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Intra-annual variability of the greenhouse gas balance of a sahelian rangeland ecosystem in semi-arid West Africa

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INTRODUCTION

It is now acknowledged that the planet's climate is changing and that human activities are mostly responsible for it via greenhouse gas emissions (IPCC, 2013). The three main greenhouse gases (GHG), in order of importance in terms of impacts on the climate, are carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O). In parallel, international reports and review studies draw attention to the contribution made by livestock breeding activities to GHG emissions (CO₂, CH₄, N₂O) and to climate change. The contribution of the world's livestock sector to GHG emissions is estimated to 14.5% (Gerber et al., 2013; Caro et al., 2014). Extensive pastoral ecosystems, a quarter of the earth's land surface, are said to be major contributors to global warming. In sub-Saharan Africa, the sahelian rangelands are supposed to be responsible for the highest rates of greenhouse gas (GHG) emissions per unit of animal product (Steinfeld et al., 2006). Main reasons put forward are the low productivity of herds, low management level of pastures and high methanogenic potential of feed intakes. These regions are characterized by restrictive climatic conditions with limited rain falling within a short season, creating highly seasonal variability in terms of forage availability (Cissé et al., 2016), and pastoralism is the dominant farming activity. Pastoralism is rangeland management and extensive livestock management that uses these rangelands in a context of seasonal resource scarcity for animal watering water and forage (McGahey et al., 2014). Pastoralism is highly dependent on the availability of these two resources, which are strongly dependent on rainfall and soil fertility. Consequently, this activity is especially vulnerable to multi-year variation in rainfall and its distribution patterns (Nassef et al., 2009). The GHG balance for these landscapes is commonly calculated at regional and yearly scales (Steinfeld et al., 2006; Gerber et al., 2013; Rakotovo et al., 2017). This study proposes a dynamic vision of a sylvo-pastoral landscape functioning by examining the intra-annual variability of the GHG balance. The objectives of this study are to describe the functioning of the sylvo-pastoral ecosystem during a full year and to propose a first assessment of the intra-annual temporal variability of its GHG balance of a study case located in the sylvo-pastoral Ferlo Region (northern Senegal) in the Sahelian zone of West Africa. The study is original in its capacity to integrate the various components of the ecosystem (animals, soil, plants) and to consider all components of the GHG balance at the landscape level.

MATERIAL AND METHODS

Description of the study area

The studied landscape is a circular area of 15 km centred on the Widou borehole (15°59'N, 15°19'W, 706 km²) representative of the sylvo-pastoral Ferlo Region in Sahelian zone of West Africa (North of Senegal) as described in (Assouma, 2016). This borehole was chosen due to the availability of a comprehensive database created by the survey activities of the group on Pastoral Systems and Dry Lands (PPZS) (Bah et al., 2010), the PAPF project (Ancey et al., 2008), and the presence of enclosed experimental grazing plots hereafter referred to as 'enclosures'. They were created 30 years ago as part of a project implemented by the German agency for Technical Cooperation (Miehe et al., 2010). Climate of the Ferlo region is characterized by three main seasons of four months each: a wet season from

July to October, a cold-dry season from November to February and a warm-dry season from March to June. Annual rainfall in the study area ranged from 105.4 to 478.4 mm/year with an average of 285.8 ± 84.2 mm/year in the period 1974-2015. Rainfall is normally distributed over 19 ± 4 days during a single wet season from July to October. The mean air temperature in the two years period (2014 & 2015) was 28.4°C fluctuating between a maximum monthly average of 31.2°C in June and a minimum of 24.5°C in January. Livestock husbandry is the main economic activity in studied area with a livestock population dominated by *Gobra* zebu cattle associated with *Sahel* and *Toronké* sheep and *Sahel* goats. Donkeys are raised as pack animals to transport water from the borehole to camps, while horses are kept for transport to and from the market and when families change camp. The studied landscape was stratified into six landscape units (Figure S1) based on topography, soils, vegetation and land use. The vicinity of the borehole (0.78 km^2 , 0.1%) and the 354 pastoralist family settlements (44.46 km^2 , 6.3%) were distinguished from the temporary ponds and surroundings low lands (19.34 km^2 , 2.7%) and from communal rangelands (635.45 km^2 , 89.9%). Tree plantations established during reforestation projects (6.23 km^2 , 0.9%) and small protected enclosures (0.24 km^2 , 0.03%) set up in 1981 by an experimental ranching project were also separated. The livestock system is extensive with free grazing in a communal rangeland with public access to fodder resources.

