J Arid Land (2017) 9(2): 210–221
doi: 10.1007/s40333-017-0001-y

Science Press Springer-Verlag

Livestock induces strong spatial heterogeneity of soil CO_2, N_2O and CH_4 emissions within a semi-arid sylvo-pastoral landscape in West Africa

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Abstract: Greenhouse gas (GHG) emissions from the surface soils and surface water receiving animal excreta may be important components of the GHG balance of terrestrial ecosystems, but the associated processes are poorly documented in tropical environments, especially in tropical arid and semi-arid areas. A typical sylvo-pastoral landscape in the semi-arid zone of Senegal, West Africa, was investigated in this study. The study area (706 km² of managed pastoral land) was a circular zone with a radius of 15 km centered on a borehole used to water livestock. The landscape supports a stocking rate ranging from 0.11 to 0.39 tropical livestock units per hectare depending on the seasonal movements of the livestock. Six landscape units were investigated (land in the vicinity of the borehole, natural ponds, natural rangelands, forest plantations, settlements, and enclosed plots). Carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) fluxes were measured with static chambers set up at 13 sites covering the six landscape units, and the 13 sites are assumed to be representative of the spatial heterogeneity of the emissions. A total of 216 fluxes were measured during the one-year study period (May 2014 to April 2015). At the landscape level, soils and surface water emitted an average 19.8 t C-CO_2 eq/(hm²·a) (CO_2: 82%, N_2O: 15%, and CH_4: 3%), but detailed results revealed notable spatial heterogeneity of GHG emissions. CO_2 fluxes ranged from 1148.2 (±91.6) mg/(m²·d) in rangelands to 97,980.2 (±14,861.7) mg/(m²·d) in surface water in the vicinity of the borehole. N_2O fluxes ranged from 0.6 (±0.1) mg/(m²·d) in forest plantations to 22.6 (±10.8) mg/(m²·d) in the vicinity of the borehole. CH_4 fluxes ranged from –3.2 (±0.3) mg/(m²·d) in forest plantations to 8788.5 (±2295.9) mg/(m²·d) from surface water in the vicinity of the borehole. This study identified GHG emission "hot spots" in the landscape. Emissions from the surface soils were significantly higher in the landscape units most frequently used by the animals, i.e., in the vicinity of the borehole and settlements; and emissions measured from surface water in the vicinity of the borehole and from natural ponds were on average about 10 times higher than soil emissions.

Keywords: greenhouse gases; soil; surface water; livestock; landscape; Senegal

Citation: Mohamed H ASSOUMA, Dominique SERÇA, Frédéric GUÉRIN, Vincent BLANFORT, Philippe LECOMTE, Ibra TOURÉ, Alexandre ICKOWICZ, Raphaël J MANLAY, Martial BERNOUX, Jonathan VAYSSIÈRES. 2017. Livestock induces strong spatial heterogeneity of soil CO_2, N_2O and CH_4 emissions within a semi-arid sylvo-pastoral landscape in West Africa. Journal of Arid Land, 9(2): 210–221. doi: 10.1007/s40333-017-0001-y

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Received 2016-01-13; revised 2016-05-17; accepted 2016-05-22

1 Introduction

Climate change is among the most pressing challenges facing humanity today. It is now widely accepted that the concentrations of greenhouse gases (GHGs) have risen at unprecedented rates since the industrial revolution and that carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the three GHGs that have contributed more than 90% of human-induced global warming (IPCC, 2013). The GHG exchanges between terrestrial ecosystems and the atmosphere play a major role in regulating the concentrations of these three greenhouse gases in the atmosphere (Chevallier et al., 2015). However, our knowledge on the magnitude of GHG exchanges between terrestrial ecosystems and the atmosphere is still rather limited (Wang et al., 2013; Ahlström et al., 2015). Particularly, large uncertainties remain regarding soil-air fluxes of GHGs in tropical drylands (Ahlström et al., 2015; Borges et al., 2015).

Pastoral systems occupy most of drylands in the world (Nori et al., 2005) and account for a quarter of the total drylands in Africa (Boval and Dixon, 2012). In West Africa (i.e., our study area), pastoral systems were estimated to have expanded considerably in recent past because of the observed global warming and the expansion trend is expected to continue in the near future under projected warming (Thornton and Herrero, 2015). Pastoral ecosystems are characterized by constraining climatic conditions with limited precipitation falling in a limited time frame (Martínez et al., 2011). Pastoralism is a way of life that is still very common in world's arid and semi-arid zones (Turner et al., 2014). Pastoral communities have succeeded in making best advantage of the natural resources based on their mobility and "ancestral" knowledge (Manoli et al., 2014) and consequently developed their economy-ecology coupled social systems in which a large number of livelihoods are reported to have the highest rates of GHG emissions per unit of animal products (Gerber et al., 2013). Despite the increasingly acknowledged importance of pastoral ecosystems in the global GHG cycles and their potentials in further elevating the GHG concentrations in the atmosphere, *in situ* measurements are still not known (Tagesson et al., 2015a).

