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Mohamed Habibou ASSOUMA

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Approche écosystémique du bilan des gaz à effet de serre d'un territoire sylvo-pastoral sahélien : contribution de l'élevage

Directeur de thèse : **Martial BERNOUX**
Co-encadrant de la thèse : **Jonathan VAYSSIERES**

Jury

M. Martial BERNOUX, Dr, IRD	Directeur de thèse
Mme. Mariana RUFINO, Pr, Lancaster University	Rapporteur
M. Cheikh MBOW, Dr, ICRAF	Rapporteur
M. Maxime BANOIN, Pr, Université Abdou Moumouni	Président
M. Alexandre ICKOWICZ, Dr, CIRAD	Examinateur
M. Raphaël MANLAY, Dr, AgroParisTech	Examinateur
M. Jonathan VAYSSIERES, Dr, CIRAD	Invité
Mme. Anne MOTTET, Dr, FAO	Invitée

CIRAD, UMR Selmet- Systèmes d'élevage méditerranéens et tropicaux,

Campus de Baillarguet, 34398 Montpellier Cedex 5, France

Dans la vie, il y a trois facteurs : le talent, la chance, le travail. Avec deux de ses facteurs, on peut réussir. Mais l'idéal est de disposer des trois.

Bernard Werber

Résumé

Il est maintenant admis que le climat de la planète change et que les activités humaines en sont majoritairement responsables via l'émission de gaz à effet de serre (GES). Les rapports internationaux et des études de synthèse pointent du doigt la contribution des activités d'élevage aux émissions de gaz à effet de serre (CO_2, CH_4, N_2O) et au changement climatique évaluant la contribution mondiale de l'élevage aux émissions de GES directes et indirectes à environ 14,5%. Les écosystèmes pastoraux d'Afrique sub-saharienne sont responsables de hauts niveaux d'émissions de GES par unité de produits animaux, à cause de la faible productivité du bétail et de rations fortement méthanogènes. Les systèmes pastoraux extensifs valorisent cependant de vastes espaces caractérisés par une hétérogénéité édaphique et une forte variabilité du climat. Cette thèse vise à évaluer l'impact des troupeaux de ruminants sur le bilan GES vis-à-vis de l'atmosphère d'un écosystème sylvopastoral sous climat tropical semi-aride. L'aire de desserte du forage de Widou (cercle de 30 km de diamètre autour du forage, soit une superficie de 706 km²) dans la région sylvopastorale du Ferlo au Nord du Sénégal a été retenue comme unité spatiale d'analyse. Pour réaliser ce bilan, l'ensemble des émissions liées au fonctionnement de l'écosystème (fermentation entérique des animaux d'élevage et des termites, émissions de GES du sol et des eaux, le feu de végétation et le fonctionnement de la motopompe du forage) et des accumulations de carbone dans les principaux réservoirs (matière organique des sols, bois et racines des ligneux et masse animale) ont été évaluées à l'échelle de temps mensuelle et sur le cycle annuel en tenant compte de l'hétérogénéité spatiale de la zone étudiée (6 unités paysagères distinguées).

Les principaux résultats de cette thèse sont :

- Une forte **variabilité spatio-temporelle des émissions de GES provenant du sol et des eaux de surface** liées aux dépôts de déjections animales, à l'activité biologique de la faune des eaux et du sol et la respiration racinaire. Les émissions de CO_2 et de N_2O du sol sont essentiellement liées à la quantité de déjections déposées au sol tandis que celles de CH_4 sont fortement associées à l'hydromorphie et aux conditions anaérobiques des sols. L'eau des mares et autour du forage constituent les principales sources de CH_4 à l'échelle du territoire étudié du fait des déjections animales déposées lors de l'abreuvement.
- Une forte **hétérogénéité spatiale du bilan GES** au sein du territoire pastoral liée à l'activité d'élevage. Les unités paysagères fournisseuses de ressources fourragères pour les animaux (parcours, plantations forestières) ont des bilans négatifs variant entre -0,08 et -0,92teq-C/ha/an. Celles recevant de forts apports de déjections et contribuant

faiblement à la fourniture fourragère (campements, mares et forage) ont des bilans positifs compris entre +0,01 et +32,70teq-C/ha/an.

- Une forte **variabilité temporelle des émissions de méthane entérique** dans le territoire expliquée par la mobilité des troupeaux d'herbivores et des régimes alimentaires variables dans le temps. En contexte tropical sec et très saisonné d'Afrique Sub-saharienne, une Unité de Bovin Tropical émettrait en cumulé sur toute l'année 27,8kgCH_4/an, ce qui correspond à 59% du facteur d'émission proposé par l'IPCC et largement remobilisé dans la littérature.
- Une forte **variabilité temporelle du bilan GES** à l'échelle de l'ensemble du territoire sylvopastoral avec un bilan positif en saison de pluie (+0,18teq-C/ha/mois) du fait des fortes émissions liées à l'humidité des sols résultant essentiellement des dépôts de matière organique d'origine animale et un bilan négatif en saison sèche froide (-0,64teq-C/ha/an) et en saison sèche chaude (-0,13teq-C/ha/an) du fait d'un départ des animaux en transhumance et d'une activité biologique réduite des sols secs.
- Le bilan GES net sur toute l'année est de -0,01±0,003eq-C/ha/an. De ce fait l'écosystème sylvopastoral serait globalement **en équilibre** ; les émissions de GES seraient compensées par le stockage du carbone au terme d'une année complète.

Cette thèse montre l'intérêt d'une **approche écosystémique du bilan GES** pour comprendre les déterminants du bilan GES et identifier des solutions d'atténuation efficaces et adaptées. En effet cette approche se construit autour du développement d'une vision dynamique et spatialisée des interactions animaux-sol-plantes au sein de l'écosystème et de l'analyse des conséquences de ces interactions sur le bilan GES.

A l'avenir, il serait intéressant de mener un tel travail sur un gradient agro-climatique pour tenir compte de la diversité des systèmes d'élevage en interaction avec une ressource plus ou moins abondante et des chargements animaux variés. Le terrain sénégalais est particulièrement adapté puisqu'on y observe un gradient Nord-Sud fort (250 à 1150 mm/an) couvrant des écosystèmes sahéliens (cette étude) à soudaniens (étude en préparation) sur des sols à dominance sableuse. Une première étape serait de vérifier comment se comporte le bilan pour des années à pluviosité contrastée, mais aussi en faisant varier la charge animale. Dans un second temps, appliquer la démarche dans des systèmes agro-pastoraux (avec sole culturale). Dans ces systèmes, le bilan peut être profondément modifié quand une fraction importante de l'alimentation du bétail est assurée par des intrants d'origine externe au terroir.

Mots clés: Bilans GES, fonctionnement de l'écosystème, Interaction animal-sol-plantes, territoire, Sénégal.

Abstract

It is now agreed that the globe climate changes and that human activities account for most of it through the emission of greenhouse gases. International reports and syntheses show that the livestock contributes to a significant share of the greenhouse gas emissions (CO_2, CH_4, N_2O) emissions at about 14.5%. Pastoral ecosystems of sub-Saharan Africa have high levels of emissions of Greenhouse Gases (GHG) expressed per unit of animal products, due to the low productivity of pastoral livestock and their highly methanogenic diets. Extensive grazing systems value vast areas with heterogeneous soils and high climate variability. This thesis aims to assess the impact of ruminant herds on the GHG balance of sylvo-pastoral ecosystems under semi-arid tropical climate. The study site is a circular area of 15 km radius centered on the Widou borehole (15°59'N, 15°19'W, 706 km²) representative of the sylvo-pastoral Ferlo Region in the Sahel belt of West Africa (North of Senegal). To achieve the GHG balance assessment, all GHG emissions related to ecosystem functioning (enteric fermentation from livestock and termites, microbial activity from soil and water, bush fire and borehole's motor pump) and total carbon accumulation in the main sinks (soil organic matter, wood and root masses and livestock mass) were assessed at the monthly time scale and over the year cycle taking into account the spatial heterogeneity (6 landscape unit identified).

The main results of this thesis are:

- A strong **spatial and temporal variability of GHG emissions from soil** and surface water due to the deposition of livestock excretions, to biological activity of water and soil fauna and to root respiration. CO_2 and N_2O emissions from soil mainly relate to the excreta deposited while the CH_4 emissions are strongly associated with the surface water and soil hydromorphic and anaerobic conditions. Stagnant water in the ponds and around the borehole are the main sources of CH_4 in the study area due to the deposition of excreta by livestock in water when watering.
- A strong **spatial heterogeneity** of the greenhouse gas balance in relation to livestock activity. The landscape units that contribute more to the provision of forage to livestock (rangelands, forest plantations) have negative balances ranging between -0.08 and -0.92teq-C/ha/year. The landscape units that contribute less to livestock fodder provision and receive a large share of the excreta deposition (pastoralist settlements, ponds and vicinity of borehole) have positive balances ranging between +0.01 and + 32.70teq-C/ha/year.
- A large seasonal **variability of enteric methane emissions by livestock** due to the regional mobility of the herds and the changing diets over time. In the context of a dry

tropical climate with marked seasons in Sub-Saharan Africa the enteric CH_4 emission of one Tropical Livestock Unit over the year would be 27.9kgCH_4/year, thus only 59% of the default IPCC emission factor largely referred to in international literature.

- A large seasonal **variability of GHG balance** across the sylvo-pastoral landscape with a positive balance in the rainy season (+0.18tC-eq/ha/month) due to high GHG emissions caused by high soil moisture and to livestock excreta and vegetal organic matter deposited in the course of the preceding dry season. The GHG balance is negative during the cold dry season (-0.64teq-C/ha/year) and hot dry season (-0.13 teqC/ha/year) because some livestock area leaving the area for transhumance and because soil biological activity decreases as soil dry up.
- The GHG balance over the year and across the pastoral landscape is -0,01±0.003teq-C/ha/year setting the sylvo-pastoral ecosystem in an overall GHG **equilibrium**. Indeed, GHG emissions would be offset by carbon storage over a full year cycle.

This thesis highlights the benefits of **an ecosystem approach of the GHG balance** to better understand the drivers of the GHG balance and to suggest effective and appropriate mitigation options. Indeed, this approach is built around the development of dynamic and spatialized visions of animal-soil-plant interactions in the ecosystem and the integration of these interactions within the analysis of the GHG balance.

In the future, it would be interesting to carry out similar studies along the agro-climatic gradient in order to account for the diversity of livestock system interacting with more or less abundant resources and herd stocking rates. Senegal is particularly suitable because of the strong north to south climatic gradient (250 to 1150 mm / year) covering divers ecosystems from Sahel ecosystems (this study) to Sudan ecosystems (undergoing).

A first step would be to check how the balance behaves in years with contrasted rainfall, and also under a range of stocking rates, and to apply, in a second step, this ecosystem approach to agro-pastoral systems (including crops). In these systems, the balance may be profoundly changed when a large proportion of livestock feed is provided by out-farm inputs.

Key words: GHG balance, Ecosystem functioning, Animal-soil-plant interactions, Landscape, Senegal

Préambules

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A mon père ***Abou Bakari ASSOUMA***

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Publications et communications réalisées au cours de la thèse

Articles publiés, soumis ou à soumettre dans des revues à comité de lecture

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Annexes

Liste des abréviations

Sigles		**Définitions**
ADF	:	acid detergent fibre
ADL	:	acid detergent lignin
ANOVA	:	analysis of variance
C	:	carbone
CEL	:	cellulos
CH_4	:	méthane
CO_2	:	dioxyde de carbone
C-OMD	:	concentrate in vivo organic matter digestibility
d	:	day
DM	:	dry matter
DMI	:	dry matter intake
DMVI	:	dry matter voluntary intake
EF	:	facteur d’émission
Eq-CO_2	:	Equivalent CO_2
ETP	:	Evapotranspiration potentielle
FAO	:	Organisation des Nations Unies pour l’agriculture et l’alimentation
FNIRS	:	near-infrared reflectance spectroscopy applied to faeces
FPCM	:	fat-protein corrected milk
g	:	gramme
GES	:	gaz à effet de serre
GIEC	:	Groupe Intergouvernemental d'Experts sur l'Évolution du Climat
GWP	:	global warming potential, PRG en français
H	:	Mahalanobis standardized distance
ha	:	Hectare
IPCC	:	Intergovernmental Panel On Climate Change, GIEC en Français
kg	:	kilogramme
kt	:	kilotonne
LW	:	live weight
Mg	:	Méga gramme
MW	:	metabolic weight
N	:	azote

NDF	:	neutral detergent fibre
NIRS	:	near infrared reflectance spectroscopy
N_2O	:	protoxyde d'azote, également appelé oxyde nitreux
OM	:	organic matter
OMDvivo	:	in vivo organic matter digestibility
OMI	:	organic matter intake
OMVI	:	organic matter voluntary intake
PLS	:	partial least square procedure
PRG	:	Potentiel de Réchauffement Global, GWP en anglais
r	:	coefficient of correlation (Pearson coefficient)
R^2	:	coefficient of determination
RMS	:	root mean square
sd	:	standard deviation
SEC	:	standard error of calibration
SECV	:	standard error of cross-validation
SEM	:	standard error of mean
SEP	:	standard error of prediction
SEPc	:	standard error of prediction corrected for bias
t	:	tonne

Introduction générale

1. Généralités

Le réchauffement climatique d'origine anthropique de notre planète est désormais sans équivoque. Ces 60 dernières années de nombreux marqueurs en témoignent (IPCC, 2015). Les incidences d'évènements climatiques extrêmes survenus récemment (vagues de chaleur, sécheresses, inondations, cyclones, etc.) soulignent la grande vulnérabilité et le degré élevé d'exposition des écosystèmes et des sociétés humaines aux variations du climat. Par ailleurs, ces changements climatiques laissent craindre des perturbations importantes pour les sociétés dans leurs relations avec leur environnement, et risquent même de menacer les services écosystémiques dont elles bénéficient directement ou indirectement (IPCC, 2015). La combustion d'énergies fossiles, l'agriculture, l'élevage et les changements d'utilisation des terres sont des activités humaines qui contribuent de façon importante au changement climatique. Le changement climatique représente un défi majeur pour les années futures et de nombreuses études sont réalisées pour évaluer l'impact des différents secteurs d'activités sur le climat (Thornton *et al.*, 2014).

Ces changements climatiques sont le fait de l'injection massive dans l'atmosphère au cours des derniers siècles d'importantes quantités de gaz à effet de serre (GES), dont les plus important sont le dioxyde de carbone (CO_2), le méthane (CH_4) et le protoxyde d'azote (N_2O) (Bernoux and Paustian, 2013).

En 2006, dans un rapport intitulé « (Livestock's Long Shadow », la FAO donnait une idée générale du rôle de l'élevage dans le changement climatique, la pollution de l'eau et les pertes de biodiversité. Cette analyse globale et agrégée au niveau mondial montre que l'impact de l'élevage sur l'environnement est beaucoup plus important que ce que l'on pensait. Le rapport imputait au secteur élevage (production-transport-transformation) la responsabilité de 18% des émissions mondiales de GES (Steinfeld *et al.*, 2006). Dans un second rapport intitulé « Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities », la FAO réévalue en 2013 à la baisse la contribution de l'élevage et ses filières aux émissions de GES à l'échelle mondiale (Gerber *et al.*, 2013). Cela correspond à 7,1 gigatonnes d'équivalent CO_2 par an pour 2005, année de référence. Ces émissions représentent 14,5% des émissions de GES d'origine anthropique en utilisant les estimations de l'ensemble des émissions anthropiques du GIEC les plus récentes (49 gigatonnes de CO_2-eq en 2004 rapporté par (IPCC, 2007)).

Les principales sources d'émissions de GES associées à l'élevage sont au nombre de quatre : la production d'aliments du bétail, la fermentation entérique, la consommation d'énergie fossile pour le transport et la conservation des produits de l'élevage, et la gestion des effluents (Pradère, 2014). Les émissions provenant de la production, la transformation et le transport des aliments comptent pour près de 45% des émissions du secteur. La fermentation entérique, à 77% d'origine bovine et 10% provenant de petits ruminants, est la deuxième plus grande source d'émissions, contribuant pour environ 40% au total. Les émissions de CH_4 et de N_2O provenant du stockage et de la transformation des effluents représentent environ 10% des émissions du secteur de l'élevage (Gerber *et al.*, 2013). Les émissions en aval telles que le transport, la réfrigération et la transformation des produits représentent une part limitée d'environ 3% des émissions totales.

L'évaluation de « l'impact environnemental GES » est classiquement réalisée en s'appuyant sur la méthode d'analyse de cycle de vie. Dans le cas des systèmes d'élevage à « faibles intrants et faibles productivités » qui est celui de nombreux agriculteurs pauvres, l'analyse du cycle de vie peut se limiter à l'évaluation des GES émis directement par les animaux et par leurs déjections, car ces systèmes ne consomment pas d'énergie fossile et n'utilisent pratiquement pas d'intrants (aliments du bétail, engrais et pesticides pour la production du pâturage). Les références sur la contribution spécifique aux émissions des GES des systèmes d'élevage des pays du Sud caractérisés par ces types d'élevage sont peu nombreuses.

L'analyse par grandes régions du monde de Gerber *et al.* (2013) montre que l'Amérique latine, les Caraïbes et l'Afrique subsaharienne sont les régions les plus émettrices en GES par kilogramme de carcasse produite. La principale source d'émission pour l'Amérique latine et la conversion des forêts primaires en pâturage et en culture destinés à l'alimentation animale. En Afrique subsaharienne cela tient davantage à la faible productivité des animaux due à une santé animale fragile (ou précaire), une nutrition très saisonnée (bonne en saison des pluies et premiers mois de saison sèche, pauvre ensuite) et aux gains de poids rapides alternant avec des pertes de poids parfois spectaculaires qui se répercutent sur les performances reproductrices. En Afrique sub-saharienne, l'intensité d'émission par kilo de viande des petits ruminants est 55% plus élevée que la moyenne mondiale et celle de leur production de lait 30% de plus que la moyenne mondiale (Gerber *et al.*, 2014).

La digestibilité moyenne de la ration des petits ruminants d'Afrique de l'Ouest est de 55% et est plus basse comparée à la digestibilité moyenne mondiale de 59%. L'utilisation d'aliments de moindre qualité avec une plus faible digestibilité conduit à des émissions entériques de CH_4 plus importantes (Chagunda *et al.*, 2010). Dans cette région, les systèmes d'élevage extensifs étaient particulièrement indexés. Ce type d'élevage valorise essentiellement les parcours pastoraux. Le pastoralisme est un mode de vie complexe qui privilégie l'optimisation de la pâture sélective et vise donc avant tout l'alimentation du bétail (Ayantunde *et al.*, 1999). Les groupes de pasteurs habitent généralement là où les ressources sont rares et là où les conditions climatiques extrêmes limitent les options d'utilisation des terres et l'adoption d'autres modes de vie puisque moins adaptés que l'élevage. Le caractère hautement variable et imprévisible (le cumul et la distribution des pluies à l'intérieur de la saison des pluies difficilement prédictibles) de leur environnement fait que des stratégies d'existence semblables sont pratiquées par différentes communautés pastorales dans des localités très différentes en partant des zones arides d'Afrique (66 % des terres du continent) (Tennigkeit and Wilkes, 2008) jusqu'aux steppes gelées d'Europe du Nord et du Canada en passant par les plateaux froids et rigoureux d'Asie centrale. Le point commun de ces différentes situations pastorales reste un climat majoritairement aride. La zone aride se caractérise par une chaleur excessive et une pluviosité annuelle insuffisante avec une variabilité interannuelle et intra-annuelle importante. La FAO utilise l'indice d'aridité (P/ETP avec P=Pluviosité et ETP=évapotranspiration potentielle) pour définir les zones hyperarides (indice d'aridité 0,03), les zones arides (0,03<P/ETP<0,20) et semi-arides (0,20<P/ETP<0,50) (FAO, 1992).

Les régions arides occupent 41% des terres émergées dans le monde et sont essentiellement constituées de prairies, steppes et savanes. Ces écosystèmes couvrent approximativement 30% de ces terres (White *et al.*, 2000). La production pastorale extensive se pratique sur 25 % des terres du globe. En Afrique, 40% des terres sont dédiées au pastoralisme (WOCAT, 2009).

