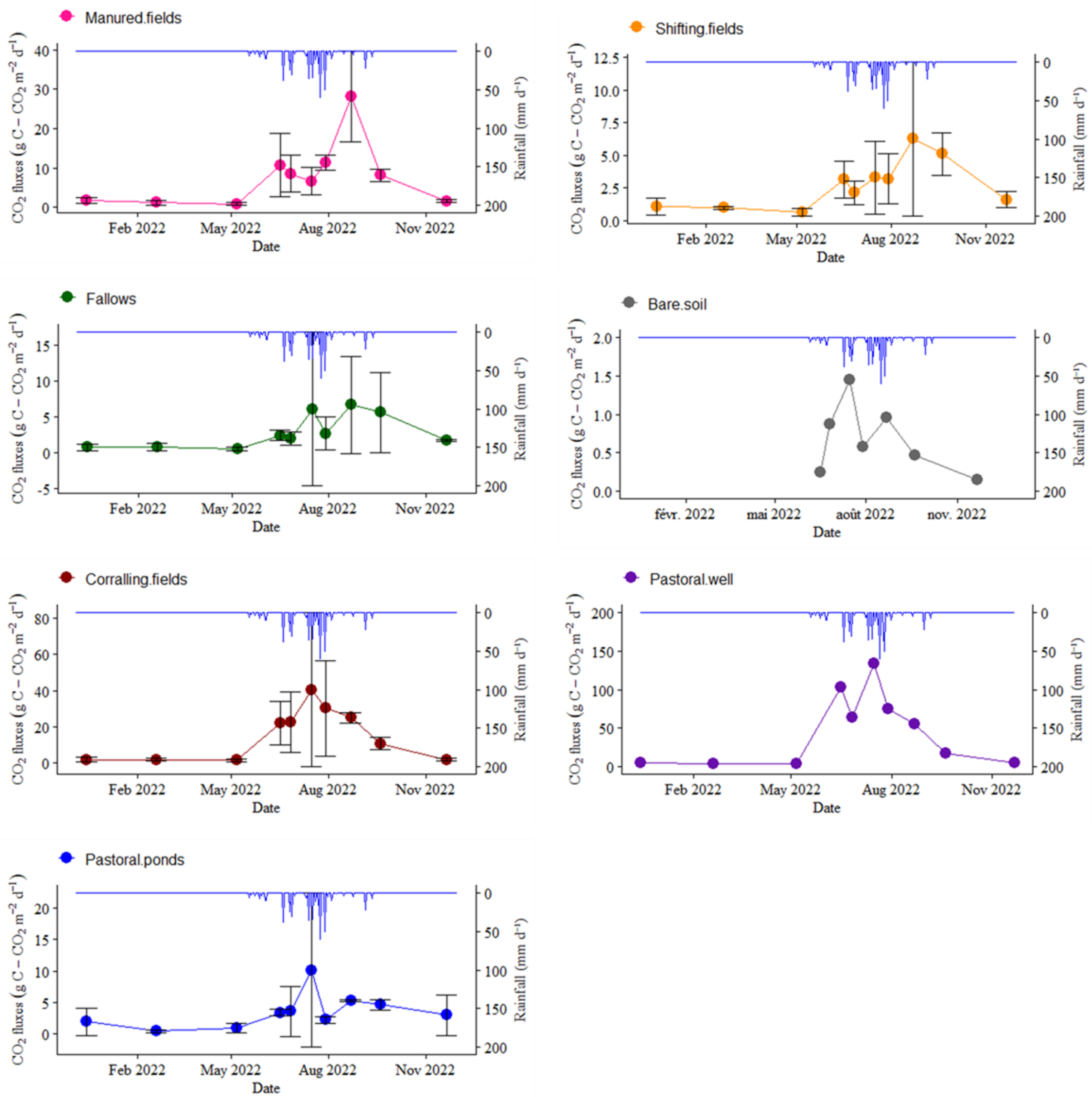

Figure 4: Seasonal dynamics of CO_2 emissions in $gCO_2\ m^{-2}\ d^{-1}$ determined with EMG-5 of the three main land use/cover: fallows, manured crop fields and shifting crop fields and in high livestock concentration spots: corralling fields, vicinity of pastoral ponds and a pastoral well. Upper blue bars represent individual rain event (see right Y axis for intensity in mm d^{-1}).