Soils in rangelands, combined with livestock productions, are reported to be responsible for a large share of GHG emissions, but these soils can also act as carbon sinks under certain conditions (Soussana et al., 2010; Valentini et al., 2014). Under arid to semi-arid rangelands, soil moisture is one of the main factors controlling emissions of CO_2 (Kuzyakov and Gavrichkova, 2010; Yemadje et al., 2016) and N_2O from the soil to the atmosphere (Ussiri and Lal, 2013). It should be noted that although CH_4 emissions occur only in hydromorphic conditions, CH_4 emissions may also be significant, since there are extensive water bodies (e.g., ponds) and wetlands in certain parts of world's drylands (Serrano-Silva et al., 2014). It should also be stressed that large amounts of manure are produced and deposited in pastoral ecosystems, thereby directly or indirectly affecting GHG emissions via the involvement of microbial processes (e.g., methanogenesis, nitrification, and denitrification) and modification of soil characteristics (e.g., texture and moisture) (Thangarajan et al., 2013). In addition, livestock, as a vector of organic matter, can result in the heterogeneous distribution of animal excreta in the landscapes and hence increase spatial heterogeneities in soil properties, available nutrients and biomasses, most likely leading to intensification of GHG emissions via enhanced microbiological processes (Smith et al., 2003).

The purpose of this study was to evaluate the magnitude of the spatial heterogeneity of the emissions of CO_2, N_2O and CH_4 from the soils and the surface water bodies in a pastoral landscape, and to identify possible links between the emissions and the livestock in ecosystem functioning. Our specific objectives were to: (1) quantify GHG fluxes in the different landscape units; (2) assess the spatial heterogeneities of GHG fluxes; and (3) link the heterogeneities to livestock habits and movements. To achieve these objectives, CO_2, N_2O and CH_4 fluxes from soils and water surfaces were monitored for a whole year across different landscape units within the area influenced by the Widou borehole. This area is assumed to be representative of sylvo-pastoral ecosystems in northern Senegal, West Africa.

2 Materials and methods

2.1 Study area

The study was carried out in the sylvo-pastoral Ferlo region of Senegal, West Africa. The Ferlo region is characterized by high seasonal, annual and decadal rainfall variabilities and relatively high mean annual temperatures (Martínez et al., 2011). Three main seasons, each lasting four months, can be distinguished: a hot-wet season from July to October, a cold-dry season from November to February of next year and a hot-dry season from March to June. The mean annual precipitation is rather low (296 mm) and highly variable (Miehe et al., 2010). Mean annual temperature is 27.7°C and monthly averages fluctuate between a maximum of 30.2°C in October and a minimum of 24.5°C in January (Ndiaye et al., 2014).

The Ferlo region is organized around a network of boreholes at 30 km intervals. The boreholes were dug in the 1950s and 1960s (Manoli et al., 2014). This study focused on a 706 km² area around the Widou borehole (15°59′N, 15°19′W), a circular zone with a radius of 15 km from the borehole (Fig. 1). The area is representative of the semi-arid sylvo-pastoral ecosystems in the region. We selected this particular borehole because of the availability of a comprehensive database created as part of the organized survey activities (Ancey et al., 2008; Bah et al., 2010). The 'enclosures' in Figure 1 refer to the enclosed experimental grazing plots created over 30 years ago as a part of a project implemented by a German agency (Miehe et al., 2010). An exhaustive survey of the 354 settlements located in the vicinity of the Widou borehole was made in December 2013 to quantify the size of the herds of the different animal species. The landscape supports a stocking rate ranging from 0.11 to 0.39 tropical livestock units per hectare (or TLU/hm^2) depending on the seasonal movements of the herds.