Les conditions de forte variabilité caractérisant ces régions amènent les éleveurs à adopter comme stratégie d'adaptation la pratique de l'élevage extensif basée sur le déplacement des troupeaux à la recherche de meilleurs pâturages afin de préserver leur capital de production que sont : le bétail et les écosystèmes. La mobilité est la principale adaptation fonctionnelle et opportuniste à ces contraintes. En effet, le **pastoralisme** s'appuie sur une grande aptitude des éleveurs à valoriser des ressources fourragères spontanées dispersées dans des milieux hétérogènes. Cette hétérogénéité de la ressource ajoutée à de fortes variations saisonnière et inter annuelle des disponibilités et qualités fourragères font que ces écosystèmes restent jusque-là très peu étudiés en termes de bilan GES exhaustif. En effet dans ce domaine on a très peu de mesures et observations de terrain sur les parcours pastoraux en Afrique alors que ces observations de terrain sont indispensables à des échelles spatiale et temporelle plus fines que le continent et l'année pour la compréhension de la contribution et la réponse de ces écosystèmes aux changements climatique (Tagesson *et al.*, 2015a). Une bonne connaissance des flux de GES à l'échelle de ces écosystèmes en région semi-aride passe par une connaissance fine du rôle de l'élevage dans le fonctionnement de ces écosystèmes étant donné l'importance de cette activité (Barton *et al.*, 2013).

Le bilan GES est l'outil majeur pour la compréhension de l'impact d'une activité anthropique sur un écosystème fournissant les informations susceptibles d'orienter les stratégies d'atténuation des effets du changement climatique (Blanchard, 2010). Les recommandations du GIEC précisent que les estimations d'émissions de GES doivent inclure toutes les sources, mais aussi tous les puits de GES associés directement ou indirectement à un produit ou à un service (IPCC, 2014). Ainsi un bilan de GES comporte l'ensemble des flux de CH_4 et N_2O. Les flux de CO_2, nombreux et complexes sont abordés par un bilan de masse des différents compartiments concernés (biomasse, litières et sols). Seuls les flux de CO_2 dus à l'utilisation d'urée ou de chaulage sont considérés en tant que flux). Une évaluation de la contribution de l'élevage aux émissions de GES nécessite donc de raisonner en termes de bilan, en considérant les compensations permises par la séquestration de carbone dans les différents compartiments. Dans l'optique d'une atténuation des émissions de GES des systèmes d'élevage, les écosystèmes sylvopastoraux peuvent jouer un rôle important vu leur étendue. Il a été démontré que les prairies tempérées par exemple ont un vaste potentiel pour atténuer le changement climatique car elles absorbent et stockent le CO_2, souvent insuffisamment reconnu (Jérôme *et al.*, 2013). Des travaux récents ont démontré la capacité de ces écosystèmes à réduire leur contribution aux émissions de GES, notamment grâce à leur capacité à séquestrer le carbone dans les sols, en particulier dans le cas de prairies permanentes en conditions tempérées (Soussana *et al.*, 2010b). Dans les systèmes prairiaux, une partie du CO_2 fixé par les plantes est restitué à l'atmosphère par la respiration des animaux et des plantes et organismes du sol, après consommation des fourrages. Une partie limitée est perdue sous forme de méthane, alors qu'une partie importante retourne au sol, par l'intermédiaire des fèces directement au pâturage ou pendant les phases de repos et d'abreuvement des animaux (Hiernaux *et al.*, 1999). Ce retour au sol via les déjections animales s'ajoute aux apports de carbone par les litières (herbacées et ligneux) accélérés par le piétinement du bétail, les résidus d'herbe et les racines (Soussana *et al.*, 2004).

On retrouve globalement les mêmes principes dans les écosystèmes pastoraux tropicaux secs mais leur fonctionnement diffère de façon importante de celui des écosystèmes tempérés et l'état des connaissances reste limité et incomplet. La **question** de la place de l'élevage dans les dynamiques de séquestration du C et d'émission de GES reste à approfondir en contexte tropical sec. Le bilan GES se calcule par rapport au sens des flux par rapport à l'atmosphère. Ainsi l'ensemble des émissions de GES est comptabilisé positivement tandis que la dynamique de séquestration de carbone négativement. Ainsi un bilan négatif suppose une séquestration de carbone plus importante (effet puits de carbone) et un bilan positif suppose des émissions de GES plus importante que la séquestration « effet source de GES ». *L'élevage est-il de façon globale un acteur négatif ou positif du bilan GES des écosystèmes sylvopastoraux tropicaux ?*

A priori il y contribue positivement via la déforestation (Barona *et al.*, 2010), l'augmentation des émissions du sol (Chadwick *et al.*, 2011), l'ouverture des cycles de l'N et du C (Rufino *et al.*, 2007). Et inversement il y contribue de façon négative via l'entretien et la conservation de parcours, l'apport de déjections au sol entraînant une accumulation de matière organique dans le sol (Hiernaux *et al.*, 1999), via les transferts horizontaux de fertilité dans l'espace (Dugué, 1998). Ce travail de thèse s'interroge donc plus particulièrement sur *« Le rôle que jouent les troupeaux et les pratiques d'élevage dans l'équilibre complexe qui existe entre les émissions de GES et la séquestration de C dans les écosystèmes sylvopastoraux sous climat semi-aride ».*

Deux **hypothèses** sont plus particulièrement explorées dans le cadre de cette thèse :

H_1: même si l'écosystème présente un potentiel de séquestration limité du fait d'une pluviosité faible et un niveau élevé d'émissions de méthane lié à la présence de grands nombres de ruminants, il est possible qu'à l'échelle d'un paysage pastoral l'écosystème soit globalement en équilibre entre émissions et séquestration du fait de pratiques pastorales qui s'adaptent au potentiel de production du milieu.

H_2: ensuite il est également probable que la variabilité temporelle et spatiale des émissions et de la séquestration soient élevées et liées à la pression variable des troupeaux du fait de leur forte mobilité.

Par conséquent l'**objectif général** de l'étude est d'analyser le bilan net entre émissions et séquestration dans un territoire large en lien avec une compréhension du rythme spatio-temporel de l'écosystème.

Cette étude est basée sur un dispositif expérimental riche et original intégrant la variabilité spatio-temporelle au sein d'un vaste territoire correspondant à l'aire de desserte d'un forage, celui de Widou. Ce territoire se situe au cœur de la zone sylvopastorale du Sénégal, dans la région du Ferlo. Le Ferlo est une région d'élevage extensif du Sénégal septentrional dont les conditions physiques (climat très saisonné et caractère aléatoire des pluies et des pâturages) font de la mobilité pastorale sur de vastes étendues une pratique très largement pratiquée. Cette mobilité se présente sous divers régimes et modalités d'accès partagé aux ressources fourragères et hydriques qui permettent aux pasteurs de s'adapter à un milieu particulièrement contrasté (Kiema *et al.*, 2015). Cette étude propose une vision originale du bilan GES d'un écosystème sylvopastoral en milieu semi-aride et aride d'Afrique subsaharienne basée sur **une analyse écosystémique à l'échelle d'un territoire** qui est ici l'aire de desserte du forage de Widou.

De façon spécifique cette étude de l'aire du forage de Widou vise à :

- Décrire le fonctionnement dynamique saisonnier du territoire étudié et de proposer une première représentation des variations saisonnières du bilan GES sur la base autant que possible d'observations sur le territoire étudié.
- Décrire l'hétérogénéité spatiale du territoire étudié et de proposer un bilan GES annuel variable en fonction des unités paysagères caractérisant le territoire sur la base autant que possible d'observations sur le territoire étudié.
- Identifier les facteurs clefs affectant l'équilibre de l'écosystème, les incertitudes et les manques de connaissances pour produire une représentation plus précise et plus fiable du fonctionnement de cet écosystème.

Pour atteindre ces objectifs, nous avons dans un premier temps défini un modèle conceptuel de type stock-flux mettant l'accent sur le recyclage du carbone et de l'azote. Ce dernier permet d'identifier les principaux puits de carbone (stocks de carbone) et les principales sources de GES (flux d'azote et de carbone) à l'échelle d'un territoire sylvopastoral. Ce modèle conceptuel a servi de base pour la réalisation d'une première estimation du bilan annuel des GES sur le territoire étudié suivant les approches de niveau 1 et niveau 2 (ou Tier 1 et Tier 2 en anglais) utilisés par le GIEC en se basant sur une synthèse bibliographique et un recensement exhaustif du cheptel présent sur le territoire.

Selon le GIEC, pour le secteur de l'utilisation des terres, les méthodes de niveau 1 sont créées pour être les plus faciles d'utilisation. Des équations et paramètres par défaut (par exemple, les facteurs de variations des stocks et d'émissions) sont fournis dans les lignes directrices pour les inventaires nationaux des GES de 2006. Le niveau 2 utilise des facteurs de variations des stocks et d'émissions basés sur des données spécifiques au pays ou à la région. En général, le niveau 2 utilise des données sur les activités plus séparées et à résolution spatiale et temporelle plus élevée. Enfin, Le niveau 3 utilise une méthodologie d'ordre supérieur, notamment des modèles et systèmes de mesures d'inventaires adaptés aux circonstances nationales, répétés dans le temps, axés sur des données sur les activités à résolution élevée et à des échelles sub-nationales.

Les résultats de ce premier bilan ont permis de cibler les principaux éléments (sources GES et stock de carbone) du bilan GES sur lesquels il fallait concentrer les efforts de production de connaissances dans le cas de l'écosystème étudié.

2. Site étudié

Les travaux de cette thèse ont été conduits dans la région sylvopastorale du Ferlo au Nord du Sénégal. Située entre les latitudes 15° et 16° 30 Nord et les longitudes 13° 30 et 16° Ouest (Ndiaye *et al.*, 2014a), la région du Ferlo correspond grossièrement à la zone sylvopastorale du Sénégal. Elle couvre environ 70 000 km^2 (figure 1), soit un peu plus du tiers du territoire

Sénégalais (Wane *et al.*, 2010), et correspond en grande partie au bassin de la rivière Ferlo. On y distingue deux grandes zones : la vallée du fleuve (Walo) au nord et la partie sud non inondable (Diéri). Le Diéri se divise lui-même en deux parties : la partie Ouest dont les sols sont majoritairement sableux et qui se nomme Kooya en langue «*Pular*» et la partie Est dont les sols sont plus argileux et plus superficiels souvent sur la cuirasse qui recouvre les grès du continental terminal, avec une végétation plus densément arbustive (Le Houerou, 1989). Le principal mode de vie dans cette région est pastoral, caractérisé par l'accès partagé à l'espace et aux ressources fourragères dans les zones de libre pâture (exclusion dans les forêts classées et les jeunes plantations forestières), ligneuses et hydriques qu'elle porte (Leclerc and Sy, 2011). Le Ferlo représente la partie la plus aride et la plus chaude du Sahel sénégalais avec un climat de type tropical de mousson, semi-aride, monomodal à variante très chaude. Les températures sont cependant atténuées par la proximité de l'Atlantique par rapport au Sahel plus continental. De même l'humidité de l'air n'est pas aussi basse que dans le Sahel continental (ces deux Sahel sont même distingués dans le zonage biogéographique historique de Aubréville and Chevalier (1949). Les précipitations annuelles sont de l'ordre de 300-350 mm (358 mm en moyenne sur la période de 1959 à 2013 à la station-météo de Linguère située dans le Ferlo à 75km au Sud-Est de Widou). Le Ferlo est caractérisé par la variabilité de la distribution temporelle et spatiale des pluies (orages convectifs et lignes de grain) au cours de la saison des pluies dont les incidences sur le niveau de remplissage des mares et le développement des pâturages ont souvent constitué une contrainte majeure pour le système pastoral d'une part, et justifié les régimes de mouvements observés en cas de crise (petite et grande transhumance) d'autre part (Sy, 2010).

A l'origine, l'organisation de l'élevage pastoral avant l'implantation des forages était caractérisée par une transhumance pendulaire entre le Walo et le Kooya-Ferlo où les parcours étaient saisonnièrement utilisés à partir des mares temporaires et quelques puits le long de la vallée du Ferlo (Adriansen and Nielsen, 2002). La mise en place d'un réseau de forages profonds distants de 5 à 30km entre les années 1950 à 1960 a réorganisé la région en un maillage de communautés centrées sur un ou deux forages (Manoli *et al.*, 2014). Dans le Ferlo, l'occupation de l'espace est centrée sur le forage (figure i.1). Cela crée des unités spatiales appelées **aires de desserte de forage** et qui sont constituées de « l'espace et de l'ensemble des ressources polarisées par un forage pastoral » (Touré *et al.*, 2004).

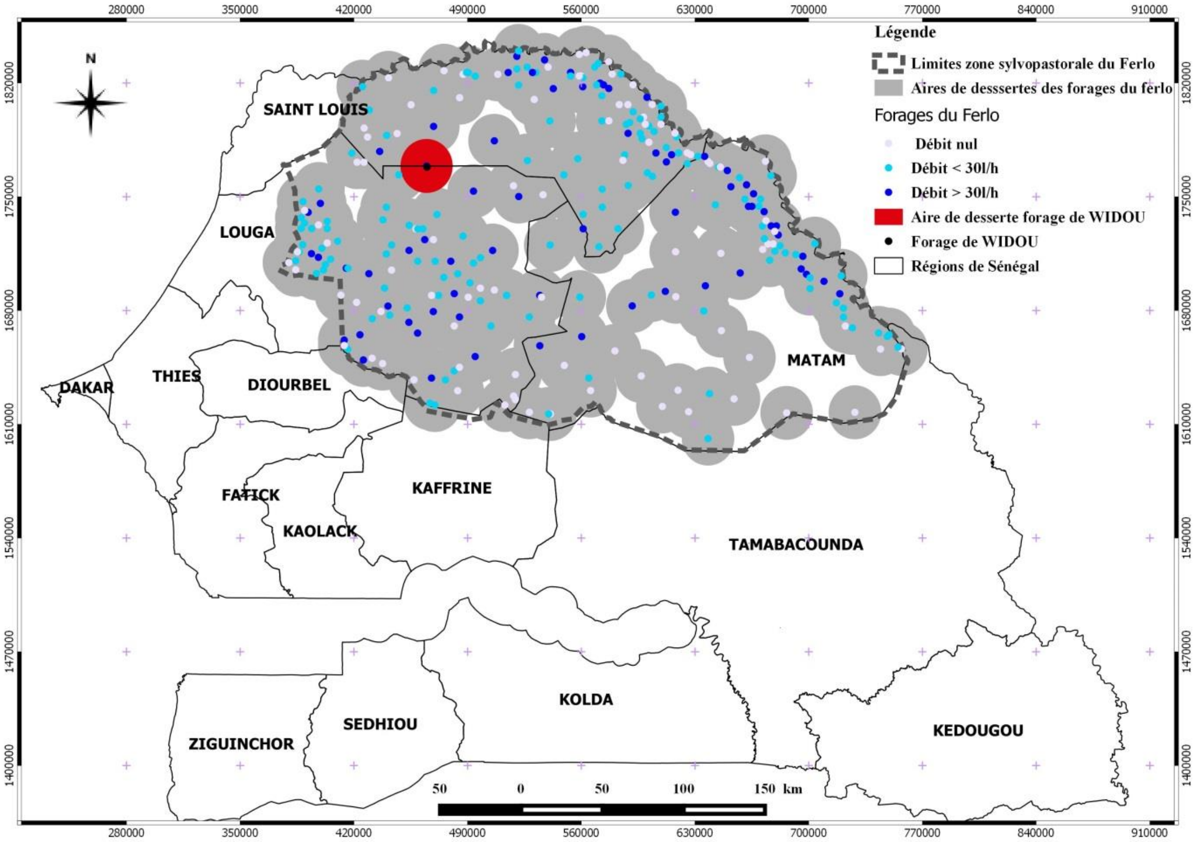

Figure i. 1. Localisation des forages du Ferlo (sensu lato)

Notre étude de cas s'est essentiellement focalisée sur le Forage de Widou situé au 15° 59'de latitude Nord et 15° 20' de longitude Ouest (Sagna *et al.*, 2014). Le choix de ce forage se justifie d'une part par la présence d'une importante base de données issue du suivi de la dynamique des écosystèmes réalisé par le Pôle Pastoralisme Zones Sèches (PPZS) depuis l'an 2000 (Bah *et al.*, 2010) et le Projet d'Autopromotion Pastorale du Ferlo (Ancey *et al.*, 2008). Ce projet fut d'abord un projet de replantation forestière puis sa dimension recherche a pris de l'importance avec la mise en place autour de ce forage d'un dispositif expérimental. Ce projet avait en particulier l'objectif de tester l'effet de différents niveaux de chargement animal sur la végétation en vue de concevoir un système de pâture contrôlé. Ce projet a permis la production d'une littérature riche. Il s'agit entre autre d'articles et de rapports décrivant les principales formations végétales (Klug, 1982; Miehe, 1992, 1998; André, 2001), l'économie pastorale (Schaffer, 1994), la variabilité de la pluie et son incidence sur la disponibilité en eau (Hein and De Ridder, 2006) et les pratiques pastorales en relation avec la production de biomasse herbacée (Thebaud, 1995; Hein, 2006; Retzer, 2006; Miehe *et al.*, 2010). La présence de placettes expérimentales mises en défend depuis plus de trente temps (Miehe *et al.*, 2010) a également été un argument fort pour retenir l'aire de déserte du forage de Widou comme site d'étude. Compris dans un rayon approximatif de 15 km autour du forage de Widou, le site d'étude couvre une superficie de 706,5 km² et présente les traits caractéristiques d'un climat sahélien de type semi-aride (Niang *et al.*, 2014b) avec alternance de deux saisons : une saison sèche qui dure 8 à 10 mois (novembre à juin) et une saison pluvieuse de courte durée pouvant s'étendre de juillet à octobre dont la durée est fortement variable selon les années. La saison sèche peut se subdiviser en deux saisons de quatre mois chacune, la première qui est la saison sèche froide de novembre à février et la saison sèche chaude de mars à juin. Les données recueillies entre 1974 et 2015 au centre forestier de Widou indiquent une forte variabilité interannuelle de la pluviosité et du nombre de jours de pluie. Le coefficient de variation est de 36,7% pour la hauteur pluviométrique et de 24,1% pour le nombre de jours de pluie. La pluviosité annuelle est en moyenne de 285,8 ± 84,2 mm (Figure i.2) répartie en moyenne sur 19 ± 4 jours de pluie. La longueur de la saison des pluies varie énormément en plus du nombre de jours de pluie. Le début et la fin de la saison sont définis par des paramètres statistiques décrit par Borona *et al.* (2016). La variabilité de la pluviosité annuelle est assez forte avec par exemple la pluviosité de 2005 (478,4 mm) qui est quatre fois supérieure à celle de 1983 (105,4 mm).