3.3. Variability in GHG emissions between land use types and livestock concentration spots

The annual mean of daily CO_2 emissions measured with EMG-5 vary greatly between land use types and livestock concentration spots. Average annual emissions are significantly higher in sites receiving livestock excreta (Table 2) with 5.8,

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9.3 and 25.4 gCO_2 m^{-2} d^{-1} in manured crop fields, livestock corrals and at vicinity of the pastoral well respectively, while the average in the eight sites with little or no livestock excreta input, including shifting crop fields and fallows is 2.4 gCO_2 m^{-2} d^{-1}. Sites near ponds used for livestock watering fall into this category, as livestock, which are always herded in the district, do not park long on the banks of the pond avoiding large deposition of excretion there. In addition, CO_2 emissions measured on the surface waters of fourteen pastoral ponds on November 22, 2022 are relatively low (1.05 gCO_2 m^{-2} d^{-1}). CO_2 emissions measured on a strip of bare sandy-loam crusted soil at the edge of one of the unfertilized millet fields averaged 0.55 gCO_2 m^{-2} d^{-1} over the year.

In four of the corralling spots, the annual CO_2 emission is linearly related to the amount of manure deposited (see equation 2):

$$eCO2 = 1.46 * Fec + 2.5 \; (n = 4, r^2 = 0.97) \qquad \text{Eq. 2.}$$

with eCO_2: the annual mean CO_2 emission (gCO_2 m^{-2} d^{-1}), and Fec the mean dry mass of feces deposited on the corral soil (kgDM m^{-2}).

The annual average of daily CH_4 emissions measured with the static chamber are four times lower in livestock corrals than in shifting crop fields, but are higher in manured crop fields than in shifting crop fields (Table 2), thus not related to the amount of manure deposit. These annual average CH_4 fluxes result of balances between emission, more active in the early wet season, and uptake more active in the late wet season (Fig. 3). The annual average N_2O emissions also result from balances between emission and uptake fluxes, they are significantly higher in shifting crop fields than in manured crop fields and the corrals, thus decreasing with increasing manure deposition.

Table 2: Annual average of daily emissions of CO_2, CH_4 and N_2O from soils of three land use types and three livestock concentration spots. CO_2 emissions calculated from EGM-5, and CH_4 and N_2O emissions from static chamber.

	Sites	n	CO_2 g m^{-2} d^{-1}	CH_4 mg m^{-2} d^{-1}	N_2O g m^{-2} d^{-1}
Land use types	manured fields	5	5.69±1.12[a]	68.56	3.85
	shifting fields	3	2.29±0.88[b]	44.12	11.08
	Fallows	3	2.35±0.52[b]	-	-
	bare soil	1	0.55	-	-
Livestock concentration spots	Corral	4	9.25±3.84[a]	11.32	1.51
	pastoral well	1	25.47	-	-
	Ponds	2	2.64±1.35[b]	-	-
	surface water	14	1.29±0.63[b]	-	-

Note: the data are expressed as averages and the standard deviations of CO_2 emissions in each land use or livestock concentration spot. The letters in superscript after the standard deviation indicate significant differences between land use and livestock concentration spot when there is more than one site (Kruskal-Wallis test; p=0.00).

3.4. Upscaling annual GHG emissions from sites to the whole territory

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In order to assess the total emissions from the Dantchandou district soils, average annual emissions per land use and livestock concentration spots were weighted by the area of each land-use type and livestock concentration spots. The annual CO_2 emission from soils of the Dantchandou district amounts to 9.9 t CO_2 ha^{-1} y^{-1}, equivalent to the daily average 2.7 gCO_2 m^{-2} d^{-1}, or a corresponding carbon emission of 0.80 gC m^{-2} d^{-1} (Table 3).