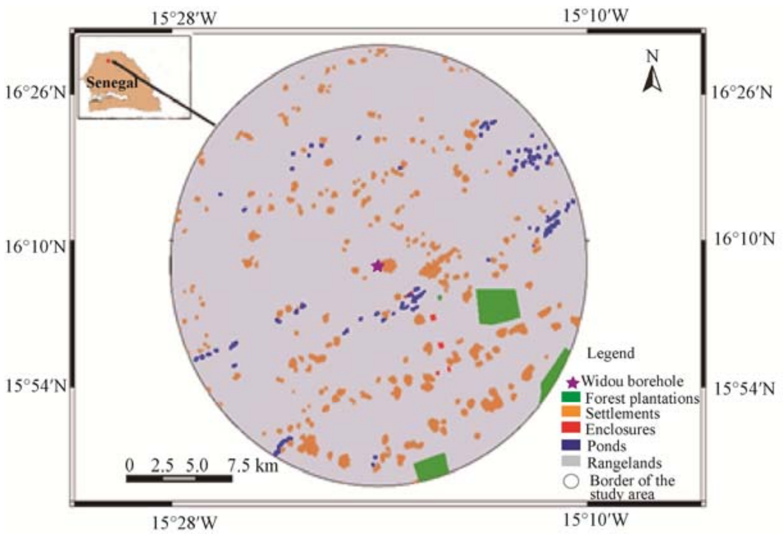

Fig. 1 Map of the study area around Widou borehole

A combination of the GIS technique and field observations was used to describe and map the main landscape units (Fig. 1). Six landscape units were defined based on land uses and topographic variations using a Landsat ETL+204-049 image acquired on 3 November 2010.

(I) Vicinity of the borehole (<1 km², or 0.1% of the total 706 km^2 area) corresponds to the part of the landscape in which the borehole is located. The borehole is used to water herds and its vicinity is the place where the animals rest after being watered. The soils near the water tank of the borehole are waterlogged all year round. We investigated both stagnant surface water and the soils around the tank.

(II) Settlements (44 km², or 6.3% of the total area) correspond to the areas occupied by herder's homestead and a corral for the herd. These areas are characterized by high soil organic matter (SOM) contents due to the long-term accumulation of animal manure during night corralling.

(III) Natural ponds (19 km², 2.7%) correspond to areas of clayey soils where stagnant water accumulates temporarily during the wet season and the ponds normally dry up soon after the wet season is over. We investigated both the water from the ponds and the soils along the shorelines of the ponds.
(IV) Forest plantations (6 km², 0.9%) were established by the government of Senegal as a part of the Great Green Wall project. They are mainly composed of *Acacia* spp.
(V) Native rangelands (635 km², 89.9%) are occupied by natural vegetation (grass, shrubs, and trees) and are actively pastured by livestock.
(VI) Enclosures (<1 km², 0.03%) refer to the enclosed experimental grazing plots created over 30 years ago.

2.2 Data collection

To investigate seasonal variabilities of GHG fluxes, we conducted field campaigns on six occasions between May 2014 and January 2015, once during the hot dry-season (May 2014), once a month during the hot-wet season (from July to October 2014), and once during the cold-dry season (January 2015). Observations were made at 13 sites (native rangelands, n=5; natural ponds, n=2; settlements, n=2; forest plantations, n=1; enclosures, n=1; and in the vicinity of the borehole, n=2). The selection of the sampling sites took into consideration both the areal extent of the area occupied by each landscape unit and the potential ability to emit GHGs.

2.2.1 CO_2, N_2O and CH_4 fluxes

GHG fluxes from each of the 13 sites were quantified using rectangular stainless steel static chambers described in Serça et al. (1994). All the measurements taken at each site were made in duplicate under parasols during the day.

Air samples (20 mL) were collected immediately after the closure of the chamber and subsequently at 30-minute intervals during the following 90 minutes. Samples for CO_2 analysis were stored in serum vials pre-flushed with N_2 (Guérin et al., 2007). Samples for CH_4 and N_2O analysis were stored in serum vials initially filled with a salt-saturated solution (Deshmukh et al., (2014). The analyses were performed by SRI 8610C gas chromatography (SRI Instruments, Torrance, CA, USA) equipped with a 63Ni electron detector (ECD) and a Flame Ionization Detector (FID) methanizer.

The diffusive fluxes were calculated from the slope of the linear regression of the concentration of gas in the chamber versus time. The measured fluxes were discarded when the correlation coefficient r^2 was <0.8 (Deshmukh et al., 2014).

Samples were collected in the ponds to measure the concentrations of dissolved GHGs in the water. The water samples were collected and poisoned according to Guérin and Abril (2007), and analyzed by gas chromatography after the creation of a headspace with N_2. Dissolved concentrations of CO_2, CH_4 and N_2O were computed with the solubility coefficient of Weiss (1974), Yamamoto et al. (1976) and Wanninkhof (1992) for CO_2, CH_4 and N_2O, respectively. Diffusive fluxes were calculated from surface concentrations using the turbulent boundary layer model (Liss and Slater, 1974) with a gas transfer velocity (k_{600}) of 2 cm/h and the *in situ* water temperature.