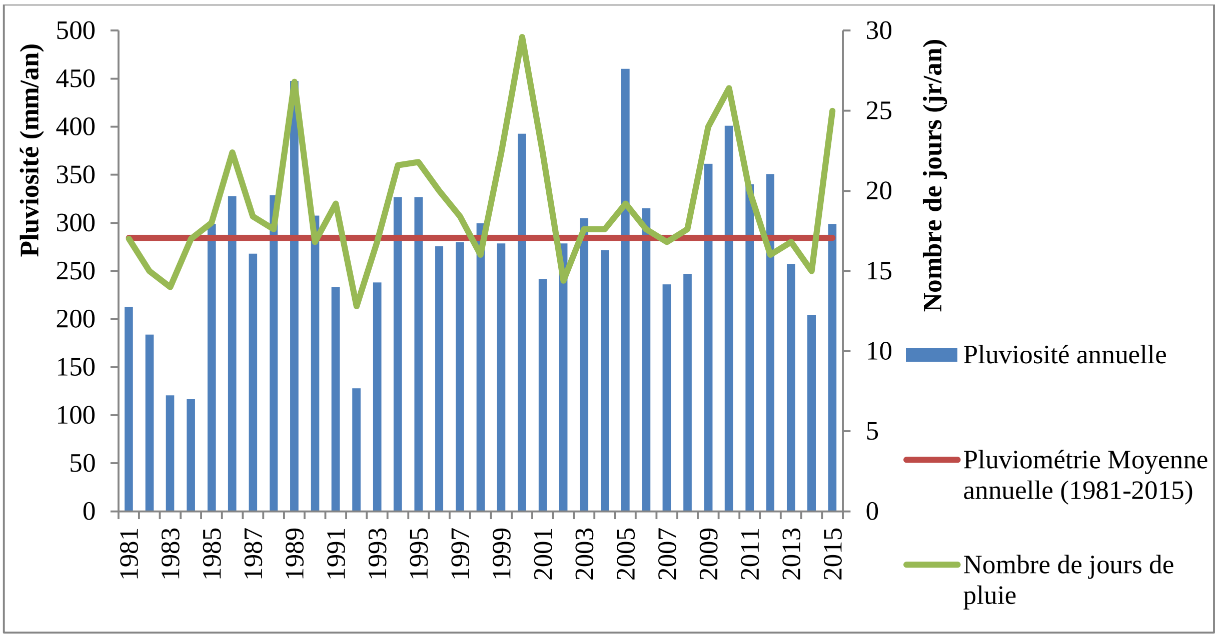

Figure i. 2. Répartition de la pluviosité annuelle en nombre de jours de pluie à Widou de 1974 à 2015 (source : Albert Biaguy, Centre Forestier, Widou)

Les autres paramètres de description du climat ont été obtenus dans la station climatique de Linguère sur la période de 1980 à 2014 ; l'humidité relative moyenne mensuelle de l'air est de 43,7±17,1% et varie entre 24,9% en février et 72,6% en août. La vitesse moyenne mensuelle du vent est de 1,4±0,4m/s et varie entre 1,02m/s en octobre et 1,81m/s en juin. La température reste globalement élevée toute l'année avec une température moyenne comprise entre 25 et 32°C, une température minimale comprise entre 18 et 25°C et une température maximale entre 32 et 42°C respectivement en janvier et mai. L'évapotranspiration potentielle reste aussi globalement élevée sur toute l'année avec un cumul de 1871,6 mm/an en moyenne sur l'année (figure i.3).

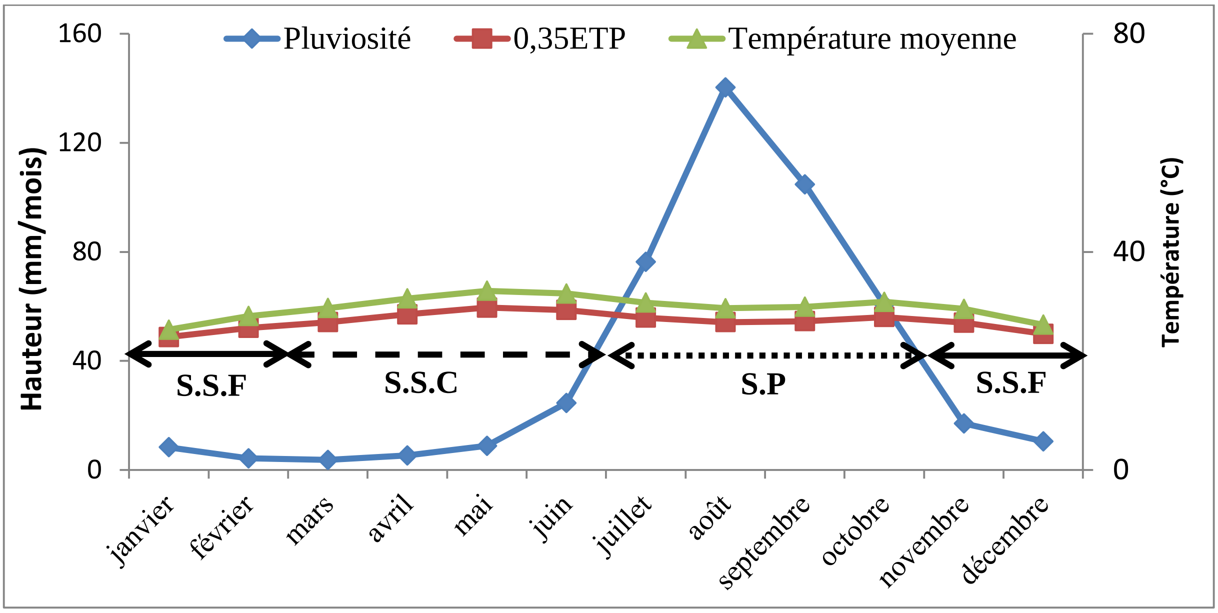

Figure i. 3. Température, pluviosité et Evapotranspiration potentielle moyenne mensuelle (source : station météorologique de Linguère ; SSF : saison sèche froide, SSC : saison sèche chaude, SP : saison des pluies)

Dans l'année on distingue classiquement deux périodes : la période sèche de Novembre à Juin (P<0,35 ETP) et la période des pluies de Juillet à Octobre (P>0,35ETP) comme décrit par (Anonyme, 1988). Dans nos travaux nous avons retenu pour l'analyse de nos données trois grandes saisons :

- la **Saison des Pluies** (SP) de Juillet à octobre correspond aux saisons identifiées par les Peuhls comme *Ndugu* et *Kaule*,
- la **Saison Sèche Froide** (SSF) de novembre à février appelée *Dabunde* par les Peuhls,
- et la **Saison Sèche Chaude** (SSC) de mars à juin correspond aux saisons identifiées par les Peuhls comme *Tchedio* et *Setselle*.

Les études antérieures faites sur la végétation et les sols du bassin versant du Ferlo (Maignien, 1965; Leprun, 1971; Stancioff *et al.*, 1986; CSE. and ROSELT/OSS, 2002) montrent que le site d'étude est caractéristique de la région Ouest du Ferlo, le Kooya. Les sols y sont sableux de types ferrugineux tropicaux lessivés. Le paysage est caractérisé par une succession de dunes fixées et d'inter-dune peu accidentés (Ndiaye *et al.*, 2014a). Les inter-dune, ou bas-fonds, ont un taux d'argile plus important que les sommets de dune. La formation végétale est de type steppique avec une prédominance d'espèces ligneuses telles que *Balanites aegyptiaca* (L. Drel.), *Acacia senegal* (L.), *Acacia seyal* (Del.), *Sclerocarya birrea (A. rich.)*.... La strate herbacée renferme de nombreuses espèces telles que *Schoenefeldia gracilis* (Kunth) (graminée annuelle), *Andropogon amplectens* (Nees) (graminée pérenne), *Aristida longiflora* (Schumach) (graminée pérenne rare dans la zone d'étude), *Aristida mutabilis* (Trin. & Rupr.) (graminée annuelle). Les principales espèces appétées par les bovins sont *Combretum micranthum* (G. Don), *Piliostigma reticulatum* (Hochst.), *Pterocarpus lucens* (Lepr. ex Guill. & Perrott.), *Guiera senegalensis* (Lam.), *Grewia bicolor* (Juss), *Pterocarpus erinaceus* (Poir), *Adansonia digitata* (L.), *Sterculia setigera* (Gelile.), *Maerua crassifolia* (Forssk.), *Anogeissus leiocarpus* (Guill. & Perr.). Sur les 51 espèces réparties dans 22 familles taxonomiques recensées dans le Sahel par Sarr *et al.* (2013), près de 53% sont des arbres fourragers parmi lesquels les plus prisés sont : *Pterocarpus erinaceus, Adansonia digitata et Sterculia setigera*.

Les outils de télédétection (image scène Landsat TM 204-049 du 03 novembre 2010) et les observations de terrain conduites dans cette étude (point GPS pour marquer les limites des unités et identifier des points particuliers) ont permis de construire une base de données spatiale de référence décrivant les modes d'occupation du sol et les paysages rencontrés dans l'aire de desserte du forage de Widou. Le territoire étudié a été subdivisé en six unités paysagères : les parcours constitués des savanes et des steppes en libre pâture (89% de la surface du territoire), les mares (2,7%), les campements (6,3%), les plantations forestières (6,3%), les placettes de mise en défens (0,03%) et l'aire immédiate autour du forage de Widou (0,1%) (plus de détails dans le chapitre 4).

Des observations complémentaires ont par ailleurs été réalisées dans une zone de parcours située à 75 Km au Sud de Widou pour préciser la dynamique des stocks de carbone dans le sol et les arbres. Ce site complémentaire se situe à proximité de la station de recherche de Dahra (15°21 de latitude Nord et à 15°28 longitude Ouest), il appartient également au Kooya dans la région sylvopastorale du Ferlo avec une végétation et des sols similaires de ceux rencontrés à Widou.

3. Plan du manuscrit et articulation des chapitres

Le manuscrit de cette thèse apporte des éléments de réponses à la question de recherche présentée dans le paragraphe précédent au travers de **cinq chapitres encadrés par une section introductive et deux sections de discussion et de conclusion générale** (figure i.4). Ces cinq chapitres correspondent à des articles scientifiques publiés ou en cours de soumission à des revues ayant un facteur d'impact auprès de Journal Citation Report (jcr.incites.thomsonreuters.com).

L'**introduction** du manuscrit (que vous venez de parcourir) insiste sur le rôle des écosystèmes pastoraux vis-à-vis du changement climatique dans un état d'**équilibre complexe entre**

émissions de GES, séquestration de C et adaptation à la variabilité climatique. L'état des lieux des connaissances sur l'importance des activités d'élevage pour le fonctionnement des écosystèmes pastoraux permet de poser la question de recherche et les hypothèses explorées dans ce manuscrit, et d'expliquer le choix du site d'étude.

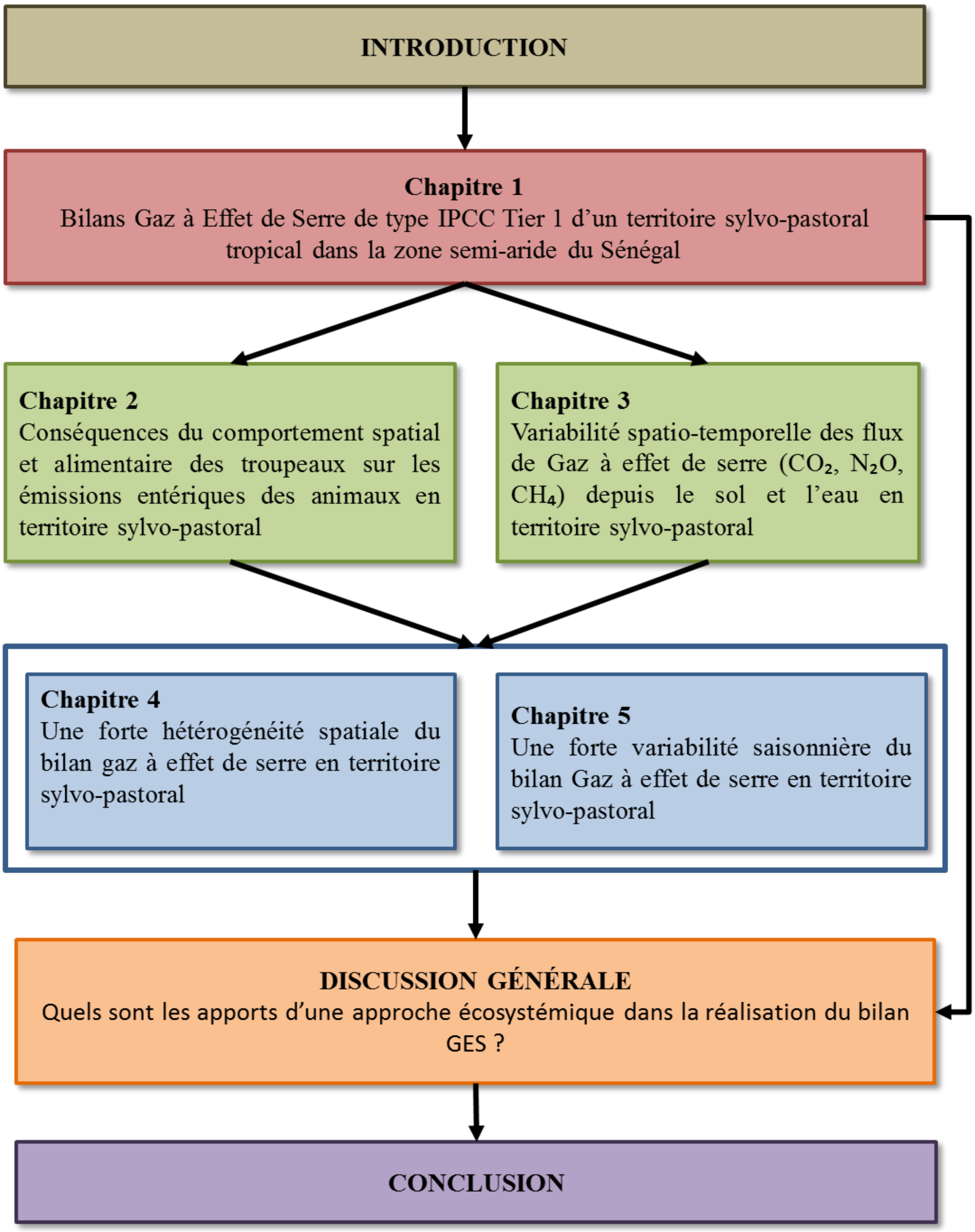

Figure i. 4. Articulation et complémentarité des différentes sections de la thèse

Le but final de la thèse étant d'évaluer l'équilibre complexe qui existe entre source et puits (émissions et séquestration) et de mesurer les variabilités spatiales et temporelles de cet équilibre, certaines étapes intermédiaires sont nécessaires. Tout d'abord un **premier chapitre** évalue *a priori* les principales sources d'émission de GES et principaux puits de carbone grâce à un premier bilan GES basé sur la méthode GIEC (IPCC, 2006). Ce dernier, s'est basé sur une synthèse bibliographique et des résultats d'un inventaire des troupeaux et des campements présents autour du forage de Widou. Sa réalisation, suivant les approches de niveau 1 et niveau 2 du GIEC, a permis de définir le dispositif de collecte de données et de cibler la fermentation entérique et les émissions liées aux dépôt de déjections animales comme principales sources d'émissions de GES, et le sol et les végétaux ligneux comme principaux puits de carbone.

A partir de ce premier inventaire, les deux principales sources d'émissions de GES sont étudiées plus en détail dans deux chapitres distincts. Ainsi le **chapitre 2** présente une évaluation des émissions de méthane (CH_4) entérique par UBT (Unité de Bétail Tropical) dans l'aire de desserte du forage de Widou. Dans cette zone l'activité pastorale est décrite en détail en tenant compte de sa variabilité intra-annuelle et les émissions sont évaluées à l'échelle du territoire. Quant au **chapitre 3**, il présente la variabilité spatiale et temporelle des émissions de CO_2, N_2O et de CH_4 au niveau du sol et des eaux liées aux dépôts de fèces sur le sol. Dans ce chapitre un certain nombre d'hypothèses sur les facteurs contrôlant aussi bien la variabilité temporelle que l'hétérogénéité spatiale de ces émissions sont proposées.

L'analyse des principales sources d'émission associé au calcul du potentiel de séquestration de carbone dans les principaux réservoirs d'un écosystème sylvopastoral permet de préciser le bilan GES du territoire. Le **chapitre 4** explore l'hypothèse de son hétérogénéité spatiale alors que le **chapitre 5** vérifie plus spécifiquement celle de sa variabilité temporelle. Ces deux chapitres constituent le cœur de la thèse, ils montrent le rôle majeur de l'élevage dans la construction de cette variabilité spatiale et temporelle du bilan GES.

La **discussion générale** confronte le premier bilan réalisé *a priori* selon la méthode IPCC Tier 1 au bilan GES réalisé *a posteriori* grâce aux nouvelles connaissances produites dans le cadre d'une approche écosystémique du bilan GES. Les différences entre les deux bilans sont discutées au regard du fonctionnement écologique de l'écosystème étudié et des différences de facteurs d'émissions constatées entre mesure *in situ* et coefficients généraux proposés par l'IPCC. Ce bilan GES plus fin et les connaissances originales produites sur le fonctionnement écologique du système étudié permettent de proposer un ensemble d'options d'atténuation du bilan GES.

Le manuscrit s'achève par une **conclusion générale** soulignant les résultats majeurs de cette thèse. Un ensemble de perspectives de recherche sont également proposées.

Chapitre 1 : Bilans Gaz à Effet de Serre de type IPCC Tier 1 d'un territoire sylvo-pastoral tropical dans la zone semi-aride du Sénégal

Ce chapitre se base sur une communication courte présentée aux 21èmes Rencontres Recherches Ruminants qui se sont déroulées les 3 et 4 décembre 2014 à Paris. Il s'agit de :
Assouma M.H., Vayssières J., Bernoux M., Hiernaux P., Lecomte P., 2014. Bilans Gaz à Effet de Serre d'un écosystème sylvo-pastoral tropical dans la zone semi-aride du Sénégal. Proceedings of the French symposium Rencontres Recherches Ruminants, Paris, France, 3-4 December, 4 pp.

Un Poster intitulé « Greenhouse Gas Balance of a Tropical Sylvo-Pastoral Ecosystem in Senegal's Semi-Arid Region » a été également présenté à la conférence internationale « Livestock, Climate Change and Food Security » qui s'est déroulée du 19 au 20 Mai 2014 à Madrid en Espagne dans le cadre du Projet Animal change.

Résumé

Les systèmes pâturant extensifs d'Afrique sub-saharienne sont responsables de hauts niveaux d'émissions de Gaz à effet de Serre (GES) par unité de produits animaux, dû à la faible productivité du bétail et à des rations fortement méthanogènes. Ce travail propose un bilan GES original à l'échelle d'un écosystème sylvo-pastoral caractérisé par un élevage extensif de bovins, d'ovins et de caprins dans la zone semi-aride au nord du Sénégal, au Ferlo. Les principales sources d'émission (en eq.CO_2) sont la fermentation entérique (56%) et la déposition de fèces des ruminants (18%). Le feu et les termites sont également d'importantes sources d'émissions. Ils représentent à eux deux environ 20% des émissions. Le bilan GES ramené au kg de produit est de 39,6 kg eq.CO_2/kg de poids vif et 9,8 kg eq.CO_2/kg de lait corrigé en protéines et matières grasses (FPCM) pour les bovins et environ 15,8 kg eq.CO_2/kg de poids vif et 7,7 kg eq.CO_2/kg FPCM pour les petits ruminants. Si l'on tient compte de l'accumulation annuelle de carbone (C) dans le sol et les arbres, l'écosystème présente globalement un bilan GES net négatif de -0,1 t.eq.CO_2/ha/an. Autrement dit, les émissions liées au troupeau sont compensées par la séquestration de carbone dans l'écosystème pris dans son ensemble.

Summary

Extensive pastoral systems of sub-Saharan Africa are said to be responsible for the highest rates of greenhouse gas (GHG) emissions per unit of animal products due to the low productivity of herds and the high methanogen potential of diets. This study offers an original GHG balance of a sylvo-pastoral ecosystem including small and large ruminants in the Ferlo, a semi-arid region of Senegal. The main sources of emissions are enteric fermentation (56%) and deposition of ruminants' faeces (18%). Fire and termites, two other important sources of emissions, together contribute to about 20% of emissions. The GHG balances per kg of animal products are 39.6 kg eq. $CO_2.kg^{-1}$ of liveweight and 9.8 kg eq.$CO_2.kg^{-1}$ FPCM (Fat and Protein Corrected Milk) for cattle and roughly 15.8 kg eq.$CO_2.kg^{-1}$ of liveweight and 7.7 kg eq. $CO_2.kg^{-1}$ FPCM for small ruminants. Taking into account annual carbon accumulation in the soil and trees, the net GHG balance is negative: - 0.1 t eq.$CO_2.ha^{-1}.year^{-1}$, i.e. emissions from herds are compensated by carbon sequestration.