Survey of C stocks and GHG fluxes

The purpose of this study was to produce a vision of the seasonal dynamics of functioning in the studied ecosystem and its GHG balance. To that end, annual monitoring of the main N and C fluxes-stocks were conducted. The results of an initial GHG balance of the scale of a sylvo-pastoral ecosystem obtained by Assouma *et al.* (2014) based on IPCC Tier 1 led to the identification of the main GHG sources (enteric fermentation, faecal excretion by ruminants, termites and fire) and the main accumulated C stocks (soil, plants and animals). This first sizing of the fluxes and stocks helped to focus observations on the main flows and stocks to be monitored and to define an annual monitoring system to describe their monthly variations.

In order to establish the GHG balance in the study territory over a full year, observations were carried out on the scale of the whole Widou borehole area for a period of 18 months (from May 2014 to October 2015).

Methane emissions from livestock enteric fermentation were evaluated monthly using indirect approach: according to livestock resource intake and digestibility estimated through near-infrared spectroscopy analysis applied to faeces (F-NIRS) as described in Decruyenaere *et al.* (2009). GHG fluxes at soil and water level were measured at 13 of the 15 sites chosen for plant biomass and soil monitoring. The measurements were taken once a month in the wet season (July to October 2014) and once per season in the cold dry season (January 2015) and the warm dry season (May 2014). The GHG fluxes in soil were measured by the static chamber method described in Assouma *et al.* (2017). GHG fluxes at the water-atmosphere interface were measured by taking water samples from ponds, using the method described by Borges *et al.* (2015). The other sources of emissions (CH_4 from termites, CO_2 from fuel consumed by borehole motor pump and CO_2 from bush fires) were evaluated with the use of emission factors proposed in the literature.

Variations in the C stock in woody plants and soil were described from an inventory of woody plants and soil samples taken at 15 sites distributed throughout the Widou borehole coverage area. For these two C stocks, just one observation was carried out in January 2015 and used to characterize the plant cover and C stock in the soil in the different landscape units of the Widou borehole coverage area. In the soil, net carbon exchange was quantified from the difference between total carbon inputs and outputs in the soil. Total carbon accumulation in trees aboveground and belowground biomass was evaluated with in situ surveys and specific allometric equations available in the literature for the main species encountered in the region (Henry *et al.*, 2011). Variations in the C stock in animals were estimated by keeping track of changes in the livestock population through surveys at 11.3% of the settlements in the coverage area (i.e. 40 herds). The surveys were conducted each month from June 2014 to October 2015. Variations in animal weight were estimated from barymetric measurements (Njoya *et al.*, 1997). The evaluation of monthly variations of herd composition (by a survey among the herders) and herd weight evolution (in situ measures) were used to evaluate carbon sequestered in the livestock.

Supplementary data on herbaceous biomass production were also collected to better explain the dynamic functioning of the studied ecosystem.

To establish the annual balance on a whole territory scale, all the emissions were accounted for positively and all the carbon variations were accounted for negatively. For the description of the temporal variability of the balance, these two flux and stock values were expressed in CO_2 equivalent and averaged over each of the three seasons described

above (wet season, cold dry season and warm dry season).

RESULTS

GHG emissions from animals, soils and water at whole landscape level

Our results underline the monthly variability of total GHG emissions in the whole study area (figure 1). Most of the emissions occurred during the rainy seasons with quantities that were slightly larger than the annual average in July and October. Emissions were lower overall in the dry season; emissions were a little higher in the cold dry season than in the warm dry season. The relative contribution of each pool was somewhat homogeneous over the year, with a major contribution of i) N₂O emissions from soil related to animal dejection onto the ground (17.4, 5.6 and 3.7 GgCO₂-eq/Month in the rainy season, cold dry season and warm dry season, respectively) and ii) enteric CH₄ emissions from ruminants (2.1, 1.6 and 1.2 GgCO₂-eq/Month in the rainy season, cold dry season and warm dry season, respectively). The only pool that varied between seasons (90.5, 2.3 and 7.2% GgCO₂-eq/Month, in the wet season, cold dry season and warm dry seasons, respectively) was CH₄ emissions from hydromorphic areas (surface water and soil). This contribution was much greater in the rainy season because of the existence of water ponds. Nitrous oxide N₂O was the most emitted GHG (59% of total emissions), then methane CH₄ was the second most emitted GHG (41%) and third came carbon dioxide CO₂ (<1%). The three main pools were animal dejection excreted onto the ground (66%) and into the water ponds (20%) and enteric methane (11%). Another flux that was not insubstantial was transfers from water to the atmosphere in the water ponds (20% of total GHG emissions). According to our estimations, termites could emit 3% of total emissions, via methane from enteric fermentation.