2.2.2 Soil chemical properties

Soils were sampled in triplicate to a depth of 10 cm at all 13 sites in January 2015. The samples were used to determine soil total carbon, nitrogen, and phosphorus, NH_4^+, NO_3^-, bulk density, and particle sizes in the certified ISO9001 LAMA laboratory (2008 by Euro-Quality System) according to the methods described by Pansu and Gautheyrou (2006).

2.2.3 Collection of solid manure and monitoring of livestock

Each month, the solid manure deposited on the surface soils was collected manually in four 0.25 hm^2 plots in all the landscape units. The total quantity of solid manure in each livestock category (cattle, small ruminants, and non-ruminants) was weighed. The samples were then dried in a stove for three days at 65°C to measure dry matter content. Three ruminant herds were also monitored for 1–2 day(s) each month to estimate the time the animals spent in each landscape unit.

2.3 Analysis

2.3.1 Correlation between fluxes and environmental parameters

All statistical analyses were conducted with R software (R Development Core Team, 2015) using the ‘‘lme4’’ package for linear regression analysis and ‘‘ade4’’ (Dray and Dufour, 2007) for ANOVA. Data were checked for normality and variance analyses. Significant differences in means between the six landscape units and between the three seasons were identified with Tukey’s honest significant differences (HSD) test. Pearson correlation analysis was used to test the relationship between soil GHG emissions and the quantity of solid manure deposited on the surface soils.

2.3.2 Scaling up measurements for temporal and spatial estimations

For temporal upscaling (monthly/season average), the observations made on a specific day of the month were generalized to the month/season assuming that the magnitude of the emissions was the same every day of the month/season. For spatial upscaling (landscape unit average), a mean and a standard deviation were calculated for each landscape unit based on all observations of the landscape unit concerned.

Two different approaches were used to extrapolate emissions to the whole landscape. The “only native rangelands” approach is a simplified and also a widely practiced method (Valentini et al., 2014). It only takes account of emissions from rangelands, as the entire landscape comprises this unit (in reality 90% of the borehole territory is covered by native rangelands). The second approach, called “all landscape units” approach, accounts for the spatial heterogeneity of GHG emissions. In both cases, each flux measurement was weighted according to the length of the sampling season and also to the relative proportions of the areal extent of the different landscape units in the context of the entire landscape concerned to calculate the total GHG emissions at the year time scale and at the landscape spatial scale.

Extrapolations at year and landscape levels were converted into CO_2 equivalents based on the global warming potentials of the three gases proposed by IPCC (2013). These global warming potentials are 1, 34, and 298, for CO_2, CH_4, and N_2O, respectively.

3 Results

3.1 Spatial variabilities of manure deposition and GHG emissions

Table 1 lists the livestock stocking rate in a given landscape unit, the quantity of solid manure deposited on the soil per month and the physical and chemical characteristics of the soil in the different landscape units. The livestock stocking rate is expressed in tropical livestock units (TLU) per unit area (hm^2), where one TLU is equivalent to an animal of 250 kg live weight. The average livestock rate in a landscape unit ranged from 0.08 (±0.02) TLU/(hm^2•month) in rangelands to 10.84 (±6.96) TLU/(hm^2•month) in the vicinity of the borehole. The resulting excretion rates ranged from 13.7 (±6.9) kg DM/(hm^2•month) in rangelands to 68.8 (±63.6) kg DM/(hm^2•month) in the vicinity of the borehole. It should be noted that the dung excretion was quantified in kilogram of dry matter (DM). The soils in the vicinity of the borehole were richer in nutrients and organic matter (including total carbon, total nitrogen, mineral nitrogen, and total phosphorus). However, the soils near settlements are richer in mineral nitrogen than the soils in the vicinity of the borehole.

Table 2 lists soil GHG emissions in the different landscape units. Soil CO_2 fluxes ranged from 1148.2 (±91.6) mg/(m^2•d) in rangelands to 97,144.1 (±52,450.1) mg/(m^2•d) in the vicinity of the borehole. The mean CO_2 flux across all landscape units was 4352.7±1220.1 mg/(m^2•d). Soil N_2O fluxes ranged from 0.6 (±0.1) mg/(m^2•d) in forest plantation to 22.6 (±10.8) mg/(m^2•d) in the vicinity of the borehole. The mean N_2O flux across all landscape units was 2.5 (±0.9) mg/(m^2•d). Soil CH_4 fluxes ranged from –3.2 (±0.3) mg/(m^2•d) in forest plantations to 691.3 (±352.6) mg/(m^2•d) in the vicinity of the borehole. The mean CH_4 flux across all landscape units was 2.6 (±2.5) mg/(m^2•d).