1. Introduction

Le rapport de la FAO de 2013 confirme la contribution importante de l'élevage aux émissions mondiales de Gaz à Effet de Serre (GES) d'origine anthropique (Gerber *et al.*, 2013). Ces émissions s'élèvent à 7,1 gigatonnes d'équivalent CO_2 par an, soit 14,5 % des émissions totales d'origine anthropique (Ripple *et al.*, 2014). La croissance démographique et l'évolution des habitudes alimentaires pourraient conduire à revoir ce chiffre à la hausse dans les prochaines décennies (McAlpine *et al.*, 2009; Janzen, 2011). Les principales sources d'émissions correspondent à la production des aliments du bétail (45 %), la fermentation entérique des ruminants (39 %) et la décomposition des déjections animales et autres effluents d'élevage (10 %). Le reste est imputable à la transformation et au transport des produits animaux (Gerber *et al.*, 2013). Cette étude de la FAO montre que l'élevage en Afrique Subsaharienne serait un des plus émetteurs de GES par unité de produit (viande ou lait). Plus particulièrement les systèmes pastoraux sahélien valorisent de vastes superficies de terres jusqu'à présent inutilisées pour l'agriculture et constituent bien souvent la seule activité agricole dans ces milieux caractérisés par une grande variabilité saisonnière et interannuelle des ressources en biomasse végétale et en eau (Touré *et al.*, 2012). Ce sont des systèmes particulièrement complexes car à conduite ouvertes et de par les fortes interactions animal-sol-plantes. Ils sont encore peu étudiés comme l'indique la faible documentation scientifique disponible concernant leur bilan GES. Les seuls résultats disponibles donnent des bilans basés sur des chiffres moyens pour l'Afrique Sub-Saharienne (Steinfeld *et al.*, 2006; Gerber *et al.*, 2013). De façon complémentaire à ces études régionales, cette communication propose un bilan GES d'une étude de cas, l'aire de desserte du forage de Widou au Ferlo, dans la zone semi-aride du Sénégal. Elle permet de faire le lien entre le fonctionnement de l'écosystème sylvo-pastoral et les différents indicateurs des bilans.

2. Matériel et méthodes

2.1. Le système étudié

La région du Ferlo est organisée en un maillage de forages espacés de 30 km en moyenne pour faciliter l'abreuvement des animaux en saison sèche. L'aire de desserte d'un forage a donc été retenue comme unité spatiale d'analyse (cercle de 15 km de rayon autour du forage, soit environ 700 km^2). L'aire de déserte du forage de Widou comporte 354 campements. Son cheptel est constitué majoritairement de ruminants (bovins, ovins et caprins) élevés pour la viande et le lait, et secondairement de monogastriques (asines et équins) utilisés comme force de traction.

Pour réaliser les bilans GES, un modèle conceptuel du fonctionnement de l'écosystème sylvo-pastoral a été proposé (Figure 1.1). Il inventorie les principaux stocks et flux de carbone et azote. En figure 1, l'épaisseur des flèches et des cadres est proportionnelle à l'importance des flux et des stocks respectivement. Le bilan GES ici proposé tient compte d'une part des principales émissions de GES (flèches arrondies vers le haut) et d'autre part des variations de stock de carbone dans l'écosystème. Le système étudié mobilisant peu d'intrants les émissions indirectes en amont du système n'ont pas été considérées.

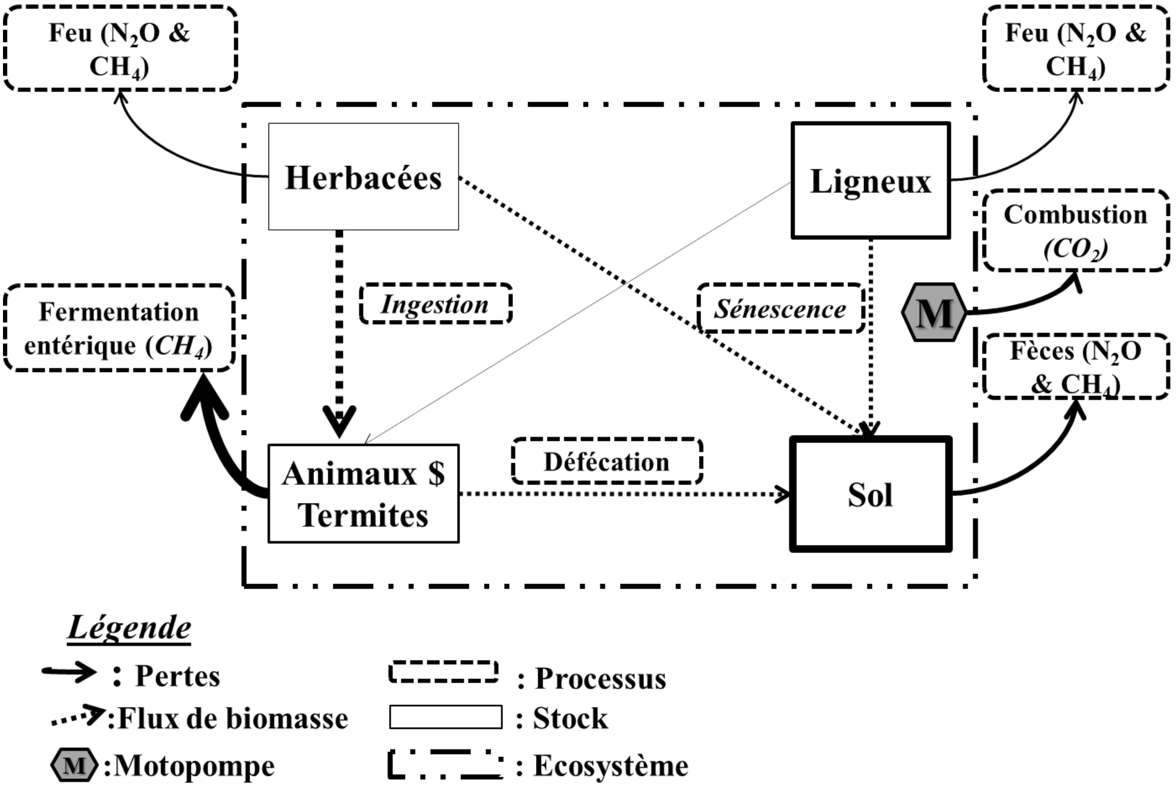

Figure 1. 1. Modèle conceptuel simplifié du fonctionnement d'un écosystème sylvo-pastoral en terme de stock-flux de carbone et azote

2.2. Evaluation des variations de stocks de carbone

Les trois stocks de carbone considérés sont les animaux, le sol, et la végétation ligneuse et herbacée. Pour les animaux, un inventaire complet des troupeaux a été réalisé par enquête auprès des 354 campements. La productivité numérique, le gain moyen quotidien (FAO, 2013), la productivité en lait de toutes les espèces (Houghton *et al.*, 1997; Corniaux *et al.*, 2012) et les facteurs de conversion des biomasses en carbone (Garnier-Laplace *et al.*, 1998) ont permis d'évaluer les variations annuelles de stock de carbone. Pour le sol, une accumulation moyenne de 0,2 t C/ha/an a été retenue (Abberton *et al.*, 2010). Pour la végétation ligneuse, l'équation[1]

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[1] Biomasse aérienne (kg MS/argre)=exp$^{(-1,99662,32\ln(\text{diamètre})}$

proposée par la (FAO, 1997) a été utilisée pour évaluer la croissance de la biomasse aérienne en considérant un accroissement moyen de circonférence annuel de 2,2cm proposé par Woomer *et al.* (2004). La biomasse souterraine a été estimée à 38% de la biomasse aérienne (Woomer *et al.*, 2004). Pour la végétation herbacée un bilan nul a été retenu étant donné la dominance de plantes annuelles entièrement consommées ou dégradées à un pas de temps annuel.

2.3. Evaluation des principales émissions de GES

Les émissions (CH_4, N_2O) liées aux troupeaux ont été évaluées selon la méthode IPCC Tiers1 (IPCC, 2006). Les émissions de CH_4 liées à la présence des termites ont été calculées selon les facteurs d'émission proposés par (Traoré *et al.*, 2008). Les émissions de gaz (CO_2, CH_4, N_2O) résultant du feu ont été évaluées suivant les lignes directrices de l'IPCC tandis que celles liées à la combustion de Gasoil de la Motopompe (CO_2) selon le facteur d'émission proposé par l' (ADEME, 2010).

2.4. Trois types de bilan GES calculés

Trois types de bilan GES sont calculés dans cette étude. Le bilan GES brut par kg de produits animaux correspond à la somme des émissions liées à la catégorie animale considérée (bovins ou petits ruminants) ramenée à la production de cette catégorie en kg de viande (en kg de poids vif) ou de lait (en kg de lait corrigé, FPCM pour Lipides-protéines corrigé lait ou en anglais «fat and protein corrected milk»). Le bilan GES brut à l'échelle de l'écosystème par ha ou par habitant comptabilise l'ensemble des émissions intervenant dans le territoire considéré à savoir les émissions liées aux activités d'élevage mais aussi celles liées aux termites et aux feux. Enfin le bilan GES net à l'échelle de l'écosystème correspond au bilan GES brut à l'échelle de l'écosystème auquel a été retranchée la variation de stock de carbone des trois principaux stocks de l'écosystème (sol, végétation et animaux). Seul le bilan GES brut par kg de produit intègre une allocation entre la viande et le lait. Cette dernière est de type protéique.

3. Résultats

3.1. Cheptel présent

Le cheptel recensé dans l'aire de desserte du forage de Widou est de 24625 Unités Bovin tropical (UBT, équivalent de l'UGB en contexte tropical) soit un chargement animal de 0,35 UBT/ha. La population totale humaine est évaluée à 4 676 habitants (hab) soit une densité humaine de 7 hab/km^2.

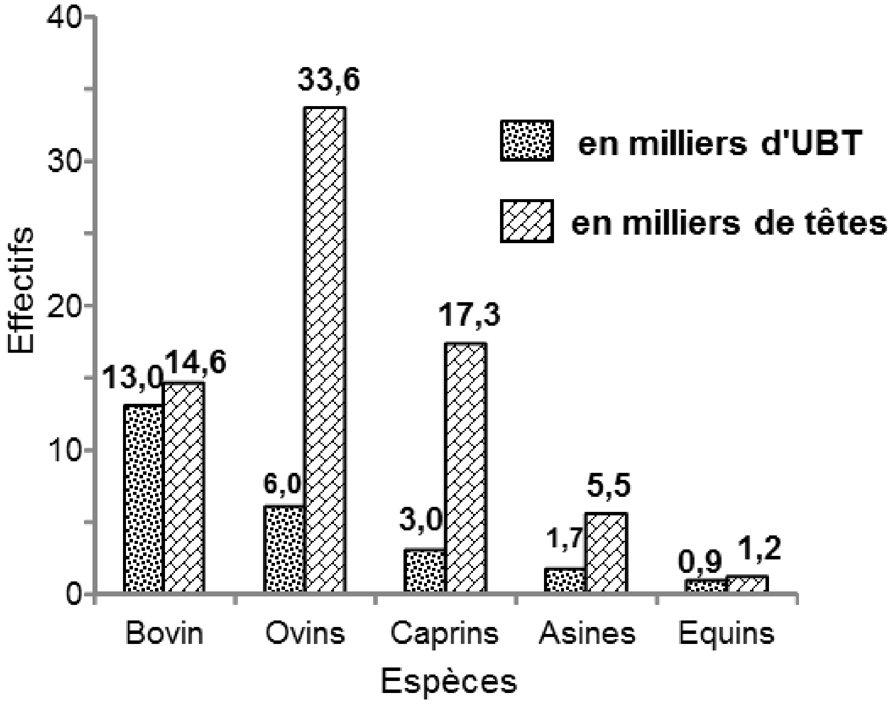

Figure 1. 2. Composition du cheptel autour du forage de Widou (données personnelles)

La répartition de la population animale par espèce est donnée en Figure 1.2. Les ruminants (bovins, ovins et caprins) représentent la majorité des effectifs (89% en têtes). Les autres herbivores (asins et équins) représentent environ 11% de tout le cheptel et sont un ensemble non négligeable dans le fonctionnement de l'écosystème. Ils sont largement mobilisés pour le transport de l'eau destinée entre autres à l'abreuvement des animaux maintenus à proximité des campements (jeunes animaux, femelles en fin de gestation).

3.2. Accumulation de carbone dans l'écosystème

L'accumulation annuelle de carbone dans tout l'écosystème en considérant les trois principales composantes (sol, végétation et animaux) est de 54,44 kt eq.CO_2/an. Le sol constitue le principal réservoir de carbone de l'écosystème et l'accumulation de carbone y est très largement supérieure à celle des végétaux et des animaux (Figure 3).

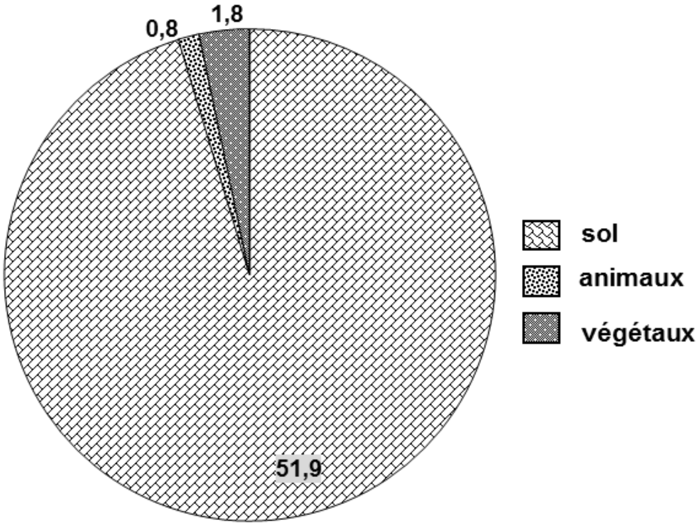

Figure 1. 3. Accumulation de carbone dans les principaux stocks de l'écosystème sylvo-pastoral (en kt eq.CO_2/an)

3.3. Principales émissions de l'écosystème

Le total des émissions de GES de l'écosystème est de 47,56 kt eq.CO_2/an. La Figure 1.4 indique la répartition de ces émissions selon leurs principales sources. Les ruminants y jouent un rôle majeur (74% des émissions totales). Elles correspondent principalement à la fermentation entérique (56%), le reste étant la déposition au sol des déjections animales (18%). Les termites et le feu sont également des sources non négligeables. Ils contribuent à environ 20% des émissions totales. Les non ruminants (asins et équins) contribuent seulement à hauteur de 6% des émissions totales.

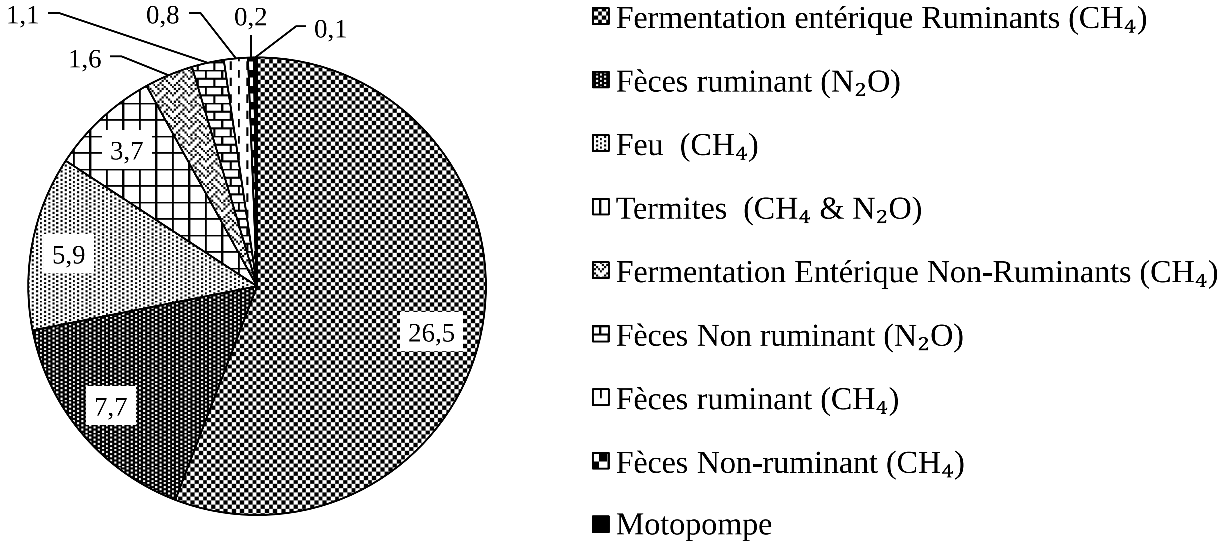

Figure 1. 4. Principales sources d'émission de GES (en kt eq.CO2/an)

3.4. Bilans GES

A l'échelle de l'écosystème, le bilan GES brut est de 67,14 kg eq.CO_2/ha et de 17.1 kg eq.CO_2/habitants. Les bilans GES bruts ramenés au kilogramme de produits animaux sont de 39,6 kg eq.CO_2/kg de poids vif et 8,9 kg eq.CO_2/kg FPCM pour les bovins et de 15,8 kg eq.CO_2/kg de poids vif et 10,8 kg eq.CO_2/kg FPCM pour les petits ruminants. En intégrant les variations annuelles de stocks de carbone dans le bilan on obtient un bilan net négatif de - 0,10 t eq.CO_2/ha/an.

4. Discussion

Les figures 5 et 6 comparent les résultats obtenus dans cette étude avec ceux disponibles dans la littérature (Gerber *et al.*, 2013). Les bilans bruts par unité de produit (viande et lait) restent globalement élevés et légèrement au-dessus de ceux proposés par la FAO (Figure 1.5). Ces valeurs élevées s'expliquent par la productivité particulièrement faible des troupeaux et de la faible digestibilité des fourrages en systèmes pastoraux (Herrero *et al.*, 2013). Cette étude confirme également l'importance des feux (Koppmann *et al.*, 2005; Lesschen *et al.*, 2011) et des termites (Jamali *et al.*, 2011) dans le bilan GES des écosystèmes sylvo-pastoraux tropicaux.

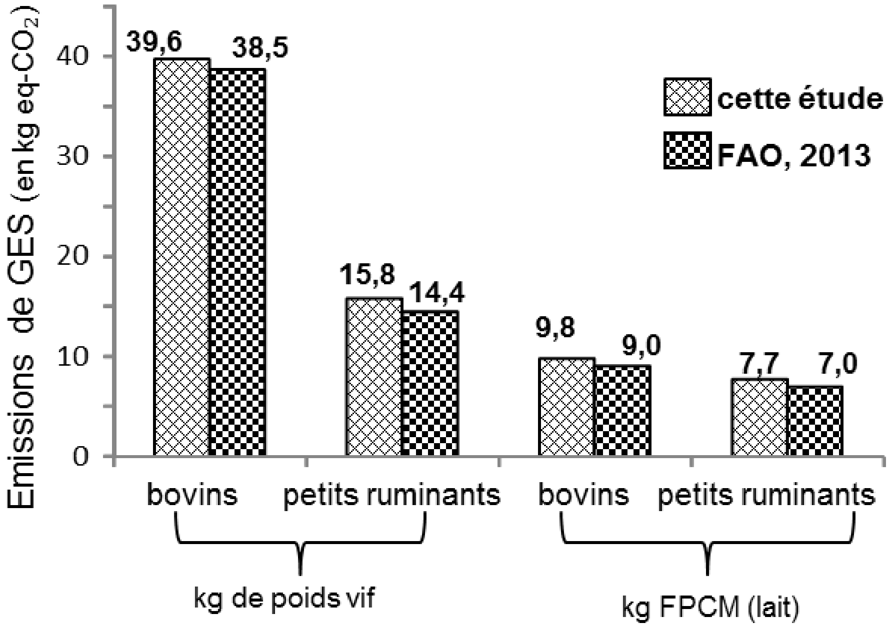

Figure 1. 5. Bilans GES brut par kg de produits animaux et par espèce

Le bilan net à l'échelle de l'écosystème est négatif. Cela signifie que les émissions sont compensées par la séquestration de carbone dans le sol et la végétation. Le potentiel d'atténuation par la séquestration dans le sol sous prairies a déjà été montré par différents travaux (Soussana *et al.*, 2004; Soussana *et al.*, 2010a). Les auteurs ont également obtenu dans les prairies d'Europe conduite de manière extensive un bilan GES net négatif de -0.38 à -0.92 t eq.CO_2/ha/an (-0,97 t eq.CO_2/ha/an dans notre étude au Sénégal). En Europe, l'herbe consommée par les animaux est non seulement plus digestible et moins méthanogène, mais aussi au regard de la littérature il semblerait que la capacité de séquestration de C dans le sol sous prairies permanentes tempérées soit plus élevée : 0,2 à 0,5 tC/ha/an en Europe (Soussana *et al.*, 2010a) versus 0,1 à 0,25 tC/ha/an en zones sèches d'Afrique de l'Ouest (Abberton *et al.*, 2010).