Table 3: Spatial distribution of GHG emissions over the annual cycle for the main land uses and livestock concentration spots. Annual averages of CO_2 emissions (EMG-5), CH_4 and N_2O (static chamber) per hectare. Contributions to annual emissions weighted by each land use and livestock concentration spot area within the Dantchandou district. Values in parentheses are extrapolated from values measured at other sites.

Sites		Average emissions			Contribution to district emissions		
		CO_2	CH_4	N_2O	CO_2	CH_4	N_2O
		t $ha^{-1}yr^{-1}$	kg ha^{-1} yr^{-1}	kg ha^{-1} yr^{-1}	t $ha^{-1}yr^{-1}$	kg $ha^{-1}yr^{-1}$	kg ha^{-1} yr^{-1}
land use types	manured fields	21.19	249.72	14.01	2.24	43.02	2.41
	shifting fields	8.38	160.70	40.36	1.52	32.00	8.03
	fallows	8.72	(160.70)	(40.36)	4.18	(65.5)	(16.4)
	rangeland	(8.06)	(160.70)	(40.36)	(1.84)	(34.4)	(8.65)
livestock concentra-tion spots	corrals	34.13	41.23	5.49	0.06	0.13	0.02
	wells	92.94	(41.23)	(5.49)	0,02	(0.02)	(0.00)
	ponds	9.97	(160.70)	(40.36)	0.03	(0.47)	(0.12)
Total GHG emissions					10.77	9.90	35.70

The annual emissions of the Dantchandou district soils is 175.6 $kgCH_4$ $ha^{-1}y^{-1}$ and 35.7 kgN_2O $ha^{-1}y^{-1}$, (48.1$mgCH_4$ m^{-2} d^{-1} and 9.8 mgN_2O m^{-2} d^{-1}, respectively). Unlike CO_2 emissions, lands receiving a significant proportion of animal manure covering 17.9% of the territory do not contribute significantly more than their area share for CH_4 (24,4%), and significantly less for N_2O (5.8%). Contributions of each site to the emissions at the district scale were calculated by multiplying the average emissions by the area of each type, and dividing the results by the total surface of the district (919km²).

4. Discussion

4.1. Daily dynamics of the GHG emissions

The similarity of the CO_2 emissions measured at 5-6 a.m., with the emissions measured at 7-8 p.m., regardless of season and site supports the use of their average to estimate nighttime fluxes (between 7 p.m. and 7 a.m. the following day). In addition, the daytime variations of the CO_2 fluxes estimated by the average of the five measurements taken between 5-6 a.m. and 7-8 p.m are very weak during the 8-months dry season, varying at most by 0.06 gCO_2 m^{-2} h^{-1} in the un-manured sites and up to 0.28 gCO_2 m^{-2} h^{-1} on the manured sites. On the contrary, the daytime dynamics of the CO_2 fluxes recorded in the 4-months

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wet season is strong in the manured sites with mean amplitude of 3.63 $gCO_2\ m^{-2}\ h^{-1}$, while this amplitude is only of 0.72 $gCO_2\ m^{-2}\ h^{-1}$ in un-manured sites. As a result, on average over the year and across sites the daytime CO_2 emissions only account for 52.3% of daily emissions. Yet, Ferreira et al., (2018) in the Caatinga region of Brazil did not record any difference in soil CO_2 emissions between day and night.

The daily dynamics of CH_4 and N_2O fluxes are weak regardless of the sites and seasons, sometimes negative fluxes pointing at uptake processes in the soils. Low intensities of CH_4 and N_2O were also recorded in Sahelian rangelands in northern Senegal (Assouma et al., 2017). In an agroforestry park in central Senegal, emissions of CH_4 and N_2O are considered negligible in all seasons (Ba et al., 2022), with low N_2O fluxes associated with low soil fertility and moisture conditions in very sandy soils that do not favor N_2O production by denitrification (Butterbach-Bahl et al., 2013).