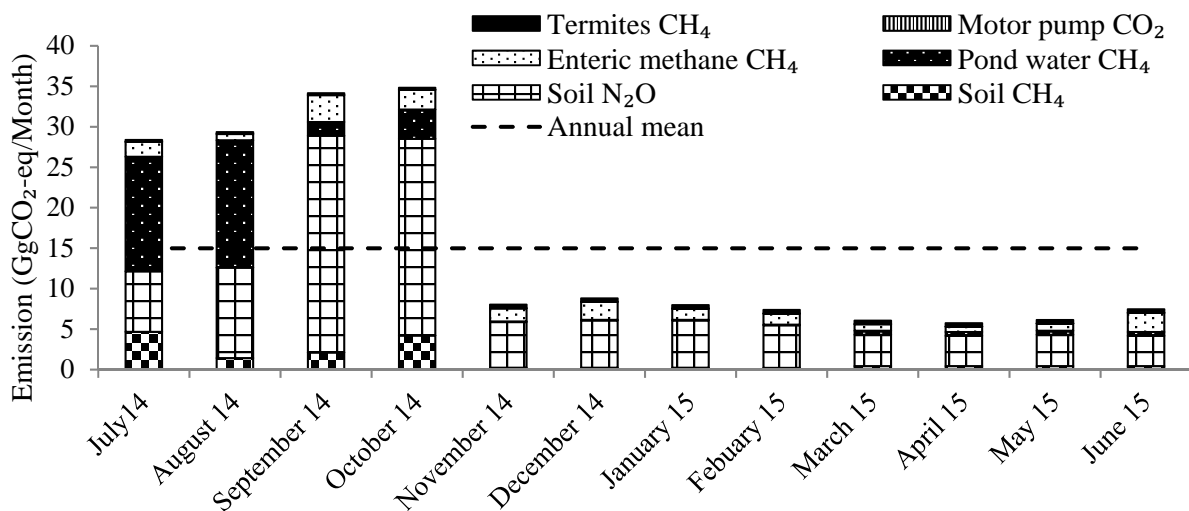


Figure 2. Monthly variability in total GHG emissions at landscape level (all sources included)

Carbon accumulation in trees, soil and Livestock

Our results underline the monthly variations in C accumulation in the main ecosystem compartments (figure 2). Most C sequestration in the different pools occurred during the dry season, and mainly during the cold dry season. Conversely, in the rainy season C stock variation was globally negative because of high gaseous C losses at soil level. Monthly variations in C stock on a territory scale were somewhat stable in the warm dry season and variable in the cold dry season and even more variable in the rainy season. There were accumulation periods (in the cold and warm dry seasons) and salting-out periods (in the rainy season) in the soil, even though there globally remained a major C sequestration source over a full year. These different results highlight the important role of soil in C stock intra-annual variation on the scale of a complete sylvo-pastoral ecosystem. C accumulation in the other fauna (termites, insects, rodent, birds, and microbes) was negligible in this study. Woody plants and soil were the main stocks where C accumulated within the whole sylvo-pastoral area. They amounted to 71% and 28% of the area's annual C sequestration potential, respectively.

As for the animals, they sequestered around 1% of the annual gain in total C stock in the form of animal biomass in

the herds. Overall, the ecosystem sequestered 0.7tc/ha/year according to this distribution: trees 0.45tC/ha/year, soil 0.26tC/ha/year and animals 0.006tC/ha/year.