Le bilan GES net de l'écosystème sylvo–pastoral au Sénégal est sensible à ce facteur de séquestration. Pour le Sénégal, un chiffre moyen de 0,2 tC/ha/an a été retenu. En hypothèse basse (facteur de séquestration de 0,1 tC/ha/an) le bilan GES net de l'écosystème sylvo-pastoral serait positif de 0,27 t eq.CO_2/ha/an. Des références supplémentaires sont donc nécessaires pour réduire l'incertitude liée à ce paramètre. Le sol est en soit un écosystème encore plus vaste que le rumen des animaux dont il faudrait à l'avenir mieux décrire la dynamique sur le temps long. La capacité de séquestration du C du sol sur parcours dépend des conditions climatiques (Hunt *et al.*, 2004; Ciais *et al.*, 2005; Gilmanov *et al.*, 2007; Soussana *et al.*, 2010a). Elle dépend également d'un ensemble de pratiques de gestion, telles que les rythmes de mise en feu (Suyker and Verma, 2001) et de déplacements des troupeaux qui conditionnent la charge animale et la pression de prélèvement exercée par les ruminants (Ammann *et al.*, 2007). En systèmes pastoraux, ces deux pratiques sont fortement variables dans le temps et l'espace, elles sont en interaction forte avec le cortège floristique et le recouvrement végétal, deux éléments essentiels de la dynamique du C dans le sol.

La principale limite de cette étude est quelle se focalise sur une année donnée sans évaluer la variabilité intra et inter-annuelle du bilan GES. En effet, les fortes variations intra-annuelles du disponible fourrager conditionne le déplacement des animaux à l'intérieur de l'aire de desserte du forage et la transhumance d'une partie du cheptel du forage en dehors du territoire considéré en période de pénurie fourragère. Cette variation du disponible fourrager occasionne également une variabilité saisonnière du régime alimentaire des animaux et des émissions de méthane résultantes. Or cette étude propose une taille de cheptel moyen et un facteur d'émission de CH_4 moyen par catégorie d'animaux (selon un régime alimentaire moyen). Ces variations sont également observées d'une année à l'autre du fait d'une pluviosité annuelle particulièrement variable (422.6±126.8 mm/an ; (Ndiaye *et al.*, 2014a)). La capacité de charge et de production de l'écosystème est donc variable et conditionne très probablement son bilan GES annuel.

5. Conclusion

Mener des études précises sur les systèmes d'élevage en zones tropicales permet de montrer que derrière les chiffres moyens régionaux proposés par la FAO se cache une variété de systèmes ayant des impacts variables. Par exemple, les bilans GES brut par kg de produit obtenus dans cette étude sont plus élevés de 3 à 10% que les résultats régionaux proposés par la FAO pour l'Afrique Sub-saharienne (selon l'espèce et le type de produit). En effet les systèmes d'élevage pastoraux sont particulièrement peu productifs et ils valorisent des ressources fourragères hautement méthanogènes.

Il est également intéressant de réaliser des bilans GES à l'échelle de l'écosystème intégrant une compréhension de son fonctionnement grâce à une quantification des principaux stocks/flux de carbone et azote. Dans notre étude de cas, l'importance des ruminants dans le bilan GES est confirmé, leurs émissions entériques ainsi que les émissions liées à la déposition de leurs déjections représentent 74% des émissions totales de GES. Cependant d'autres sources sont également importantes telles que le feu et les termites (environ 20% des émissions à eux deux). Et cette étude confirme la possibilité d'une compensation des émissions par la séquestration du C dans le sol et la végétation en zones tropicales sèches. Un bilan GES à l'échelle de l'écosystème facilite donc la mise en évidence des options d'atténuation potentielles.

Cependant les chiffres proposés dans cette étude restent des moyennes annuelles ne tenant pas compte de la forte variabilité intra et interannuelle des pluies et du disponible en ressources fourragères. Or elle sous-entend de fortes variations de la capacité de charge et de la productivité des troupeaux, ce qui se traduit très certainement par un bilan GES fortement variable selon les saisons et les années. Par conséquent, cette étude doit être approfondie par un suivi mensuel et pluriannuel des différents flux de carbone et d'azote dans l'écosystème.

Conclusions intermédiaires et transition

Ce premier chapitre suggère l'importance de la contribution de l'élevage au bilan GES des territoires sylvo-pastoraux en conditions semi-arides. Il permet de constater sur la base de calcul suivant une approche IPCC Tiers 1 que ces écosystèmes pourraient en moyenne compenser l'ensemble de toutes les émissions de GES par la séquestration de C intervenant dans les principaux compartiments de l'écosystèmes à savoir le sol, les arbres et les animaux.

Cette première étape a été déterminante pour cette thèse en ce sens qu'elle a permis d'élaborer et de définir un dispositif de mesure complexe et original. Ce dernier permet de quantifier les principales sources d'émission de GES et les principaux réservoirs de Carbone et d'avoir une vision relativement complète du fonctionnement de l'écosystème étudié.

Selon ce premier bilan (Chapitre 1), les émissions entériques des animaux jouent un rôle déterminant, elles représentent 59% des émissions totales du GES du territoire. Elles font donc l'objet d'une attention particulière dans le chapitre suivant (Chapitre 2). Un suivi des troupeaux dans le temps a donc été mis en place afin de comprendre le fonctionnement de ce type d'élevage extensif très particulier d'un point de vue purement zootechnique. Les connaissances zootechniques produites permettent de préciser le facteur d'émission correspondant aux émissions entériques.

Chapitre 2 : Conséquences du comportement spatial et alimentaire des troupeaux sur les émissions entériques des animaux en territoire sylvo-pastoral

Ce deuxième chapitre essentiellement zootechnique se base sur un article qui sera soumis dans la revue Animal. Il s’agit de:

Assouma M. H., Lecomte P., Hiernaux P., Corniaux C., Ickowicz A., Vayssières J. Herders adjust livestock stocking to resources availability and quality: impact of the feed intake and digestibility on the grazing efficiency and enteric methane emission in a Sahelian pastoral landscape. To be submitted to Animal

Abstract

Pastoralism is practiced over more than a quarter of the world's land surface, in rich and poor countries, and contributes significantly to both food production and management of natural resources. It is estimated that the livestock sector, with 14.5 % of global anthropogenic greenhouse gas (GHG) emissions, plays an important role in climate change. Sub-Sahara African (SSA) livestock systems suffer from a criticism about their impact when GHG emissions of these systems are expressed per kg of product, due to their limited productive efficiency and their large enteric emission rates related to the seasonal variability of the forage resources quality. But most assessments are based on regional livestock populations and default emission factors (IPCC Tier 1 method) or calculated with a semi detailed approach of the diet a priori consumed (IPCC Tier 2 method). The objective of the study is to improve the assessment of the year round and seasonal livestock natural forage resources balance and discusses its consequences in terms of grazing efficiency, and resulting fluxes including enteric methane emission.

This chapter presents a case study of a typical sylvo-pastoral landscape in the semi-arid zone of Senegal where mobile livestock and human activities are organized around a network of boreholes and temporary ponds. The case study covers an area close to 707 km² within the influence of the Widou Thiengoly borehole. The monitoring of the livestock populations present over time and the assessment of livestock performances and pressure on the resources were achieved throughout the investigation of 354 pastoral households and their herds, the monthly survey of 40 herds movements, completed by a retrospective survey of 12 herders. Available forage over the studied area has been monitored using destructive sampling of standing vegetation, and the forage grazed has been estimated by the hand plucking method. Finally the NIRS related methods were used on forage daily diets (75 samples) and feces (816 samples) to estimate the assessment of feed intake, digestibility and to calculate excretions and derive methane emissions.

The livestock population of the pastoral households living within the studied area varies between 49 926 – 116 227 heads or 15 274 – 33 095 TLU (Tropical Livestock Unit, cattle 60%, sheep 20%, goats 5%, horses 5% and donkeys 10%) corresponding to 1.1 – 2.55 kt of total metabolic weight. The stocking rate of the effective rangelands (680 km²) within the Widou Thiengoly borehole service area fluctuates largely (0.22-0.48TLU/ha), depending on the available herbaceous forage mass and the herder's management strategies. The sex-and-age structures of cattle herds and sheep flocks indicate a large dominance of females as expected from the reproduction objective of the pastoralists. Based on the livestock mass within the studied area the simulated intake cumulated over the year appears less than 30% (27.06 kt DM) of the available herbaceous mass at the peak of abundance. The mass of the forage grazed by cattle ranges between 6.3 kg DM/TLU/day in the wet season and particularly low values ranging between 1.5 and 2 kg DM/TLU/day in the hot dry season. The yearly average of the daily intake is estimated at 3.67 kg DM/TLU/day. For the cattle, according to intake and digestibility of the diet, methane emission varies from 1.49±0.02 in May to 2.84±0.02 kgCH$_4$/hd/month in September cumulating at 23.4±0.17 kgCH$_4$/hd/yr. Enteric methane emission from sheep is between 0.46±0.00 in May to 0.99±0.01 kgCH$_4$/hd/month in September cumulating at 7.37±0.06 kgCH$_4$/hd/yr. While for the goats, enteric methane emission varies from 0.48±0.01 in April to 0.89±0.01 kgCH$_4$/hd/month in September cumulating at 7.34±0.10 kgCH$_4$/hd/yr. Totalized CH$_4$ emissions for the whole ruminants population (animal movements taken into account) varies between 0.30±0.01 kgCH$_4$/ha/month in hot dry season to 0.62±0.01 kgCH$_4$/ha/month during the wet season and cumulating to 5.54±0.03 kgCH$_4$/ha/yr. Enteric methane emissions intensity were 16.77±0.12 kg CO$_2$-eq/kg CW (carcass weight) and 1.75±0.01 kg CO$_2$-eq/kg FPCM (fat and protein corrected milk) for cattle, 8.16±0.04 kg CO$_2$-eq/kg CW and 0.85±0.01 kg CO$_2$-eq/kg FPCM for sheep and 7.62±0.08 kg CO$_2$-eq/kg CW and 0.79±0.01 kg CO$_2$-eq/kg FPCM for goat. These values highly differ from the actual literature.

Keywords: Stocking rate, forage intake, forage digestibility, Faecal NIRS, enteric methane

1. Introduction

The vegetation growth in sahelian rangelands is driven by the highly seasonal rainfalls brought by the convective storms of the West African monsoon that reaches the Sahel in summer between June and October with a peak rainfall in August (Nicholson, 2013). Mean annual rainfall decreases with increasing latitude, however, all over the Sahel gradient, rainfalls are patchy (Ali *et al.*, 2003) and are highly variable between years (Lebel and Ali, 2009). In contrast with the short hot and humid wet season, the dry season lasts 8 to 10 months with very low air humidity associated to mild temperatures from November to February and to extremely hot temperatures from March to the first rains (Guichard *et al.*, 2009). In adaptation to the regular rainfall seasonality, solar radiation, temperature and air humidity, the herbaceous vegetation is largely dominated by short cycle annual plants, associated with more or less scattered woody plants among which deciduous plants dominate (Hiernaux and Le Houerou, 2006). Annual herbaceous plants germinate with the first rains, sometimes between May and July depending on years and locations. Their growth starts slowly for a couple of weeks during which grasses seedlings establish their rooting system and tillers (Cissé, 1986). Then, when the soil moisture allows it, the growth of the plants is very fast (up to > 45 kg dry matter/ha/d) for about three weeks during which grasses head and flower (Hiernaux *et al.*, 2016). Growth then progressively decreases during fructification followed by the wilting and the death of annual plants rapidly turning out to standing hays. The vegetation composition strengthen the high seasonal contrast in grazing resource quality with highly nutritious growing annuals available during the few weeks in the wet season followed by poorly nutritious straws and litters for months in the dry season (Fernández-Rivera *et al.*, 2005). Only a few evergreens and long cycle deciduous woody plants (the air humidity is too low for succulents) provide complementary fodder, richer in protein although often poorly digestible (Le Houerou, 1989).

In such environments livestock mostly adapt to the local resource availability. Pastoral husbandry is taking advantage of the high quality of the rangeland forage selectively grazed in the wet season (Ayantunde *et al.*, 1999) to grow and built fat reserves that the animal will progressively burn during the long dry season to compensate for the poor digestibility of the forages and attenuate losses in condition (Ezanno *et al.*, 2003). Moreover, herders help livestock adaptation to resources scarcity through daily feeding management and transhumance strategies. Year round, livestock recycle about approximately half of the organic matter and larger fractions of the nutrient intake through their faeces and urine excretions (Lançon, 1978). Part of the recycling occurs along grazing itineraries; however excretion get also concentrated where livestock are resting and ruminating: around the water points (shallow ponds) in the wet season and early dry season, around borehole the rest of the year; around the pastoral settlements, but also in the pastoral settlements corrals from which part of the manure is harvested to manure small cropped fields (Schlecht *et al.*, 2004). It results in a spatial transfer of organic matter and nutrients from large rangeland areas to concentrated spots of higher soil fertility that benefit either to crop yield and diversification (vegetable gardening, cash crops), or to biodiversity (Gandah *et al.*, 2003). Yet, the concentration of livestock excretion also contributes to locally increase the soil emissions of green-house gases (GHG: N_2O, CH_4 in particular) (Assouma et al. 2016 in press). Moreover, concerns have been raised for a long time (Boudet, 1972; Dodd, 1994) about the risks of rangeland degradation due to grazing pressure in the Sahel pastoral system: increased livestock numbers having to feed on shrinking rangeland areas (Touré *et al.*, 2012). However, little evidence of such degradation is really observed over time at least, at large landscape scale (Dardel *et al.*, 2014a). Indeed, annual herbaceous vegetation's are only sensitive to grazing during their growth, a few weeks in the year (Hiernaux and Turner, 1996) during their active vegetative period. Most of the grazing applies during the long dry season on largely senescent or dead standing straws and litters, with unavoidable trampling helping to fragment and bury the litter, limiting intake to at most one third of the initially existing herbaceous biomass at the onset of the dry season (Hiernaux *et al.*, 2016). This trampling effect adds up to the considerable amounts of biomass recycled through faecal excretions, and both contribute to speeding up further organic matter cycling and mineralisation in the soil, enhancing the plant production potential generally limited by nitrogen and phosphorus availability during the wet season (Penning de Vries and Djiteye, 1982).

Beside these positive ecological contributions, global assessments of the contribution of grazing livestock to the GHG emissions underline that 68% of total GHG emissions can be attributed to enteric fermentation (methane emission) for pastoral livestock in Sahel (Gerber *et al.*, 2013). Yet, the assessment of enteric methane part of these emissions based on standard annual mean intake and digestibility estimations is prone to approximations, considering that both intake quantity and quality of the forage ingested largely vary throughout the seasons.

The objective of this study is to improve the assessment of the year round and seasonal livestock forage resources balances and estimates the consequences in terms of grazing efficiency, and resulting fluxes including enteric methane emissions. This study was based on large series of data and samples collected in a pastoral livestock system grazing Sahelian rangeland and on the monitoring of the vegetation and of the livestock herds. Beside inventory approaches on vegetation and herds the study takes opportunity of Near Infrared Reflectance Spectroscopy (NIRS) methods applied on both the forage diets and the faeces samples collected during one year to monitor the quality of the diet and the level of intake variations.

Because Sahel rangelands are generally communal and managed by large groups of families, the study is performed at the scale of the service area of a borehole (named Widou Thiengoly) and includes the monitoring over a year cycle of all rangelands resources, herds and pastoral household within a 15 km radius around the borehole; this circular area being considered the Service Area of the Widou Thiengoly borehole (WTSA) (Figure 2.1).

There are relatively few reliable whole year monitoring describing the extensive livestock uses of the vegetation under arid and semi-arid climate in sub-Saharan Africa (Guérin *et al.*, 1986; Schlecht *et al.*, 1999; Chirat *et al.*, 2008). Those results all converge to stress the strong seasonality of livestock production in relation with nutrition, reflecting resource condition and adapted feeding practices. To develop an integrated and comprehensive view, a monitoring of the interacting components of the landscape and of the pastoral system has been undertaken over the WTSA (Figure 2.1) from May 2014 to October 2015.

The pastoral specificities of the WTSA are summarized in the material and methods in chapter 4. The present chapter focuses on the methods used to monitor the forage resource available over the area, and its use by livestock is described, together with the methods to assess livestock populations present over time and livestock pressure on the resource in the area, to assess livestock production and finally the NIRS methods used on forage and faeces to estimate feed intake, digestibility and calculate excretion and methane emission. Results are presented starting with the livestock population numbers and assessment of livestock annual production; followed by the availability of forage resources and their seasonal dynamics, and finally, the seasonal and annual estimations on feed intake, digestion and enteric gas emission are presented. The discussion focuses on the shift in feed intake, digestibility, and enteric gas emission resulting from the NIRS method compared to classical norms and field observations based on hand-plucking. The implication of these observations on global assessment of Sahel pastoral production and environment impact are drawn to conclude.

2. Material and methods

2.1. The Sahelian pastoral ecosystem at Widou Thiengoly

The study was conducted from June 2014 to October 2015, within the WTSA (15°59'N, 15°19'W, elevation 20 m) located in the "6 boreholes sylvo-pastoral reserve" in the Koya natural region of Western Ferlo in Northern Senegal. The boreholes having been dug roughly 30 km apart from each other, the service area of a borehole such as Widou Thiengoly is conventionally set to a circular area of 15 km radius centered on the borehole (707 km²).

A Sahelian climate. The climate at Widou Thiengoly is semi-arid tropical influenced by the West African Monsoon (Martínez *et al.*, 2011). The bioclimate is classified as 'semi-arid steppe hot', BSh in (Köppen, 1936) classification with an Aridity Index of 0.24. Annual rainfall ranges between 105.4 and 478.4 mm/yr, with an average of 285.8 ± 84.2 mm over the period 1974-2015 for the Widou station. Rains are distributed on 19±4 days during a unique wet season (WS) from July to October. In 2014-2015 total rainfall was 204 mm with early rains from July 3rd to August 21st separated from later rains by 41 dry days. The monsoonal wet season is characterized by large variations in temporal and spatial rainfall distributions that impact the annual yield and the timing and spatial distribution of the herbaceous vegetation mass. Over 2014 and 2015 the mean air temperature 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 (Valentini *et al.*, 2014). Temperatures differentiate the Cold dry season (CDS) from November to February and the Hot dry season (HDS) from March to June.

Rangelands on sandy soils. The Koya is a flat region covered with a fixed sand dune system oriented North-East to South-West and lying above sandy loam Tertiary sediments. The predominant soils are slightly leached ferruginous soils on the dunes and arid red-brown soils in the inter-dunes flats. The vegetation over the dunes is an open shrub savanna dominated by annual grasses such as *Aristida mutabilis*, *Cenchrus biflorus*, *Eragrostis tremula* and *Brachiaira xantholeuca* with scattered shrubs and low trees among which *Combretum glutinosum*, *Sclerocarya birrea*, *Acacia raddiana* and *Balanites aegyptiaca*. The woody plant canopy cover did not exceed 5% of the area. The interdune savanna is also dominated by annual grasses among which *Schoenefeldia gracilis*, *Dactyloctenium aegyptiacum* and *Chloris prieurii* and also the legume *Zornia glochidiata* but woody population is denser and more patchy than on the dunes, with a few scattered large trees among which *Adansonia digitata* and *Anogeissus leiocarpa* and thickets with *Combretum micranthum*, *Guiera senegalensis*, *Grewia bicolor* and *Boscia senegalensis*.