4.2. Seasonal dynamics of GHG emissions

The sudden increase of CO_2 emissions with first rain events corresponds to the Birch effect, i.e. both the CO_2 displacement by the water infiltration and the microbial activity triggered by the moisture of very sandy soils, which had remained relatively inactive during the long dry season (Slevin, 2025). This effect has already been described in semi-arid regions in Africa (Ago et al., 2015; Ba et al., 2025; Brümmer et al., 2008; Tagesson et al., 2015; Wieckowski et al., 2024). Following this first surge, the timing and intensity of the CO_2 emissions during the rainy season vary with the quantities and nature of decomposable organic matter, plant litter and livestock feces in or at the soil surface. In sites receiving little or no animal excreta, the emission peaks at 3 to 10 $gCO_2\ m^{-2}d^{-1}$ between August and September (Fig. 4), while in sites receiving more animal excreta, there is a first peak at the beginning of the rains in June-July, peaking at 11 to 23 $gCO_2\ m^{-2}d^{-1}$ followed by a second peak at the end of the season, between 27 and 41 $gCO_2\ m^{-2}d^{-1}$. In the case of the surroundings of a pastoral well intensely used throughout the dry season the first peak reaches 103 and the second 131 $gCO_2\ m^{-2}d^{-1}$. The early emission maximum therefore appears to be associated with the rapid decomposition of fecal excretions deposited by livestock during the previous dry season, while the late maximum could be rather linked to the decomposition of plant organic matter at the end of the growing season. The strong seasonality of the CO_2 soil emissions is also strengthened by the uneven livestock effluent deposition. Indeed, the wet season mean rate of CO_2 soil emissions reaches 12.3 $gCO_2\ m^{-2}d^{-1}$ in manured crop fields, 25.2 $gCO_2\ m^{-2}d^{-1}$ in corrals and up to 74.8 $gCO_2\ m^{-2}d^{-1}$ at the vicinity of the pastoral well where effluents accumulate during the dry season, while it remains at 4.3 $gCO_2\ m^{-2}d^{-1}$ in un-manured cropped fields, fallows and rangelands compared to 1.28 $gCO_2\ m^{-2}d^{-1}$ over the whole territory during the dry season. All sites considered together, 81.2% of the soil CO_2 emissions occur during the four months of the rainy season, i.e. between June and September (Figure 4). This higher contribution of wet season on the annual CO_2 emission was also found in other studies conducted in the Sahel (Assouma et al., 2017; Boulain et al., 2009; Delon et al., 2017; Tagesson et al., 2016), as well as in more humid tropical climates (Leitner et al., 2024).

From the CO_2 fluxes measured by Eddy covariance over a millet field in the district, the average over three years of the dry season nighttime fluxes equals 0.12±0.02 $gCO_2\ m^{-2}\ h^{-1}$. The same nighttime fluxes measured in a nearby bushy fallow

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average of 0.13±0.03 gCO_2 m^{-2} h^{-1} (Boulain et al., 2009). These values stand above the 0.078 ± 0.051 gCO_2 m^{-2} h^{-1} emissions we measured during the dry season from the soil of un-manured millet fields. Indeed, flux towers located above the canopy integrate both emissions and uptake by the soil and by the vegetation (Ba et al., 2025; Tagesson et al., 2015, 2016a). They are therefore not directly comparable to soil emission measurements. However, since there is no photosynthesis during nighttime, the respiration from vegetation and soil is measured by Eddy covariance at night. Moreover, in the dry season, vegetation respiration is limited to the contribution of trees, shrubs and bushes and their roots as the annual herbaceous are dead, so that the nighttime CO_2 flux measured during the dry season from the tower is close to soil respiration alone (Roupsard et al., 2020). With the first rain events, daytime and nighttime respiration increased sharply due gas displacement and to the reawakening of soil microbial activity. However, the herbaceous vegetation that grows after these rains contributes significantly to CO_2 fixation through photosynthesis. During the night it also increases soil and plant respiration up to 1.34 gCO_2 m^{-2} d^{-1} in millet field and to 0.99 gCO_2 m^{-2} d^{-1} in the bushy fallow on average over the three years. This corresponds well to the surge in soil CO_2 emissions we observed at the onset of rains with 2.63±1.03 gCO_2 m^{-2} d^{-1} in the three un-manured millet fields and 2.20±0.76 gCO_2 m^{-2} d^{-1} in the three fallows (Figure 4).