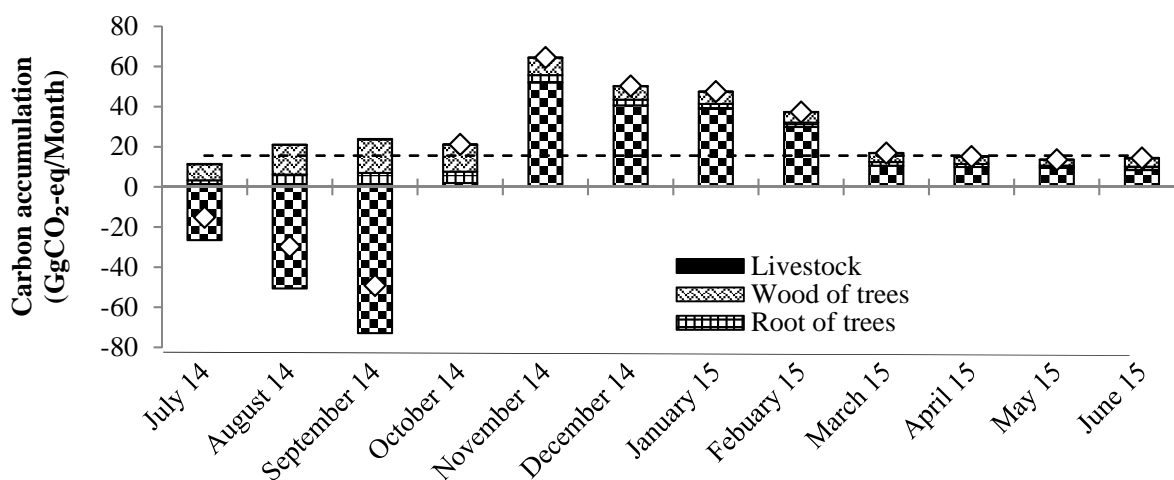


Figure 3. Monthly variability of C stock variations at the whole landscape level

Temporal variability of the GHG balance at the Whole ecosystem level

Our result highlights seasonal variation in the GHG balance on a territory scale (figure 3). This representation enables a distinction to be made between emissions and sequestration depending on the season. The GHG balance was positive in the rainy season (+199.33Ggeq-CO₂). It varied from +13.65 to +8.32Ggeq-CO₂/month in October and September, respectively. The GHG balance was negative in the dry season; it was intermediate at -67.47Ggeq-CO₂ in the cold dry season and -34.64Ggeq-CO₂ in the warm dry season. In the cold dry season, the monthly balance varied between -56.48 and -29.96 Ggeq-CO₂/month in November and February, respectively. In the warm dry season, the monthly budget varied between -10.85 and -7.40 Ggeq-CO₂/month in March and May, respectively. A seasonal or monthly negative balance meant that GHG emissions were compensated for by C accumulation. Overall, all the landscape units of the territory emitted +2.601 teq-CO₂/ha/year, on average, and sequestered -2.64 teq-CO₂/ha/year, on average. That is equivalent to an annual GHG balance of -0,72teq-CO₂/ha/year. Thus the sylvo-pastoral ecosystem might sequesterate -0,01teq-C/ha/year.

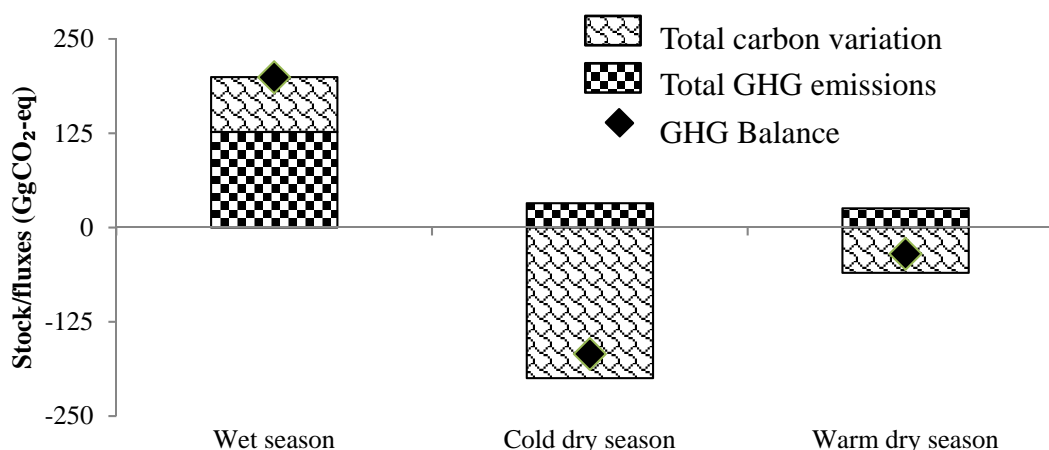


Figure 4. Seasonal variability in the GHG balance at the whole ecosystem level

DISCUSSION

It seems important to take into consideration the main GHG transfers from the ecosystem to the atmosphere in order

to understand the impact of land-use management on global warming (Smith *et al.*, 2001). This study provides the first rather detailed balance of the net CO₂, N₂O and CH₄ transfers on a sylvo-pastoral territory scale, while covering spatial heterogeneity of land uses. We approached this balance from an eco-systemic angle, thus considering all the ecosystem components (animals, soil and plants) and their interactions.