The WTSA (707 km²)? comprised six different landscape units (Figure 1) based on topography, soils, vegetation and land use. The vicinity of the borehole (0.78 km², 0.1%) and the 354 pastoralists family settlements (44.46 km², 6.3%) are distinguished from the temporary ponds and surroundings in the low lands (19.34 km², 2.7%) and the dominant communal rangelands (635.45 km², 89.9%). Also separated, are tree plantations established by reforestation projects (6.23 km², 0.9%) and small rangeland protected enclosures (0.24 km², 0.03%) set in 1981 by an experimental ranching project (Miehe *et al.*, 2010).

A pastoral land use. The main land usage in the WTSA is the communal grazing by a livestock population dominated by cattle (*Bos indicus)* mostly of the local *Gobra* breed (a few *Moorish* and *Gudali* breeds), associated to sheep (*Ovis aries)* of the local *Sahel* and *Toronké* breeds and goats (*Capra aegagrus hircus*) of local *Sahel* breed. Donkeys are raised as pack animals ensuring water transport from the borehole to camps, as well as horses are kept for goods and furniture transports to and from the market, and houseware transport when families are moving camps. Grazing occurs year-round with occasional transhumance out of the service area when feed resources become too scarce. Reciprocally, livestock from pastoralists from other locations may stay for a while in the WTSA, if the rangeland resources are in better conditions than theirs. Widou Thiengoly has been equipped in 1950 with a borehole (200 m deep, 50m^3/hour) and a motor pumping system. 354 pastoralist families live in settlements spread across the service area dependent of the borehole for livestock watering after the ponds have dried up, early in the dry season. They also rely on the village that progressively established near around the borehole for public services and market. The total population of the WTSA is estimated at 4800 inhabitants among which 51.3% are females and 68.8% are children, setting the population density over the service area to 6.0 hab km^{-2}. All the ponds dry up rapidly early in the dry season (November-December), and the water for human and for livestock consumption is then only provided by the borehole, provided that there is no pump failure. Feed resources strongly decline during the dry season, and many pastoralists progressively migrate with part of the more mobile animals southwards, up to the more humid Sudan savanna zone where livestock graze the regrowth of perennial grasses such as *Andropogon gayanus*, browse trees and also feed on weeds and crop residues left in the fields (Leclerc and Sy, 2011). Main transhumance occurs between March and May in rainy years but may start between January and March in low rainfall years. Permanent surface water, wells and boreholes along the itineraries and at destination allow the transhumance (Hein *et al.*, 2008). The mobility of the herds *de facto* regulates the grazing pressure on rangelands in adaptation to forage availability. With the return of the rains (starting from June to August), the herders and animals return back to their main home settlements.

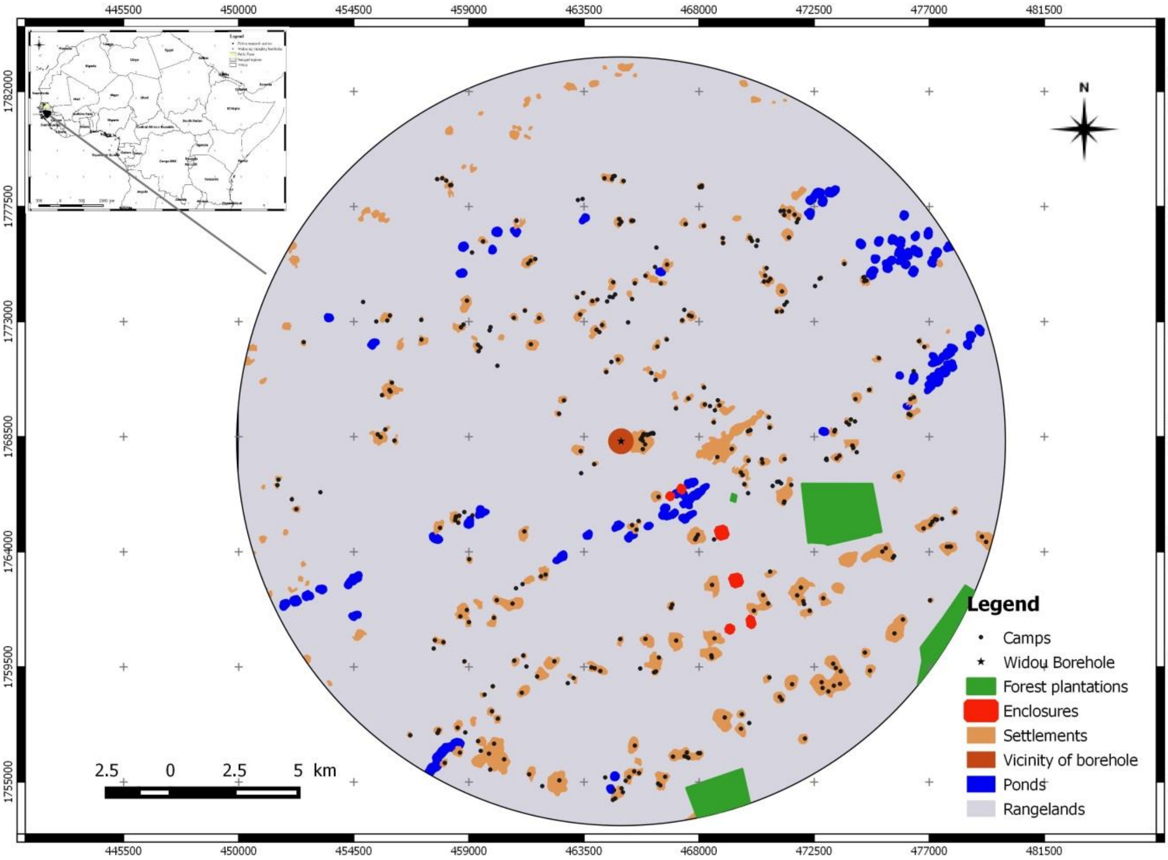

Figure 2. 1. Widou Thiengoly service area WTSA (15°59’N, 15°19’W, elevation 20 m), main landscape units

2.2. Monitoring livestock numbers and performance

A monthly survey was conducted over a year to assess the livestock population that remained within the WTSA or that had moved out of it in transhumance. A sample of 40 herds selected in the 354 settlements to cover the different classes of herd size (i.e. small, medium and large herders) was surveyed monthly from June 2014 to September 2015. The number of animals by sex and age classes: male, female, young and adult of each species; cattle, sheep, goats, donkey and horses; the number of animal death births, sales, purchases, loans and entrustments that occurred during the previous month, and the number of animals sent on transhumance out of the WTSA were systematically recorded with the herd manager at each visit. During this survey, amount of milk sold was also recorded. Total milk produced was estimated based on annual average milk production for sahelian cow (226.7 l/cow/ yr) as proposed by Corniaux *et al.* (2012) in Senegal and 38.8l/head/yr for small ruminant proposed by (IPCC, 1996).

To calculate the main livestock production parameters the herd monitoring was complemented by a retrospective herd dynamics survey based on the “12MO” method (Lesnoff *et al.*, 2013) designed to estimate annual demographic parameters in ruminant livestock populations

(Lesnoff, 2015). This retrospective survey was carried out with 12 herd managers carefully selected among the keepers of the 40 herds monitored to represent the 354 pastoralists of Widou Thiengoly. The survey was only applied to cattle and sheep; the two main ruminant species present in all pastoral camps.

During interviews, the enumerators enquire each animal present in the herds at the date of the survey and describe its sex, age and the parity of the adult females. Then the enumerators collected precisely the demographic events (births, natural deaths, slaughtering, loans, entrustments, sales, purchases, etc.) that occurred in the herd over the 12 months preceding the date of the survey, specifying the sex and when applicable the age of the animal. The annual demographic *rates*: parturition, prolificacy and mortality *rates* were calculated as suggested by Lesnoff *et al.* (2011). The calving *rate* is calculated as the average number of parturitions per reproductive female having spent all the year in the herd, the net prolificacy *rate* as the average number of offspring born alive per parturition and the mortality *rate* as the number of natural death referring to all types of death except off take relative to the mean number of animals in the herd during the year. Two synthetic *rates* were further derived from the basic *rates* in order to summarize the dynamics and productions of the herds over the year cycle: annual growth *rate* and the production *rate*. To estimate productivity parameters, standardized live weights (LW) were attributed to the different categories (Appendix 1).

To address the link between animal mass and vegetation, the concept of tropical livestock units (TLU) provides a convenient method for quantifying a wide range of different livestock types and sizes in a standardized manner. The numbers of livestock in the different species were converted into Tropical Livestock Unit using TLU conversion factors (Appendix 1) for the different livestock species based on their live weight as described in (Jahnke, 1982). The standard used in this study for one TLU is one cattle with a body weight of 250 kg. The animal/resource interaction may further be estimated assuming "*a priori*" average daily dry matter intake of 2.5% of bodyweight, each TLU consuming 6.25 kg of forage dry matter (DM) per day (Boudet, 1984).

This standard however is general and most of all provisional to fully cover the animal needs. It does not take into account the differences between categories, species and metabolic size of the animals. The dry matter voluntarily ingested by the animal increases non linearly with its bodyweight. The increase is related to the energy requirements of which a large part is the maintenance. Reported to body weight (BW), the voluntary dry matter intake decreases according to the conformation of the animal. It remains almost constant if it is related to a power of the body weight which is between 0.60 and 0.75 (Jarrige 1978). Internationally, it is recognized in most systems a factor of 0.75 in the expression of which is then referred to as the metabolic weight of the animal ($P^{0,75}$). This allows, for a given animal species, the expression in terms of net energy requirements in calories (MCal) or the uniform expression of the voluntary intake of the animal in g dry matter per kg of metabolic weight. Along to total numbers, stocks of animals in the WTSA were calculated as TLU, live weight and metabolic weight.

2.3. The survey of forage resources and their use by livestock

The available herbaceous mass within the WTSA is assessed through systematic observations and standing biomass destructive measurements on a set of 15 sites selected to represent the six landscape units mapped inside the service area (Figure2.1). Because 'communal rangelands' extend on a large proportion of the area, the unit is sampled at 5 sites while the five other landscape units are sampled at 2 sites each. To account for the spatial heterogeneity of the herbaceous mass in each of these sites, the herbaceous layer was stratified into four strata based on the apparent bulk of the herbaceous layer: either nil in bare soil patches, low, medium or high vegetated patches (Dardel *et al.*, 2014b). The frequency of each strata was assessed, by visual estimate and classification of the herbaceous layer every meter within a 1 m wide band along a 500m long transect (Hiernaux *et al.*, 2009c). Total and green vegetation cover (visual estimates as % cover), standing and litter mass (destructive cutting, with harvest, air drying and weighing) are assessed in three 1 × 1 m plots randomly sampled in each strata along the transects. The total herbaceous mass of the site was then computed by weighting the mean mass per strata by the strata frequency along the 500m. Eight measurements were performed from July 2014 to May 2015 (monthly during the wet season from July to October and every two months in the dry seasons). Additional observations and measurements of the herbaceous mass were carried out in September 2015 at the peak of standing mass, in order to compare with the mass observed in September 2014 and to illustrate the variability of the herbaceous production between years. Total monthly available vegetation was calculated according to recorded landscape unit areas.

Furthermore, animal grazing behavior was monitored to assess the proportions of the forage components grazed by livestock. The survey involved 5 herds and reference adult cows that were monitored monthly during 24 h for 17 consecutive months as described in Schlecht *et al.* (2006). The hand plucking method developed by Guérin *et al.* (1986) and validated by Wallis

De Vries (1995) was used to sample the daily forage intake of each animal (Chirat *et al.*, 2014). Hand-plucking was performed by a same person for each animal monitored from sunrise to the next sunrise, in order to obtain a representative sample of forage consumed by the animal at that date. Daily plucked samples were collected in 50-L bag. The bags were weighed on the next day, sorted in three main forage categories (grasses, herbaceous forbs and woody plant leaves) in order to assess the mass and composition of the diet. The sorted diet components were dried in a forced-air oven at 65°C for 72 h to determine dry matter (DM) content. Sub-samples were grinded at 2mm. The mass proportion of the three categories of forage was used to reconstitute the daily diet and to further evaluate the diet quality using Near Infrared Reflectance Spectroscopy (NIRS). NIRS is based on the selective absorption of the near infrared wavelengths (800 – 2 500 nm) by the different constituents of the organic matter (Fanchone *et al.*, 2007; Decruyenaere *et al.*, 2009b). When applied to forage and feeds, according to dedicated reference databases and regression models it allows the prediction of composition parameters expressed as % of the DM such as the ash content (Ash), the Kjeldahl crude protein (CP) described by Conklin-Brittain *et al.* (1999), the structural fibers according to Van Soest and Wine (1967) as neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL); it also allows to estimate the enzymatic digestibility of the organic matter according to (Aufrere and Michalet-Doreau, 1988) and further calculate along standards (INRA, 1988) the metabolisable energy content and final forage value unit (UFL) and Digestible Crude Protein (DCP) standard feeding values (Corson *et al.*, 1999).

In total, 76 daily diets were reconstituted and send to lab for NIRS scanning (ASD 350 to 2500 nm wavelength by 1 nm steps) and further predicted according to Winisi 3 (FOSS Tecator Infrasoft International LCC, Hillerød, Denmark) procedures as described in Shenk and Westerhaus (1991) and Naes *et al.* (2002).

The reference database used to predict the different parameter is made of a large dataset of more than 2000 references on grass and legume forages collected by CIRAD and partner institutions in tropical and temperate contexts (Chirat *et al.*, 2014).

The characteristics of the references established on classical and normalized methods and the global performance of the prediction models that were used for the prediction of the different constituents are summarized as numbers, average and standard deviation of the references in the database, standard error SE_{CV} and Rsquared R^2cv of the calibration as tested in cross validation of each model, for the different constituents as follows (Table 2.1):

Table 2. 1. Performance of the Global prediction models used to characterize the diets

Parameters %DM	**N**	**Mean +/- SD of the references**	**SEcv**	**R²cv**
ASH	4138	9.52 ± 2.99	1.20	0.84
PROTEIN	4908	12.77 ± 5.44	0.96	0.97
NDF	2111	59.92 ± 11.81	2.61	0.95
ADF	2380	34.82 ± 6.96	1.80	0.93
ADL	2105	4.82 ± 2.30	0.88	0.85
DMSauf	2120	60.45 ± 15.97	3.75	0.94

SEcv :standard error of cross-validation,
Rcv^2: coefficient of determination of cross-validation

2.4. Assessment of forage intake and digestibility by grazing livestock using faecal NIRS

The hand plucking method gives a description of the diet qualitative composition, and a raw estimate of the forage mass intake of the animal monitored. The method is however quite tedious, highly dependent to the operator, high time consuming on the field and further in the lab; and limited in terms of repetitions that could be deployed in space and over time. It gives a first estimate of the diet quality along international nutrition standards; however, it does not measure forage intake and the use of the feed ingested by the animal. Following several authors (Boval *et al.*, 2004; Tran *et al.*, 2010; Decruyenaere *et al.*, 2013) more relevant assessments of forage intake and selected feed digestibility can also be addressed by near infrared spectroscopy analysis directly applied to the faeces emitted by the animal (F-NIRS). Faeces composition reflects the diet recently consumed; the faeces can be sampled in large numbers on the field, and F-NIRS method are easily applied at very low cost. The Widou Thiengoly monitoring project seized the opportunity of the existence of large international spectral libraries as recently described by Decruyenaere (2015) in her thesis. To cover local conditions these databases have been complemented with a set of additional and highly contextualized references collected in the WTSA. Along to the grazing activities observation, the total daily faeces productions were monitored all along the survey period to further estimate daily intake. Specific faeces bag were fit to 5 young growing male cattle (115-140 kg LW) belonging to and grazing within the selected herds in order to collect all the day faeces. The collected faeces (over 24h) were weighted fresh, immediately after collection and subsamples were taken, dried in a forced-air oven at 65°C for 72 h to determine DM content and assess the total indigestible DM excretions. This operation has been repeated on a monthly basis and produced a final set of 64 daily excretion values. Digestibility values associated to these faeces were estimated by NIRs

(Decruyenaere, 2015) and DM intake was then recalculated as the observed total DM excreted per kg metabolic weight of the animal divided by (100 – DM digestibility) and multiplied by 100 to have a final estimated intake in gDM / kg $P^{.75}$.

In addition, due to the inherent large variability of such methods and to the low cost opportunity offered by NIRS, to optimize the final average estimations through an increase of individual samples, large sets of faeces freshly deposited from cattle, sheep and goat were randomly and systematically sampled along the livestock grazing itineraries (48 samples collected each month of the survey period) to constitute a final dataset of 816 samples.

All the dried and grinded (at 2 mm) faecal samples were scanned using the same ASD spectrometer (Lab Spec ® 4) as detailed above. The large spectral library used to manage and predict the unknown samples is the one initiated and described by Decruyenaere *et al.* (2009b). It contains actually more than 3000 referenced spectral data related to ruminant diet characteristics collected along in vivo trials conducted by several institutions in temperate and tropical contexts and for different species bovine, sheep and goats.

With the spectra, referenced parameters are the *in vivo* organic matter digestibility (OMd%) and/or the mean daily dry matter voluntary intake as expressed per kg $P^{.75}$ (DMviP.75). While digestibility prediction equation on faeces are quite robust, on the more sensible intake parameter, to include the local variability and the sometime very low intake levels observed in hot dry season, the database has been complemented with the set of 64 cattle daily dry matter intake references estimated as described above from faecal bag observations in this survey.

As in table 2.1 the characteristics of the references and the global performance of the prediction models are as follows (Table 2.2). R squared values are all above 80% with quite large standard errors for DM intake although remaining in the range (18.7 %) of biological error generally occurring in such measures. The model appears particularly interesting as it may be applied to large series from repeated samplings for which average predictions provide most relevant estimates.

Table 2. 2. Performance of the Global prediction models including the WTSA reference for intake

Parameters	N	Mean +/- SD of the references	SEcv	R^2cv
DMviP.75 g kg/MW	3407	64.78 ± 28.51	11.49	0.84
OMd %	3166	65.06 ± 10.51	3.52	0.89

DMvi: dry matter voluntary intake per kg metabolic weight, OMd: organic matter digestibility, N: number of faecal spectra referenced for the parameter in the whole database; SEcv, R^2 cv standard error and R squared of the calibration as tested in cross validation of each global model.

Further as stated by Tran *et al.* (2010) when large referenced database are available, local calibration techniques represent an alternative promising method that generally performs better than classical global techniques and further increases (15-20%) the accuracy (SE and R²) of the prediction.

The Local Calibration technique (Winisi 3, Foss tecator) , described by Shenk *et al.* (1997), was used to predict forage intake from all the 816 faecal samples. According to the 'Local' procedure, a subset of references spectrally similar to the sample to be analyzed is selected from the wide reference database. The subset of spectra is then used to develop a specific prediction model for each sample and parameter. The Local NIRS models are set up with a modified partial least square regression, using the first derivative mode spectrum with scatter correction using standard normal variate and detrended of the spectral absorbencies. The population boundaries for the calibration are set with a maximum standardized H (Mahalanobis distance) value of 4.0 (Shenk and Westerhaus, 1991). In order to optimize the 'Local' procedure the number of samples to be selected from the spectral library was set to 200, the maximum number of PLS terms was set to 10, and the number of factors to be removed from the prediction was set to 3 (Figure 2.2).