The CO_2 emissions we measured with EGM-5 during the dry season from the soil of un-manured millet fields (0.078 ± 0.051 gCO_2 m^{-2} h^{-1}) are very close to the dry season average nighttime respiration rates (0.067 ± 0.024 gCO_2 m^{-2} h^{-1}) established from six flux towers distributed across the Sahel region (Tagesson et al., 2016). As expected, these values are lower than dry season nighttime emissions (0.182±0.052 gCO_2 m^{-2} h^{-1}) measured from flux towers in a degraded sub-humid woodland of northern Benin (Ago et al., 2015).

The small number of measurement dates (5) performed with the static chamber limits the study of seasonal dynamics. Even with such a small data set, we were able to catch the surge of CO_2 emissions at the onset of the rainy season with a peak in June followed by a gradual decline at all three sites regardless of land use. Soil CH_4 emissions are low, peaking in June-July, turning into uptake which dominates during the dry season (Figure 3). N_2O fluxes are low with often negative values during the rainy season including in the heavily manured corral site. This result corroborates those of Wachiye et al., (2020) in the plains of southern Kenya, where N_2O emissions did not vary according to the seasons. However it is in apparent contradiction with the high emissions observed in active and even inactive corrals named "*bomas*" in Kenya (Butterbach-Bahl *et al.*, 2020). Indeed, the deposition of livestock excretions reported in these *bomas* range between 108 to 345 kgDM m^{-2} (Leitner et al., 2024) about 100 time more than the 1 to 4 kgDM m^{-2} deposited in the Dantchandou corrals (Yakoubou Alzouma et al. article submitted). The livestock only remains for a few days or weeks on each corral spot that most often are not fenced as there is no fears of predatory carnivores in this region of Niger while they remain for several weeks or month, and return on the same spot for years in Kenya. Moreover, the highly sandy texture (> 94% sands) of the deep soils in Dantchandou, in contrast with the black cracking clay soils (<40% sands) that support the *bomas* could contribute to explain the different behavior together with the longer duration of moist soil condition in Kenya in relation with the bimodal distribution of the rains compared to the monomodal distribution of the monsoonal rains in Niger.

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4.3. Spatial heterogeneity of soil GHG fluxes

Once daily and seasonal dynamics are considered, average annual emissions vary greatly between land uses and livestock concentration spots (**Table 1**). Low-emission sites include shifting crop fields with 2.3±1.2 gCO_2 m^{-2} d^{-1} annual average of daily CO_2 emissions, fallows with 2.4±1.1 gCO_2 m^{-2} d^{-1}, and the banks of ponds with 2.7±1.9 gCO_2 m^{-2} d^{-1}. The relatively modest rate of CO_2 emissions on these ponds banks contrast with the high emissions (6.9±4.0 gCO_2 m^{-2} d^{-1}) recorded in the vicinity of the ponds in the Ferlo region, Senegal (Assouma et al., 2017). Indeed, in Niger, the animals do not rest by the pond banks as they are herded to avoid damage to the crops in the surrounding fields, while they are freely grazing in the Ferlo. CO_2 emissions from the other land uses increase with the amount of organic matter deposited by the livestock with 4.1±0.2 gCO_2 m^{-2} d^{-1} in manured crop fields and 9.3±5.1 gCO_2 m^{-2} d^{-1} in the livestock corral. However, this is much less than 42.9 g m^{-2} d^{-1} mean daily CO_2 emissions reported in Kenya active *bomas* or even 14.7 gCO_2 m^{-2} d^{-1} reported for inactive *bomas* (Leitner et al., 2024). With 2.4±1.1 gCO_2 m^{-2} d^{-1}, the mean annual daily CO_2 emissions in grazed rangeland we reported in Dantchandou is comparable to 2.0±1.6 gCO_2 m^{-2} d^{-1} measured in the Kenyan Kapiti station, 100m away from *bomas*. The average annual CO_2 emissions around the studied pastoral well heavily used by livestock during the dry season reached 25.4±12.7 gCO_2 m^{-2} d^{-1}, ten times the emissions of an un-manured site. In the four corralling sites for which the amount of manure deposited and the CO_2 emissions have been measured, the CO_2 emission is found linearly related to the amount of manure deposited which is consistent with observations by Assouma et al., (2017), (Agbohessou et al., 2024), and (Leitner et al., 2024).