Monthly monitoring of all the components of the GHG balance highlighted strong seasonal variability in the balance. This is rarely found in the estimations of annual GHG balances usually implemented on a production system scale (Schönbach *et al.*, 2012) or a territory scale (Karki *et al.*, 2015). The rainy season was the most sensitive period, as highlighted in the seasonal variability obtained in this positive balance due to major GHG emissions. Indeed, organic matter decomposition occurs during the rainy season (hot and humid season) (de Souza Rezende *et al.*, 2016) while organic matter accumulation, its fragmentation and burying mostly occur during the dry season (Coleman *et al.*, 1989). This balance highlights the direct and indirect roles played by animals in sylvo-pastoral ecosystem functioning. During the rainy season which was absolutely fundamental in this balance the high rate of animal presence in the study area was explained by the return of transhumant herds to the study area due to rainfall resumption and subsequent grass regrowth. This high presence rate resulted in a large quantity of dejection onto the ground with a major concentration around settlements and ponds full of water at that period. Together with rainfall effects (increase in soil moisture and filling of ponds), major animal activity stimulated a rather significant increase in soil emissions and above all from water ponds (Figure 5.11). Indeed, the input of faecal matter on the ground, directly followed by a humidification period after rainfall, stimulated biological activity at soil level, thus emitting large amounts of CH₄ and N₂O (Franzluebbers *et al.*, 2000; Kim *et al.*, 2012). Moreover, in this season, large emissions of CH₄ occurred from the surface water of ponds, because of direct excretion into the water while the herd was drinking (Assouma *et al.*, 2017). On the one hand, the positive balance in this period resulted from a low return of plant biomass to the soil (herbaceous growth period and renewal of woody plant leaves). On the other hand, negative balances during both dry seasons resulted from a decrease in emissions due to soils and ponds drying up, and also high biomass returns to the soil via animal dejection, woody plant leaf senescence and burying of herbaceous litter. The high animal presence rate and the large quantity of available litter in the cold dry season stimulated more carbon accumulation during that season, thus making the balance even more negative.

The strong variability in the balance arose from i) seasonal climate variations that influenced GHG emissions processes as well as carbon fixation processes, and ii) pastoral practices characterized by seasonal herd mobility. The rainy season balance was positive because of high GHG emissions. As demonstrated before, free-grazing leads to *in situ* consumption of slightly more than one fourth of herbaceous biomass production in the whole borehole area, and to *in situ* recycling of more than 50% of this ingested biomass via animal dejection. This recycling facilitates the return of faeces to the soil, thus contributing to carbon sequestration (Soussana *et al.*, 2010) and positively influencing GHG emissions (Akinori and Masayuki, 2015). In addition to this, the effect of cattle trampling during grazing facilitated the transfer of standing biomass (e.g. straw) to the litter, and its fragmentation and burying in the soil. For this strong seasonal variability, the tropical sylvo-pastoral ecosystem balance was still globally negative over the annual cycle. This study confirms the sequestration potential of grazed ecosystems as demonstrated by (Soussana *et al.*, 2007) working on pastures in temperate climates. However, sequestration potential seems to be lower in a semi-arid tropical climate because of faster organic matter turnover on sandy soils (Kalbitz *et al.*, 2000), and in hot climates (Kotir, 2011).

CONCLUSIONS

This study highlights strong **seasonal variability** in the GHG balance on a sylvo-pastoral ecosystem scale. The rainy season was characterized by major emissions from the soil (N₂O), water and animals (CH₄). Conversely, the dry seasons were more particularly carbon accumulation periods at tree and soil level. Carbon biomass inputs mainly occurred at the beginning of the dry season, in the cold dry season, when animals had yet to leave for transhumance (animal dejection, burying of litter in the soil) and trees were still in their growth period (humid soils in the deep layers). This strong seasonal variability was explained by abiotic factors (e.g. rainfall seasonality, soil humidity and forage availability), biotic factors (e.g. seasonality of livestock animal presence, soil biological and termite activity) and by

livestock farmer practices (e.g. adaptation of the animal stocking rates to the available forage).

The annual net GHG balance was -0,01teq-C/ha/year over the 2014-2015 cycle. The sylvo-pastoral ecosystem seemed to generally perform as a **net sink of carbon**, like other grazed ecosystems, such as systems in temperate climates better documented in the literature.

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