Table 1 Livestock stocking rate, manure deposition, physical and chemical characteristics of the soil (0–10 cm)

Landscape unit	Stocking rate (TLU/(hm²·month))	Excretion rate (kg DM/(hm²·month))	Soil total carbon content (g/100g)	Soil total nitrogen content (g/100g)	Soil mineral nitrogen content (μg N/g)	Soil total phosphorus content (mg/kg)	Soil sand content (g/100g)
Rangelands	0.08±0.02	13.7±6.9	0.3±0.07	0.02±0.008	8.0±1.7	85.8±26.6	87.8±3.5
Settlements	1.44±0.28	53.6±25.9	0.8±0.5	0.1±0.08	423.1±479.1	210.3±307.7	88.1±0.9
Vicinity of borehole	10.84±6.96	68.8±63.6	4.0±1.6	0.4±0.2	93.0±100.9	236.5±55.7	82.1±7.7
Shorelines of the ponds	0.97±0.50	31.0±18.8	0.8±0.2	0.07±0.007	57.8±49.5	187.7±56.5	69.4±8.7
Enclosures	0	0	0.3±0.01	0.03±0.002	7.04±0.9	63.5±12.8	84.5±2.8
Forest plantations	0.64±0.07	ND	0.4±0.09	0.02±0.004	10.6±1.1	102.0±62.6	89.9±1.2

Note: Stocking rate means the allocation of the whole landscape livestock stocking rate among the different landscape units. Excretion rate takes account of monthly variations of the whole landscape stocking rate and the relative proportion of the areal extent of each landscape unit. TLU refers to tropical livestock units; DM, dry matter; ND, not determined. All data are expressed as means±SD.

Table 2 Soil greenhouse gas emissions in the six different landscapes

Landscape unit	CO_2 flux (mg/(m²·d))	N_2O flux (mg/(m²·d))	CH_4 flux (mg/(m²·d))
Rangelands	3893.7±915.3^{b}	2.4±0.8^{b}	0.6±0.4^{b}
Settlements	9819.7±4356.6^{ab}	3.5±1.4^{ab}	0.9±0.5^{b}
Vicinity of borehole	17,915.6±8602.8^{a}	6.2±3.4^{a}	277.9±72.3^{a}
Shorelines of the ponds	6898.5±4023.6^{b}	3.0±0.6^{b}	58.8±74.3^{ab}
Enclosures	3544.7±216.7^{b}	1.3±0.3^{b}	0.1±0.1^{b}
Forest plantations	2250.2±140.5^{b}	0.9±0.1^{b}	0.1±0.1^{b}
Landscape level	4352.7±1220.1	2.5±0.9	2.6±2.5

Note: Water-atmosphere exchanges were not included. All data are expressed as means±SD. The superscript letter after the standard deviation indicates significant differences between landscape units (Tukey's HSD test; P<0.05).

CO_2 and N_2O fluxes exhibited similar trends. CO_2 and N_2O emissions from the soils in the vicinity of the borehole and in the settlements were significantly higher (P<0.05) than the fluxes from forest plantations, enclosures, rangelands and the shoreline of the ponds. But, there were no significant differences in CO_2 and N_2O emissions between the vicinity of the borehole and the settlements. The differences in CO_2 and N_2O emissions among forest plantations, enclosures, rangelands and the shorelines of the ponds were also not significant.

The spatial pattern of CH_4 emissions from the soils slightly differed from those of CO_2 and N_2O. The highest CH_4 emissions were measured in the vicinity of the borehole and the shorelines of the ponds, being significantly higher (P<0.05) than the fluxes from forest plantations, enclosures, rangelands and settlements. There were no significant differences between the vicinity of the borehole and the shorelines of the ponds and also no significant differences among forest plantations, enclosures, rangelands, and the settlements.

Concerning GHG exchanges between water surfaces and the atmosphere (in the natural ponds and in the vicinity of the borehole), all the water samples were under-saturated in N_2O relative to the atmosphere, and N_2O concentrations were below the limit of detection. CO_2 fluxes ranged from 5855.1 (±970.5) mg/(m²·d) in natural pond water to 97,980.2 (±14,861.6) mg/(m²·d) in the stagnant water in the vicinity of the borehole. The calculated overall mean (for both landscape units) of CO_2 fluxes was 30,640.9 (±5481.2) mg/(m²·d). CH_4 fluxes ranged from 142.2 (±1.1) mg/(m²·d) in natural pond water to 8788.5 (±2295.9) mg/(m²·d) in the stagnant water around the borehole. The calculated overall mean (for both landscape units) of CH_4 fluxes was 3170.8 (±659.4) mg/(m²·d). The pond CO_2 fluxes were not significantly different from the soil CO_2 fluxes, whereas pond CH_4 fluxes were significantly higher (P<0.05) than the soil CH_4 fluxes. On average, CH_4 fluxes from ponds were 45 times higher than those from the soils.