CO_2 emissions from soil also depend on the amount of litter, which explains why emissions from fallows are 2.4±1.1 gCO_2 m^{-2} d^{-1} and emissions from shifting fields are 2.3±1.2 gCO_2 m^{-2} d^{-1}, higher than from bare soil (0.45±0.27 gCO_2 m^{-2} d^{-1}). It is also explaining why CO_2 emissions from crop fields with a history of manure application and no effluent deposition in the previous year are higher than emissions from shifting crop fields (Table 2). Past manure application increases the production of millet and weeds, resulting in more litter than on shifting crop fields (Hiernaux et al., 1999). The spatial transfer of organic and mineral matter, particularly nitrogen and phosphorus, by livestock via the highly uneven deposition of fecal and urinary excreta (Schlecht et al., 2004) has an effect beyond the year of deposition on CO_2 emissions through increased plant production that persists for at least four years after deposition (Hiernaux et al., 2009).

CH_4 fluxes show little variation between the three sites studied, with higher annual averages of daily emission from the soils of manured crop field (68.6 mgCH_4 m^{-2} d^{-1}) than from the soils of shifting crop field (44.1 mgCH_4 m^{-2} d^{-1}). However the CH_4 emissions are lower at the corralling site (11.3 mgCH_4 m^{-2} d^{-1}) due to a dominant CH_4 uptake by soil during the dry season (Li and Kelliher, 2007; Macharia et al., 2020).

The annual N_2O fluxes resulting from emission and uptake are small (1.5 mgN_2O m^{-2} d^{-1}) with dominant uptake during the dry season at the corralling site (Saggar et al., 2007). As in our work, (Rosenstock et al., 2016) found that manure inputs increased CO_2 emissions, but not those of N_2O or CH_4.

4.4. Contribution of livestock farming to the GHG emissions from soil

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Weighting the average annual emissions by the area of each land use type and livestock concentration spot gives an annual CO_2 emission from soils in the Dantchandou district of 10.77 $MgCO_2$ ha^{-1} or 2.95 gCO_2 m^{-2} d^{-1} (Table 3). This is slightly lower than the 15.91 $MgCO_2$ ha^{-1} or 4.36 gCO_2 m^{-2} d^{-1} estimated for the pastoral area (706 km²) of the Ferlo region by (Assouma et al., 2017). The difference between annual soil CO_2 emissions from the two territories is mainly due to higher emissions from the main land use type in the Ferlo region: the rangelands than from the dominant land uses in the Dantchandou district: the shifting fields, fallows and rangelands. Although the manured crop fields in the Dantchandou district emit more than the rangelands in the Ferlo, their area is not large enough to compensate for the difference between emissions from the shifting crop fields, fallow and rangelands in the Dantchandou district and those from the rangelands in the Ferlo. This could be explained by the lower amount of plant litter returned to the soil in the Dantchandou crop fields (Hiernaux et al., 2009) than in the Ferlo rangelands (Assouma, 2016) despite higher rainfall in Niger. In both regions, livestock concentration spots have much higher emissions than the surrounding land use types, but they cover a too small proportion of the land to have a significant impact on emissions at the territory scale. With annual soil respiration equivalent to 294 gC m^{-2} yr^{-1}, the agro-pastoral territory of Dantchandou ranks closer to the desert scrubs (224±38 gC m^{-2} yr^{-1}) than the tropical savannas (629±53 gC m^{-2} yr^{-1}) respiration rates reviewed by (Raich and Schlesinger, 1992). However, the linear regression between soil respiration and net primary production (NPP) given by these authors would predict the NPP of the Dantchandou territory to be 302 gC m^{-2} yr^{-1}(6.4 t DM $ha^{-1}yr^{-1}$) which is close to the field estimates (Hiernaux et al., 2015).