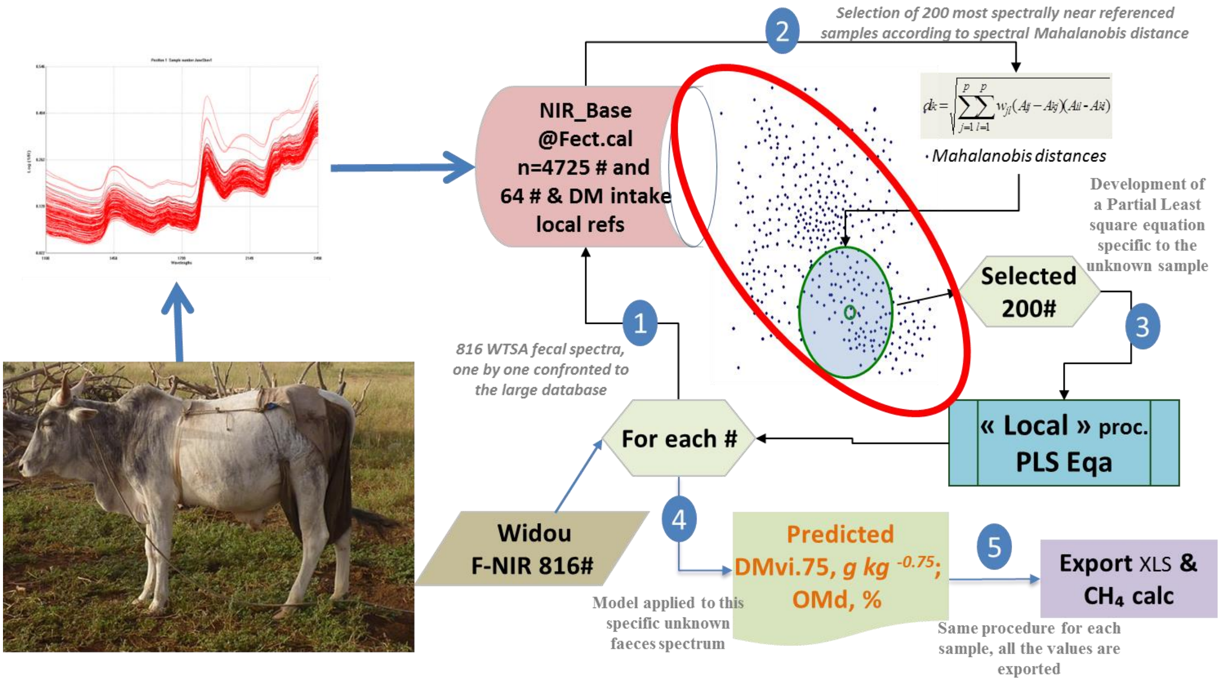

Figure 2. 2. Step for F-NIRS processing of the Widou samples for prediction of digestibility and intake, and further calculation of enteric methane.

The predicted values were used to evaluate the monthly variations of intake and digestibility across time and main species. The predicted DMVi and OMd results were also useful reference to estimate the methane enteric emission. The total digestible organic matter intake (DOMI, g/kg BW) was calculated as (DMvi x 89% OM x OMd) and the derived CH_4 emission were estimated according to the general model proposed by Archimède et al. (2011): CH_4 (g/kg BW) = 0.082 + 0,028 × DOMI, adapted for tropical conditions.

This daily methane emission and the total livestock population were used to estimate the contribution of the three main ruminant species (cattle, sheep and goat) on the total enteric methane emission at the whole WTSA level. This total enteric methane emission was allocated along the two main products (meat and milk) in order to evaluate enteric CH_4 emissions intensity in this pastoral area. The impact was allocated to meat and milk based on protein content allocation as described by FAO (2010) and Weiss and Leip (2012). This was based on the protein content in the live weight mass of each product. The functional units were 1 kg of carcass weight (CW) for meat and 1 kg of fat and protein corrected milk (FPCM) for milk. Carcass mass produced was calculated by multiplying animal live weight by a standard carcass yields of 48% as proposed by Pugliese and Calvet (1973) for the three species. Produced milk was expressed as kg FPCM using equation described by Gerber et al. (2011).

2.5. Upscaling local observations to the whole WTSA level and enteric methane emission intensity

The point herbaceous monitoring in the six landscape units are weighted according to the surface area of the different landscape units in the study area (the WTSA) and summed for each period to calculate the total herbaceous production.

Outputs of the monthly surveys carried out among the 40 sampled herders were extrapolated to the 354 herders population according to the size of each class (i.e. small, medium and large herders). Total livestock number calculated were converted in TLU numbers of a 250 kg standard live weight and total metabolic weight according to numbers and standard weight per age class and species as proposed in the literature (Jahnke, 1982). For cattle we have used 200kg, 320kg, 250kg and 17kg respectively for young, adult male, adult female and calves. For Sheep we have used 20kg, 40kg, 30kg and 2.3 kg for young, adult male, adult female and new born. For goat we have used 18 kg, 25kg, 20kg and 1.6kg for young, adult male, adult female and new born kids. Finally for donkey and horse we have used for young animals 100kg and 140kg respectively and for adult animals 175kg and 200kg respectively.

Total animal calculated population was used to estimate total forage intake and total excreta deposited on the soil. For cattle particularly, three approaches were used to estimate forage intake. The first was based on the simulated feed intake obtained using the hand plucking method. The second and the third were based on predicted intake from F-NIRS respectively on 64 faeces collected with the faecal bags and on 375 faeces samples randomly collected on the soil from other cattle.

In a general way all the classical statistics and graphical exploitation for description of the different sets of results were processed with Minitab (v15, 2007; Minitab, State College, PA) and excel 2012.

3. Results

3.1. The livestock population and production

3.1.1. Total livestock herd Composition

The overall livestock population of the pastoral households living within the WTSA varies between 49 926 – 116 227 heads corresponding to 15 274 – 33 095 TLU and 1.1 – 2.55 kt of metabolic weight respectively in August and December (figure 2.3a). On annual average when calculated on a TLU basis, it is composed of cattle (52%), sheep (25%) and goats (7%) as ruminant and horses (3%) and donkeys (13%) as monogastric herbivores, whereas when calculated on metabolic weight basis, it is composed of cattle (39%), sheep (33%) and goats (13%) as ruminant and horses (3%) and donkeys (13%) as monogastric herbivores. This second approach gave a larger weight to small ruminants in the landscape.

Animal numbers expressed in TLUs and in metabolic weight, as present within the WTSA or away in transhumance are detailed in figures 2.3 and 2.4. The stocking rate of the service area fluctuates largely depending on the available herbaceous forage mass and the herder's management strategies. Between August and December the stocking rate over the service area varies between 0.22 and 0.48 TLU/ha (x 2.1) or in metabolic weight between 16.41 and 37.50 kg MW/ha (x 2.21).

The highest stocking rate over the service area is expected during the wet season (WS); in 2014 it actually occurred from June to July. However, it dropped in August 2014 in response to an unexpected rainfall shortage that stopped vegetation growth and caused the departure of a large fraction of the herds to nearby rangelands to the south of the Ferlo valley. Herds came back in the service area in September with the return of rains in late August, the stocking rate keeping high till December. In 2015, the at the start of the dry season transhumance began in January and continued until end of February. This early departure and the large proportion of herds leaving are explained by the low herbaceous forage mass remaining, due to low annual rainfall and long dry spell in July-August 2014. The stocking rate in the borehole service area progressively decreased down to a minimum in August. Herds came back from transhumance with the first rains at the beginning of July 2015. As a matter of fact 90 % of cattle, 75% of sheep, 65% of donkeys, 50% of horses and only 10% of goats had to move out of the service area for a more or less long period of time from January to May of the studied period. The results illustrate the large temporal variability of the number of animals present and the differential relative weight of the species in a typical sylvo-pastoral landscape. It shows the real existing challenge in considering an annual stocking rate under such contrasted conditions.

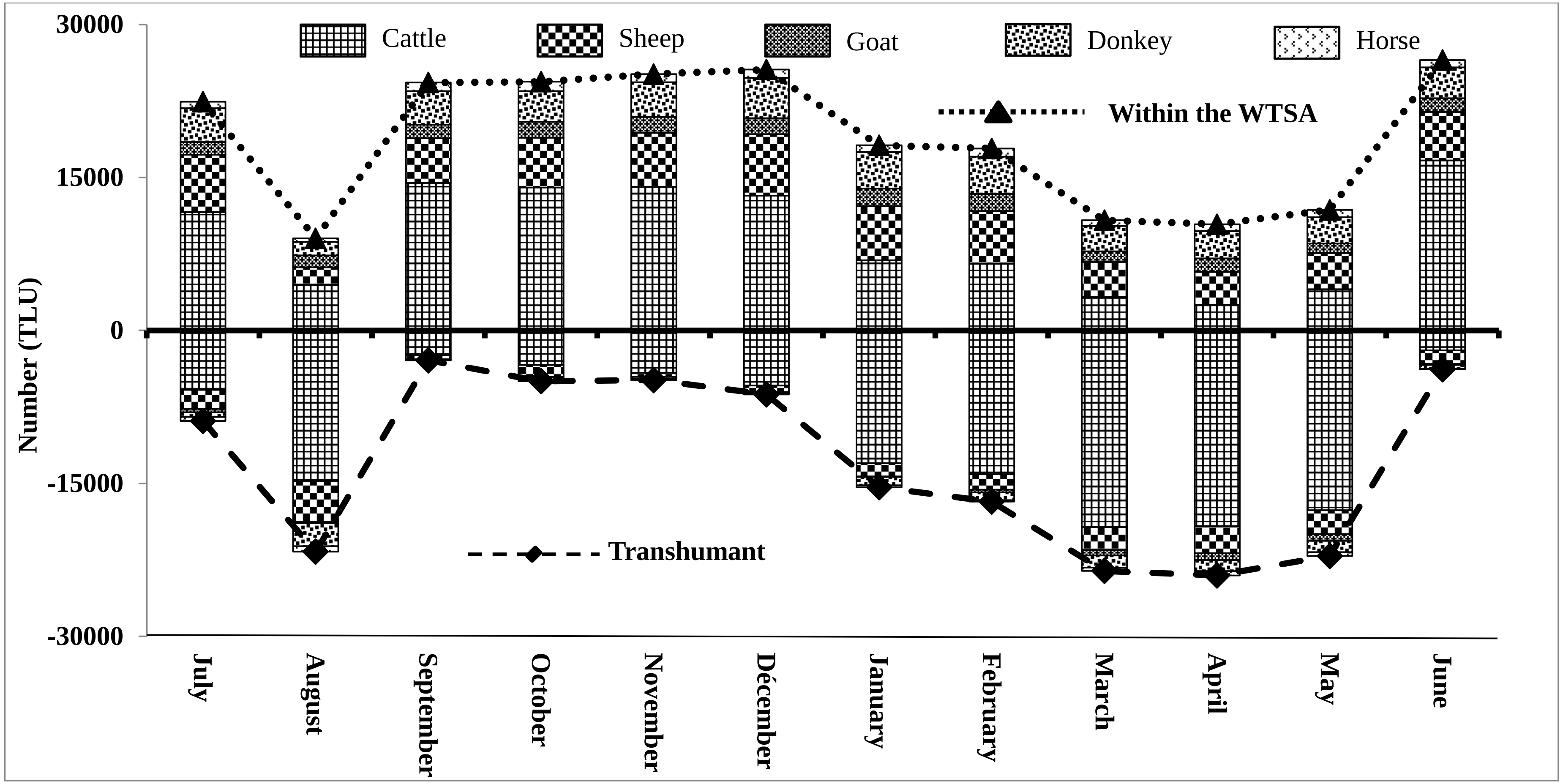

Figure 2. 3. Monthly dynamics of livestock numbers (in TLU) per species within the Widou Thiengoly service area (WTSA) or away in transhumance from July 2014 to June 2015
Negative values indicate that herds are away from the Widou Thiengoly service area. This estimation is based on the survey of the 40 herders described in the methodology. Each herder holds some 3530TLU.

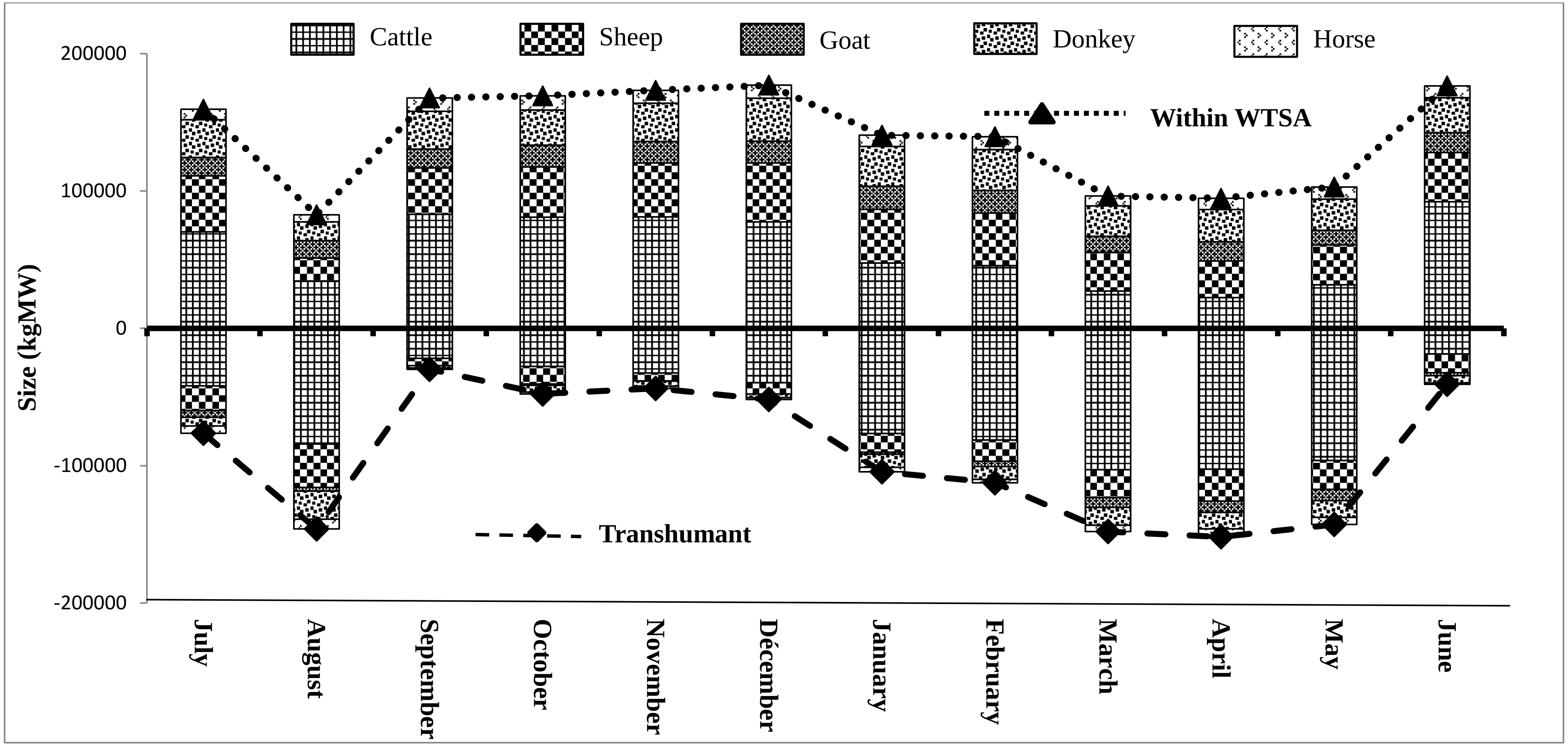

Figure 2. 4. Monthly dynamics of livestock numbers (in kg MW) per species within the Widou Thiengoly service area (WTSA) or away in transhumance from July 2014 to June 2015

Negative values indicate that herds are away from the Widou Thiengoly service area. This estimation is based on the survey o the 40 herders described in the methodology.

Averaging stocking rates per season (tables 2.3 & 2.4) attenuates the contrasts observed monthly with a maximum of 0.43 TLU/ha in cold dry season and a minimum of 0.31 TLU/ha during the hot dry season. The stocking density within the WTSA varies from 0.97 head/ha during the hot dry season and 1.43 head/ha the cold dry season. This stock expressed in kg of metabolic weigh also varies between 23.67 kg MW/ha during the hot dry season and 33.02 kg MW/ha during the cold dry season.

Table 2. 3. Seasonal variations of the livestock population in heads, TLU and metabolic weight and stocking rates (expressed per ha) within the WTSA

		Cattle		**Sheep**		**Goat**		**Donkey**		**Horse**		**All species**		**Stocking rate** (/ha)
		Values	**%**	**Values**	**%**	**Values**	**%**	**Values**	**%**	**Values**	**%**	**Values**	**%**	
WS	Hd	18221	21.70	40386	48.09	19417	23.12	4923	5.86	1035	1.23	83982	100	1.24
	TLU	15077	56.70	6214	23.37	1450	5.45	3085	11.60	764	2.87	26590	100	0.39
	MW	895.07	44.94	614.47	30.85	213.38	10.71	217.03	10.90	51.69	2.60	1 991.64	100	29.29
CDS	Hd	17544	16.95	53399	51.59	25089	24.24	6348	6.13	1126	1.09	103506	100	1.52
	TLU	14494	50.07	7629	26.36	1840	6.36	4125	14.25	858	2.97	28946	100	0.43
	MW	847.83	37.75	768.05	34.20	284.19	12.66	287.93	12.82	57.67	2.57	2 245.68	100	33.02
HDS	Hd	12560	17.66	35609	50.08	17092	24.04	4862	6.84	986	1.39	71108	100	1.05
	TLU	10343	49.57	5481	26.27	1301	6.24	3009	14.42	731	3.50	20865	100	0.31
	MW	588.52	36.56	544.09	33.80	215.60	13.39	212.25	13.18	49.406	3.07	1 609.86	100	23.67
Annual	Hd	16108	18.69	43131	50.04	20532	23.82	5378	6.24	1049	1.22	86199	100	1.27
	TLU	13305	52.24	6441	25.29	1531	6.01	3406	13.38	784	3.08	25467	100	0.37
	MW	777.14	39.87	642.20	32.95	237.73	12.20	239.07	12.27	52.92	2.72	1 949.06	100	28.66

WS: Wet Season, HDS: Hot Dry Season, CDS*:* Cold Dry Season

TLU: tropical livestock units of 250kg LW; Hd: number of heads; MW: metabolic weight in tons for the total and in kg/ha for the stocking rate

Table 2. 4. Seasonal variation of the livestock population in transhumance (Out of the WTSA)

		Cattle		**Sheep**		**Goat**		**Donkey**		**Horse**		**All species**	
		Values	**%**	**Values**	**%**	**Values**	**%**	**Values**	**%**	**Values**	**%**	**Values**	**%**
WS	Hd	7131	26.36	16748	61.91	1589	5.87	1226	4.53	358	1.32	27053	100
	TLU	6913	68.52	1905	18.88	126	1.24	858	8.51	287	2.84	10088	100
	MW	437.73	59.43	205.88	27.95	14.88	2.02	58.98	8.01	19.05	2.59	736.54	100
CDS	Hd	9921	47.63	8973	43.08	1021	4.90	747	3.59	165	0.79	20827	100
	TLU	9644	84.72	1004	8.82	80	0.71	523	4.59	132	1.16	11384	100
	MW	610.30	78.90	108.89	14.08	9.55	1.23	35.94	4.65	8.79	1.14	773.48	100
HDS	Hd	15953	36.36	20117	45.85	5981	13.63	1431	3.26	393	0.89	43874	100
	TLU	15236	79.33	2187	11.39	466	2.43	1002	5.22	314	1.64	19205	100
	MW	968.18	71.60	238.80	17.66	55.46	4.10	68.85	5.09	20.88	1.54	1 352.17	100
Annual	Hd	11001	35.97	15280	49.96	2863	9.36	1135	3.71	305	1.00	30585	100
	TLU	10598	78.16	1699	12.53	224	1.65	794	5.86	244	1.80	13559	100
	MW	672.07	70.44	184.52	19.34	26.63	2.79	54.60	5.72	16.24	1.70	954.06	100

WS: Wet Season, HDS: Hot Dry Season, CDS: Cold Dry Season

TLU: tropical livestock units of 250kg LW; Hd: number of heads; MW: metabolic weight in tons

3.1.2. Structure of ruminant herds

The sex-and-age structures of cattle herds and sheep flocks indicate a large dominance of females as expected from the reproduction objective of the pastoralists, but with different proportions depending on the animal species (Figure 2.5). Indeed females account for 75.2% of the animals in cattle herds including 39.6% young females (≤4 years) and 35.6% of adult females (>4 years), while young and adult males only account for 20.1% and 4.6% respectively. Among the adult cattle there are 13 males for 100 females. Females are accounting for 63.3% of the animals in the sheep flocks including 29.4% young (≤1 year) and 33.8 adult females (>1 year), while young and adult males account for 29.6% and 7.0% or the flock respectively. The low percentage of males over 1 year of age is attributed to large fraction of males sold young. Among the adult sheep (>2 year) population in the flock, there are 10 males for 100 females.