3.2 Contribution of the different landscape units to total emissions

Figure 2 shows the contributions of the three GHGs to total GHG emissions at landscape level. CO_2 was the main contributor and accounted for 82% of total emissions. N_2O accounted for 15% and CH_4 for 3%. Rangelands, which represent 90% of the entire territory, were the main contributors to CO_2 and N_2O emissions despite of the fact that the flux per unit area in the rangelands is low. The vicinity of the borehole and the shorelines of the ponds were the main sources of CH_4 emissions (93% of CH_4 emissions) despite the fact that the borehole and the ponds accounted for less than 3% of the entire study area.

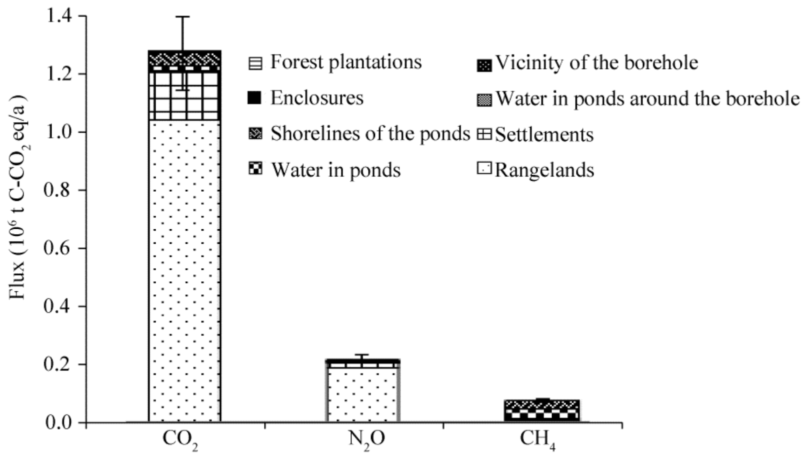

Fig. 2 Contributions of the three greenhouse gas (CO_2, N_2O, and CH_4) emissions from soil and water at the landscape level

Figure 3 shows the contributions of the three seasons (wet, cold-dry, and hot-dry seasons) to average daily emissions of GHG from the soils and water at the landscape level. Most emissions (65%) occurred during the hot-wet season. The cold-dry and hot-dry seasons represented 14% and 21% of total emissions, respectively. Rangelands were the main sources of GHG emissions, especially during the cold-dry and hot-dry seasons, accounting for more than 90% of total emissions. The contributions of settlements, ponds, and the vicinity of the borehole increased during the hot-wet season mainly due to the higher CH_4 emissions rates (see Section 3.1).

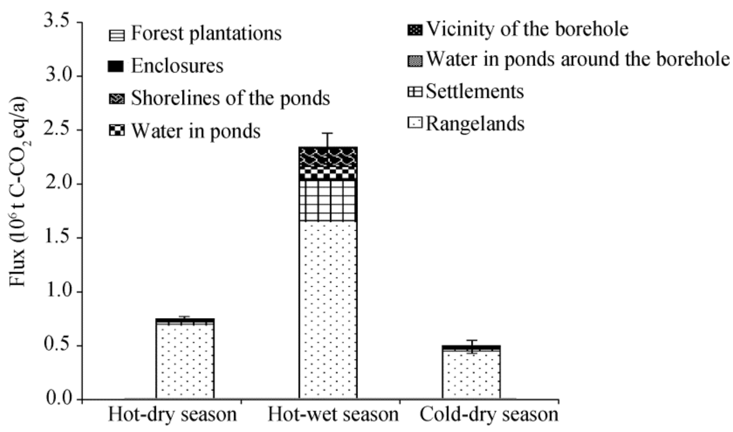

Fig. 3 Contributions of the greenhouse gas emissions in three seasons (hot-wet, cold-dry, and hot-dry seasons) from soil and water at the landscape level

4 Discussion

4.1 Impact of livestock on spatial variability of GHG emissions

This study illustrates the high spatial heterogeneity in GHG exchanges with the atmosphere. In the case of CH_4, the highest emissions per surface unit were recorded in permanently or temporarily flooded landscape units (borehole and ponds) where hydromorphic conditions favor methanogenesis (Serrano-Silva et al., 2014). These units are also frequently visited by animals that contribute to the accumulation of manure (Table 1). When only soil CH_4 emissions were taken into account, ponds and the vicinity of the borehole emitted 58.8 (±74.3) and 277.9 (±72.3) mg/(m²•d), respectively. When surface water CH_4 emissions were also taken into account, these two landscape units emitted 147.7 (±92.9) and 656.7 (±145.7) mg/(m²•d), respectively. CH_4 emissions from the remaining landscape units were very low or negative especially from units with sandy soils and limited manure inputs (rangelands and forest plantations). This is quite consistent with reports in the literature that consider non-flooded grassland soils to be sinks for atmospheric CH_4 (Mosier et al., 2004) and that CH_4 emissions are negligible in rain-fed agro-ecosystems (Nyamadzawo et al., 2014).