Out of the 2.95 g CO_2 m^{-2} d^{-1} annual soil CO_2 emission of the Dantchandou territory, all the land manured (17.9% of the area) contribute for 0.63 gCO_2 $m^{-2}d^{-1}$ i.e. 21.3% of annual CO_2 emissions from soils in this agro-pastoral area. Among these lands the livestock corralling (0.3% of the area) alone accounts for 0.022 gCO_2 $m^{-2}d^{-1}$ while they receive 1444 MgDM yr^{-1}, 10.4% of annual fecal excretions (Yakoubou Alzouma et al., article submitted). Assuming that the effect of excretion deposits on soil CO_2 emissions is proportional to the amount of feces deposited (equation 2), the remaining excretions, 12432 MgDM yr^{-1} deposited diffusely in the landscape during grazing would contribute 0.189 gCO_2 m^{-2} d^{-1} to soil emissions. The total contribution of annual excreta to soil CO_2 emissions would thus amount to 0.211 gCO_2m^{-2} d^{-1}, i.e. 7% of CO_2 emissions.

In semi-arid regions, soils usually act as CH_4 sinks because of generalized low carbon content and continuous low soil moisture (Delherbe et al., 2025). Very low N_2O emissions are also usually measured in these regions (Bigaignon et al., 2020; Delon et al., 2017). Denitrification, usually the main N_2O production process in soil is rather inefficient due also to the environmental conditions and soil characteristics. This study highlighted large annual CH_4 and N_2O emissions from soil compared to those measured in other semi-arid sites, such as a pastoral site in the Ferlo region of Senegal (Assouma et al., 2017), On that site, very high emissions were measured in livestock concentration points by the ponds and the borehole, but not in rangelands which were always, acting as CH_4 sinks. CH_4 average emissions in this study are 175.6 kg CH_4 ha^{-1} yr^{-1} (vs 9.7±9.2 kg CH_4 ha^{-1} yr^{-1} in the Ferlo) and N_2O average emissions are 35.7 kgN_2O ha^{-1} yr^{-1} (vs 9.0±3.0 kgN_2O ha^{-1} yr^{-1} in the Ferlo). These differences in CH_4 emissions could result from diverse factors: 1- with an average pH of 5.5, soils in the Dantchandou district are mostly acidic. This could explain a reduction of the methanotrophic microbial efficiency in soils with a subsequent reduction of the CH_4 uptake leading to higher methane reaching the soil surface and being emitted to the

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atmosphere, compared to emissions that are less important in the Ferlo region where pH is neutral. Indeed, acidic pH favors inhibition of CH_4 oxidizing bacteria, and stimulates CH_4 production is soils (Li and Kelliher, 2007; Su et al., 2025; Zhao et al., 2020). 2- termites are very active across the Dantchandou district at the onset and the end of the wet season and have been observed especially in manured fields building galleries on millet litter and dry dungs. They could partly participate in these larger CH_4 emissions to the atmosphere.

Non-negligible N_2O emissions at the annual and district scale may result from dominant nitrification processes vs denitrification (Serça et al., 1998) due to the aerobic character of the soils (and low soil moisture), as already highlighted in Sahelian soils in Senegal by Agbohessou et al., (2023) or other semi-arid soils in Central Africa and Mongolia (Serca et al., 1994; Zhang et al., 2023). However, one must keep in mind that the uncertainty in CH_4 and N_2O flux calculations is larger than for CO_2 emissions, due to less sites explored (3), less available data and more interpolations. Indeed, these fluxes estimated at the district scale result from fluxes really measured in sampled sites representing only 37.45% of the district (manured fields + shifting fields + corrals) with therefore 62.65% of the budget being extrapolated. These results remain reliable and useful considering the very few measurements performed in this region, but should be used with an awareness of their uncertainties.

5. Conclusion

Soil CH_4 and N_2O emissions were measured using a static chamber repeated five times per day, in a subsample of five days during the year, and in three of the sites in which CO_2 emissions were measured. From this, we were able to provide estimates of annual soil emissions over the district territory of 175.6 $kgCH_4\ ha^{-1}y^{-1}$and 35.7 $kgN_2O\ ha^{-1}y^{-1}$. CH_4, and N_2O fluxes did not reveal any clear daily nor seasonal dynamics, neither any relationship between flux intensity and quantities of livestock effluents deposited. From this, it can be concluded that none of the CH_4, and N_2O emitted by the soil can be attributed to livestock. Measures on a larger diversity of sites and at larger frequency during the year are needed to better understand and evaluate the balance between emission and uptake of CH_4, and N_2O, at local and territory scales.

Systematic measures of soil CO_2 emissions using EMG-5 repeated five times per day and ten days between December 2021 to November 2022 provided estimates of the annual soil emission for the three main land use and the three livestock concentration spots in Dantchandou landscape. Weighted by the surface areas of each land use and livestock concentration spots, these estimates provided an assessment of the whole district soil annual emission at 9.9 $MgCO_2\ ha^{-1}y^{-1}$ equivalent to a mean daily emission of 2.7 $gCO_2\ m^{-2}d^{-1}$ i.e. 0.80 $gC\ m^{-2}\ d^{-1}$.

CO_2 emissions vary largely within the landscape and between seasons. On a temporal scale, 81.2% of annual CO_2 emissions are produced during the four months of the wet season from June to September. On a spatial scale, livestock enhance the heterogeneity of soil CO_2 emissions through their spatially uneven deposition of effluents, a phenomenon reinforced by the diversity of farmer manure management (ref article Yakoubou Alzouma et al, in prep).

15.3% of the annual soil CO_2 emissions are due to livestock, either from manured land or concentration spots (for a total of 10.7% of the territory). Those 15.3% result from continuous field manuring for several years, 7% out of that percentage being related to feces deposited by the livestock during the studied year. The concentration of livestock on a small fraction of the territory (0.3%) results in high CO_2 emissions in the wet season, however it only marginally affects the annual CO_2 emission at the scale of the territory.

In pastoral systems the effluents deposited in high spots only benefit to the spontaneous vegetation, whereas in agro-pastoral systems a fraction of the livestock effluents can be deposited in crops and used as fertilizer, enhancing the crop yields. Previous experiments showed that the increase in millet yield was proportional to the amount of effluent deposited, an effect remaining over four years, although decreasing progressively (Yakouba Alzouma et al, in prep). In Dantchandou only a small fraction of those effluents deposited is presently managed by the farmers (Yakouba Alzouma et al, in prep). This is the result of corralling livestock on cropland during the dry season, and of harvesting of manure deposited in livestock pens and its application to the crop fields. Crop production could benefit from an expansion of the corralling or manuring practices at constant concentration of livestock. As seen before, this would lead to a marginal impact on the magnitude of soil CO_2 emissions at the scale of the territory. CO_2 emitted by the soil of corral spots is proportional to the amount of effluent, but do not represent a net increase of CO_2 released at the territory scale, but only a different spatial distribution of emissions. Furthermore, the corralling and the manuring practices also enhance significantly the organic carbon, total nitrogen and soluble phosphorus concentration in the top soil. Enhanced crop yield and organic carbon content in the soil both contribute to larger carbon storage, which could contribute more widely to balance the carbon effluxes due to CO_2 and CH_4 emissions, highlighting the positive influence of livestock management in agro-pastoral systems. The results obtained in this study, together with calculated enteric methane emissions by livestock will be used to assess the full contribution of livestock to the carbon balance at the territory scale.

Code, data, or code and data availability

Data related to this study are available on the "Zenodo Science Europe platform", accessible via the DOI: https://doi.org/10.5281/zenodo.21410594

Author contributions

YYA contributed to the study design and planning, field data collection, statistical and laboratory analyses, and drafting of the first version of the manuscript. PH participated in the study design and planning, analysis, interpretation of data and critical revision of the manuscript. DS and CD contributed to analysis, interpretation of data, laboratory analyses and in the critical review of the manuscript. SMB contributed to analysis, interpretation of data and critical review of the manuscript. MK and LM contributed to the design and planning of the study and the critical review of the manuscript.

Competing interests

The authors declare that the research was conducted without any commercial or financial relationships and without any personal, professional, or institutional issues that could be interpreted as a potential conflict of interest.

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