The highest CO_2 and N_2O emissions per surface unit mainly came from the landscape units in which the animals spent the longest time, i.e., the vicinity of the borehole, settlements and around the ponds. This can be explained by the high inputs of manure that stimulate microbial activities. Figure 4 shows the positive effect of inputs of manure on GHG emissions as reported by Lin et al. (2009). The correlation is stronger for CO_2 and N_2O fluxes ($R^2>0.5$, $P<0.05$; Figs. 4a and b) than for CH_4 (Fig. 4c). Manure is a direct source of CO_2 emissions and also a direct source of N_2O emissions (Yamulki et al., 1999; Clemens and Ahlgrimm, 2001; Li and Kelliher, 2007; Saggar et al., 2007). The elevated emissions were normally accomplished through increasing soil C and N contents (Hiernaux et al., 1999) and also through stimulating soil microbiological activities (Chotte et al., 2012; Petersen et al., 2013).

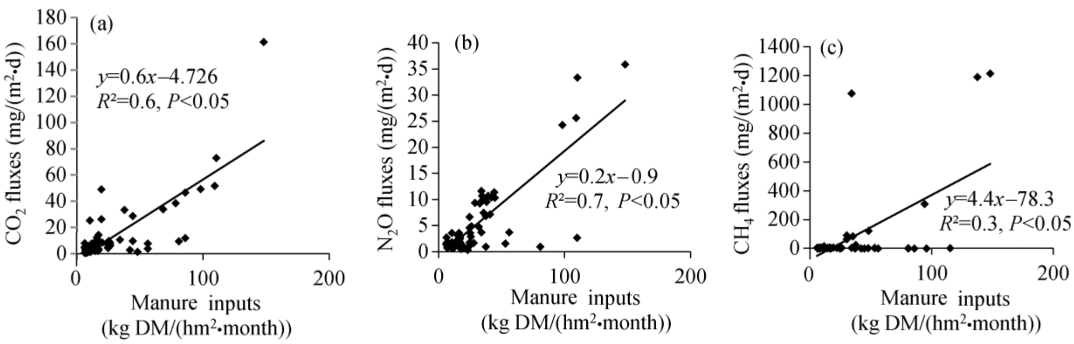

Fig. 4 Regression relationships between soil greenhouse gas emissions and inputs of manure within the study area including all landscape units

The spatial distribution of manure deposition certainly explains a large proportion of the spatial heterogeneity of the GHG emissions observed in this study. Other studies (e.g., Schlecht et al., 2004) have also demonstrated the important role played by livestock in the spatial distribution of soil nutrients and carbon stocks. In the Sudanian savanna agro-pastoral ecosystems in West Africa, traditional practices like free grazing and night corralling lead to nutrient and carbon transfers from the periphery to the core of the landscapes (Manlay et al., 2004a), resulting in ring-like organization of the landscape with a positive gradient of nutrients and carbon storage in the soil from the rangelands to the dwellings (Diarisso et al., 2015). This organization may explain the marked differences in CO_2 emissions rates between rangelands and croplands in Sudanian savanna agro-pastoral ecosystems (Brümmer et al., 2009). Similarly in Sahelian drier sylvo-pastoral ecosystems, quite like the ecosystem studied here, the spatial heterogeneity of GHG emissions can be explained by livestock-related nitrogen and carbon transfers. That is, animals mainly intake biomasses in certain landscape units (e.g., rangelands, tree plantations) while excretion preferentially occurs in others while resting (in settlements) or drinking (stagnant water around the borehole and in natural ponds). Consequently, organic matter is concentrated in particular landscape units.

4.2 More accurate assessment of total GHG emissions at landscape level

Figure 5 compares the total annual emissions (in CO_2 equivalent) of the three main GHGs using two approaches described in Section 2.3.2. The estimate of total annual emissions (in CO_2 equivalents) using "only native rangelands" approach was 1.2×10^6 t C-CO_2 eq/a and the estimate using the "all landscape units" approach was 1.4×10^6 t C-CO_2 eq/a in the Widou territory (706 km^2). CH_4 emissions are not taken into account in the "only native rangelands" approach because they are negligible in rangelands, and mainly occur in the vicinity of the borehole and the natural ponds. The "only native rangelands" approach leads to a 14% underestimation of total emissions. These results question the fact that extrapolations at landscape and sometimes at regional levels are frequently based on spatially limited measurements because data on tropical regions are scarce (Merbold et al., 2009; Galy-Lacaux and Delon, 2014; Tagesson et al., 2015b). For instance, most regional African GHG balances are based on data provided by the regional network of flux towers (Bombelli et al., 2009; Mbow, 2014; Valentini et al., 2014).

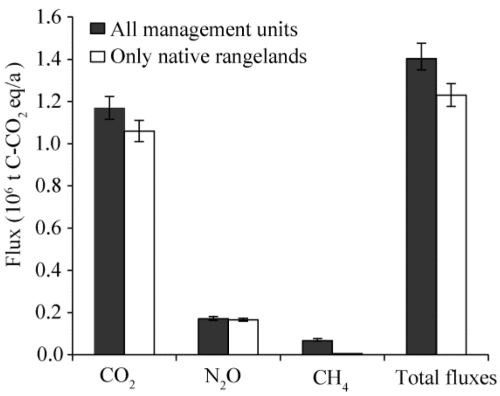

Fig. 5 Annual total greenhouse gas emissions from soil and water at landscape level calculated using two different approaches

4.3 More accurate assessment of total GHG emissions at year level

Another way to increase the robustness of the assessment of the yearly total GHG emissions from soil in tropical sylvo-pastoral ecosystems is the frequency of the GHG measurements. In the dry seasons (both hot-dry and cold-dry seasons), emissions fluxes remain stably low over time because the soil is dry and the microbiological activity is considerably slowed down, justifying less frequent measurements (see Section 3.2). But during the wet season (i.e., the hot-wet season), microbiological activity and the resulting GHG fluxes are extremely high. The occurrence of scaling up errors is certainly higher in the wet season despite the fact more frequent measurements were made in this season in the present study. Indeed, the microbiological activities and other GHG emission-related processes in the soils of tropical arid and semi-arid areas go through a dormant period during the dry season and are subjected to mineralization flushes after rainfall events at the onset of the wet season (Kim et al., 2012). It is thus difficult to capture the resulting variability of GHG emissions. It would require a dedicated monitoring program with very frequent measurements. Unfortunately, the present study did not have the required measurement frequency during the wet season because our primary objective was to analyze the spatial variability of GHG emissions. To better represent the mineralization flushes and peak emissions, modeling would be required to correlate emissions with the dynamics of soil humidity (Saggar et al., 2007; Song et al., 2015). To date, modelling efforts have been constrained by the lack of available data mainly due to the inaccessible nature of tropical rangeland ecosystems (Krüger et al., 2013).

5 Conclusions

To our knowledge, the data set on the carbon dioxide, nitrous oxide, and methane fluxes in northern Senegal reported here is the first from a tropical sylvo-pastoral ecosystem. Our results provide evidence for quite notable spatial heterogeneity of GHG emissions. The spatial heterogeneity of GHG emissions can be explained by livestock movements within the study area, and the resulting stocking rate variations, which affect the spatial distribution of solid manure and result in hotspots of GHG emissions. The vicinity of the borehole and the settlements had the highest manure input rates and thus the highest CO_2 and N_2O emissions. The stagnant water in natural ponds and in the vicinity of the borehole was the main contributor of CH_4 emissions due to permanent or seasonal hydromorphic conditions. The high CH_4 emissions were further enhanced by the large quantity of manure excreted by animals while they are drinking.

At the landscape level, CO_2 is the main GHG (83.1% of all GHG emissions) and native rangelands are the main landscape unit (78.8% of all GHG emissions) contributing to total GHG emissions. It should be stressed that the "only native rangelands" approach underestimated the total annual emissions by 14% because most of CH_4 emissions occur elsewhere than in rangelands and yet only rangelands were considered in the "only native rangelands" approach. Further investigations are needed to refine the GHG footprint of sylvo-pastoral systems in the region including more frequent monitoring during the seasonal transitions with a focus on the onset of the wet season, known to be a period in which a flush of mineralization of organic matter occurs in the tropics. Long-term efforts should also be made to assess possible inter-annual variability of GHG emissions, since climate fluctuations can have impacts on the presence, movements, and excretion rates of livestock and since the impacts can modify the spatial heterogeneity of the GHG balance.

Acknowledgements

The study was funded by the Islamic Development Bank (the Merit Scholarship Program for High Technology) and the European Union (the FP7-KBBE-2010 Animal Change Project).

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