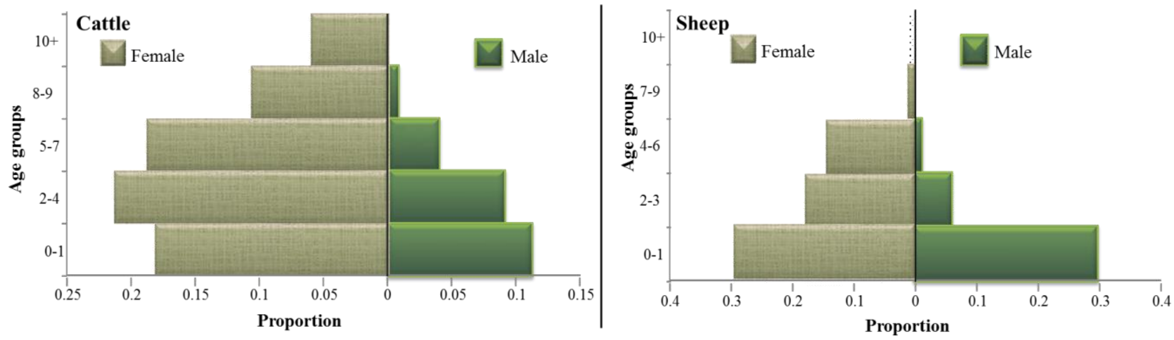

Figure 2. 5. Average sex-and-age structure of 12 cattle herds (533 animals) and 12 sheep flocks (552 animals) from Widou Thiengoly

3.1.3. Key demographic parameters

From the monthly surveys of 40 herds the monthly distributions of animal birth, death, sale and slaughter events indicates different seasonal patterns for cattle, sheep and goats (Figure 2.6). Cattle and sheep sales vary across season with a largest peak observed between August to December matching with the Muslim celebrations. The seasonal pattern of goat sale is less obvious. The sale of sheep and cattle represent more than 85% of the animal exchanges here. On an annual basis, for cattle 5% of the females and 15% of the males were sold, whereas for sheep 10% of females and 32% of males were sold. Slaughtering for family consumption also varies with a peak during the wet season following the return from transhumance. Less than 1%

of females and 3% of male cattle were slaughtered in the year whereas it reached 2% of females and 5% of male sheep's.

Cattle birth events peak in the wet season while sheep and goats birth events peak during the cool dry season. The parturition rate of the adult cows (4 to 5 years old) was estimated at 0.41±0.02/cow/yr. The average interval between parturitions (IBP) estimated by inversion of the parturition rate is 365/0.42 = 869 days. The abortion rate over the twelve-month period was estimated at 0.02/cow/yr. The prolificacy rate is estimated at 1 living calf per parturition. For sheep, the parturition rate is estimated at 0.78 ± 0.05/ewe/yr. The average interval between parturitions (IBP) is thus of 365/0.78 =468 days. The abortion rate over the twelve-month period is estimated at 0.03/ewe/yr. The prolificacy rate is 1.03 lambs alive per parturition.

The rate of mortality of cattle and sheep increase towards the end of the dry season, and in 2014, these peaked in early wet season with the severe dry spell. The mortality rates of young cattle (<1year) are 0.24±0.06/animal/yr for females and 0.15±0.06/animal/yr for males. The mortality rates decrease with age at 0.06±0.02 and 0.07±0.03/animal/yr females and males between 1 and 4 years old. It remains low at higher age for females and males. Globally for cattle, the mortality rate is 0.09±0.01/animal/yr. The mortality rates of young sheep (<1year) are 0.17±0.04 and 0.15±0.04/animal/yr, for females and males respectively. They are lower for adults (≥1year) at 0.09±0.02 and 0.08±0.03/animal/yr for females and males respectively. Globally sheep mortality rate is 0.11±0.05 /animal/yr.

The relative low rates of fertility and high rate of mortality, especially of juveniles, reflect the harshness of the breeding conditions. Both contribute to reduce the efficiency of the pastoral production. The total number of animals sold (8012 heads detailed as follows: 1337 cattle, 5472 sheep and 1201 goat) corresponds to 0.39 thousand tons of LW while total slaughter is estimated at 0.05 thousand tons of LW (13% of animals sold + slaughtered) over one year. The annual cattle's milk production within the WTSA is estimated at 3.78 thousand tons of Fat and Protein Corrected Milk (FPCM). 88% of this milk production was either consumed by pastoralist families or and suckled by the calves, lambs and kids.

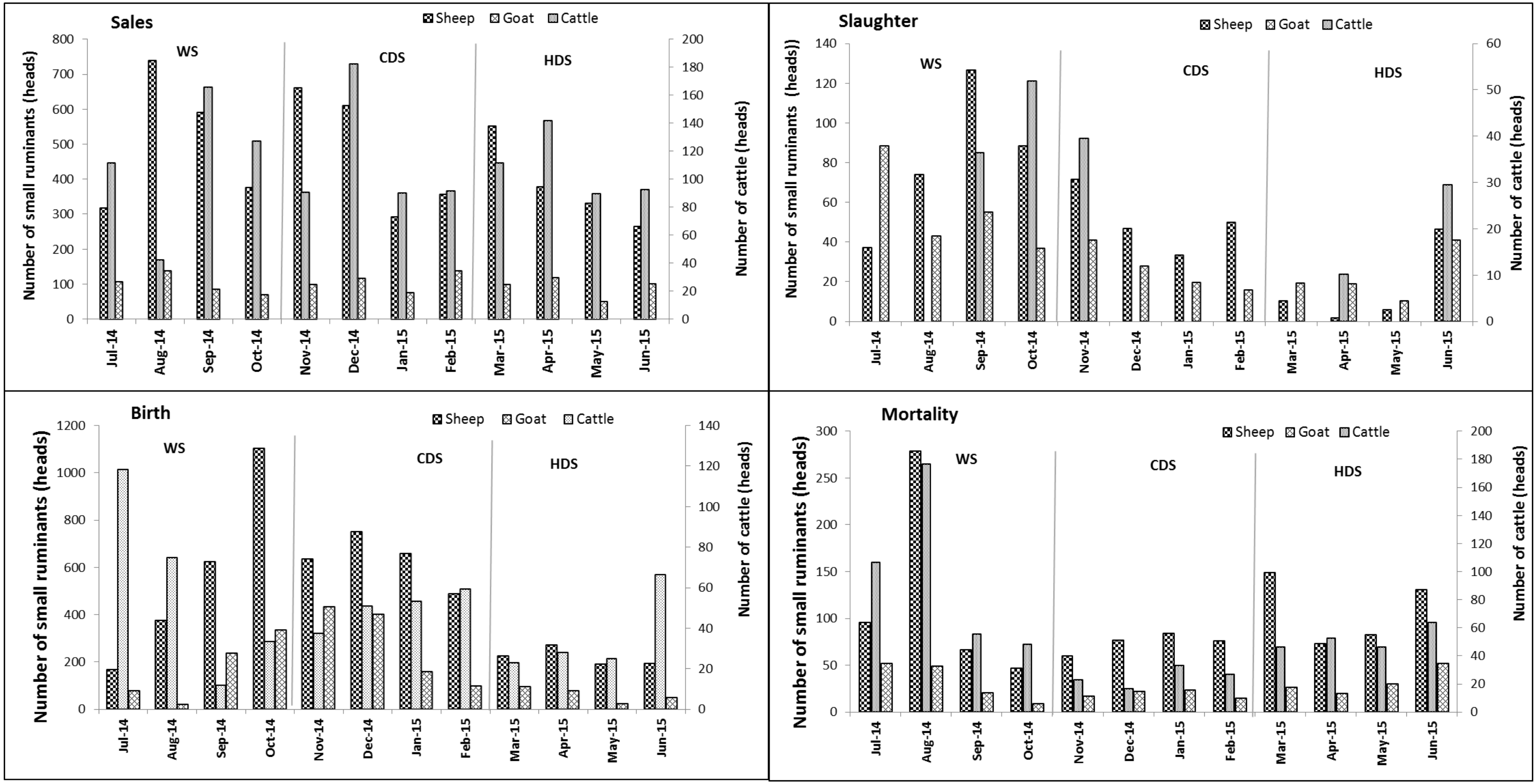

Figure 2. 6. Monthly distribution animal sales, slaughter, birth and death as observed from June 2014 to May 2015 in 1944 cattle herds, 5195 sheep and 1964 goat flocks

3.2. Forage resource monitoring

3.2.1. Available forage mass and simulated diet mass

The seasonal dynamics (Figure 2.7) of (i) the animal live weight mass present inside the WTSA, (ii) the available forage resource within the WTSA and (iii) the estimate of the total forage mass collected by livestock according to the hand-plucking simulation method are summarized in table 2.5. The peak of the available total herbaceous resource, 103 kt DM, was observed in September. The herbaceous mass declined rapidly to 38% of this value in only two months. Starting in November, litter progressively accumulates at soil surface with a maximum in March followed by a progressive decrease till the end of the dry season. By the end of the dry season the available mass of herbaceous is reduced to 2.65 kt, mostly as litter (98%). The total metabolic weight of grazing animal within the WTSA varies from 1.11 kt in December to 2.55 kt in August. The total live weight of grazing animals within the WTSA also varies between 8.2 kt in December to 3.8 kt in August (figure 2.7). Based on the livestock mass (live weight) within the WTSA the simulated intake cumulated over the year is less than 30% (27.06 kt) of the peak herbaceous mass. This simulated intake varies from 5.21% to 79.75% of the existing herbaceous mass respectively in October and December (Table 2.5). The diet is largely constituted of grasses and forbs tallying at 22.3 and 4.7 10^3 tons DM for the year respectively, grazed mainly in wet and cold dry seasons. During the hot dry season with the lowest level of available herbaceous forage (2.76 to 103.1 kt DM depending on months), additional tree leaves and pods mass contributed importantly to livestock diets with estimated contribution ranging from 29.9% to 72.2% in hot dry season averaging at 14.1% over year.

Table 2. 5. Monthly variations of the available herbaceous mass and simulated mass collected by livestock in the rangelands within the WTSA (680 km²)

		Total animal mass *(kt LW)*	**Total animal mass** *(kt MW)*	**Available herbaceous mass** (ktDM)			**Simulated intake "hand plucking method"** *(ktDM)*					**Ratio herbaceous forage intake to available** *(%)*
				Standing mass	**Litter mass**	**Total Aboveground mass**	**Grasses**	**Forbs**	**Simulated herbaceous mass intake**	**Additional tree leaves intake**	**herbaceous + browses**	
July	**WS**	7.32	2.25	3.91	13.66	17.56	1.39	0.32	1.71	0.18	1.89	9.74
August		3.82	1.12	20.64	0	20.64	1.07	0.2	1.27	0	1.27	6.15
September		7.67	2.25	99.32	0	99.32	4.41	0.76	5.17	0	5.17	5.21
October		7.78	2.35	60.16	0	60.16	2.61	0.47	3.08	0.01	3.09	5.12
November	**CDS**	7.87	2.37	36.69	4.56	41.24	2.13	0.55	2.68	0.06	2.74	6.50
December		8.27	2.55	27.82	2.71	30.53	3.15	0.55	3.7	0	3.7	12.12
January		6.48	2.06	18.96	0.87	19.82	2.09	0.58	2.67	0.22	2.89	13.47
February		6.33	2.01	10.72	4.48	15.20	1.89	0.59	2.48	0.06	2.54	16.32
March	**HDS**	4.41	1.38	2.48	8.09	10.59	0.78	0.18	0.96	0.41	1.37	9.07
April		4.22	1.36	1.29	6.00	7.29	0.5	0.1	0.6	0.45	1.05	8.23
May		4.57	1.44	0.09	3.91	4.00	0.51	0.11	0.62	1.61	2.23	15.51
June		7.67	2.27	0.06	2.61	2.66	1.85	0.27	2.12	1.46	3.58	79.75
Total							22.38	4.68	27.06	4.46	31.52	27.24
% Simulated diet							71.00	14.85	85.85	14.15	100	-

WS: Wet Season, HDS: Hot Dry Season, CDS: Cold Dry Season

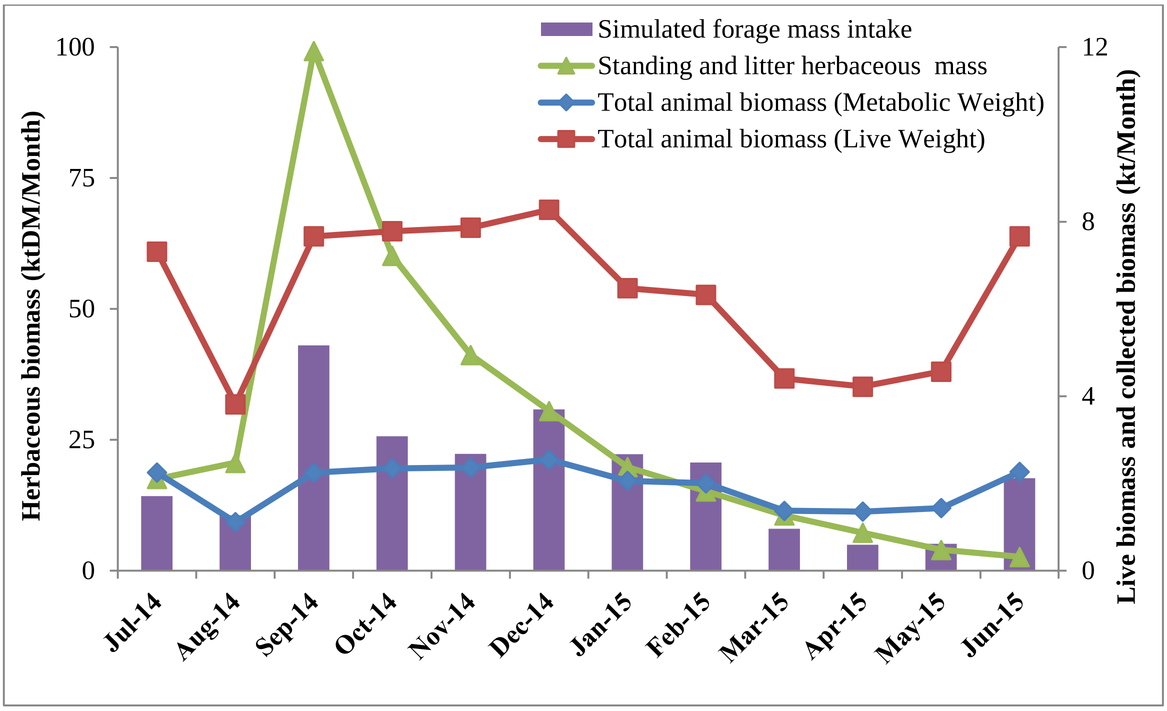

Figure 2. 7. Monthly variations of the herbaceous standing biomass, the animal live and metabolic weights and the simulated feed intake

3.2.2. Nutritional value of the daily diets

The variations of the estimated (hand plucking) daily mass grazed by the cattle within the WTSA expressed as kgDM per TLU and the proportions of main constituents of the diets and their NIRs predicted composition and feeding values along month and seasons are detailed in table 2.6. The feed intake ranges between 6.3±0.9 kg DM/TLU in the wet season and particularly low values between 1.5 and 2 kg DM/TLU in the hot dry season. The average annual intake according to hand plucking method is estimated at 3.67 kg DM/TLU. Grasses account for the largest part (71 %) of the daily diet, however it varies according to availability; forbs account for 14.85 % of the daily diet mass and it also varies along decreasing availability and it accounts for less than 10% in the hot dry season. Tree browses are a major constituent in the hot dry season diet with up to 72% of the diet in May and an average at 48 % of the diet during the hot dry season while it contributes to an average of 14.1% of cattle diet all over the year.

The main quality traits of the diet show also large variations. Protein content (12.4 %DM in WS) is at the highest in September when grass is mature and still green and when forbs are abundant in the diet, the protein content then decrease progressively with dry seasons to reach low values (6.0% DM in HDS). Fiber content (NDF, ADF) are generally elevated due to the large proportion of grasses that mature rapidly and or tree component in the diet. September is the period where the diets have relatively lower ADF and ADL (lignin fiber). In the following months the trend is of a progressive decrease of the protein, with no observed effect on nitrogen or lignin contents in the diet for the cattle browsing larger proportions of young tree leaves which should have higher protein and ADL contents. Energy feeding values calculated as metabolisable energy or forage units (UFL) appear at the best (0.66 - 0.7 UFL; 1.93-2.05 MCal/kg DM) in September and March with strikingly different forage intake. Digestible crude protein is quite similar and directly related to nitrogen content. Averaged over the year the feeding value of the diet is summarized by 0.58 UFL/kg DM or 1.75 Mcal metabolisable energy per kg DM and 51.8 g digestible crude protein per kg DM.

Table 2. 6. Monthly variation of the composition and feed quality of the simulated cattle diet

		Daily mass collected (1)	**Botanic composition of the diets (%)**			**Diet biochemical composition**						
			Grass	forbs	Tree browses	Protein	NDF	ADF	ADL	UFL	EM	DCP
		kg DM/TLU	%	%	%	% DM	% DM	% DM	% DM	/ kg DM	MCal /kg DM	g /kg DM
Jul	WS	2.34	73.28	17.14	9.57	11.54	69.54	45.21	7.70	0.57	1.73	76,85
Aug		3.23	84.39	15.47	0.14	11.40	72.77	42.47	6.31	0.53	1.62	75,55
Sept		6.30	85.32	14.68	0.00	17.08	67.48	37.36	4.51	0.66	1.93	127,59
Oct		3.56	84.50	15.10	0.40	9.43	69.39	45.89	6.52	0.57	1.71	57,50
Seasonal Average		**3,86**	**81.87**	**15.60**	**2.53**	**12.36**	**69.80**	**42.73**	**6.26**	**0.58**	**1.75**	**84.37**
Nov	CDS	3.26	77.75	20.14	2.12	6.62	72.95	53.15	8.62	0.50	1.56	31,77
Dec		4.47	85.20	14.80	0.00	6.12	70.63	49.61	7.27	0.55	1.67	27,17
Jan		4.42	72.43	20.04	7.53	7.77	69.81	47.79	7.42	0.58	1.74	42,23
Feb		5.29	74.44	23.12	2.44	11.71	63.95	41.44	6.83	0.68	1.98	78,33
Seasonal Average		**4,36**	**77.46**	**19.53**	**3.02**	**8.06**	**69.34**	**48.00**	**7.54**	**0.58**	**1.74**	**44.88**
Mar	HDS	1.33	56.95	13.28	29.77	5.71	65.75	38.85	7.99	0.70	2.05	23,41
Apr		1.98	47.25	9.72	43.03	6.05	74.92	49.72	6.96	0.53	1.64	26,50
May		3.97	22.92	4.88	**72.21**	7.51	69.82	44.71	6.71	0.62	1.83	39,91
Jun		3.90	51.74	7.54	40.72	4.74	76.43	52.71	7.96	0.49	1.49	14,48
Seasonal Average		**2,80**	**44.72**	**8.86**	**46.43**	**6.00**	**71.73**	**46.50**	**7.40**	**0.58**	**1.75**	**26.07**
Annual Average		**3,67**	**68.01**	**14.66**	**17.33**	**8.81**	**70.29**	**45.74**	**7.07**	**0.58**	**1.75**	**51.77**

(1) According to the hand plucking method

WS: Wet Season, HDS: Hot Dry Season, CDS: Cold Dry Season

3.3. Variations of digestibility and intake as predicted by fecal Nirs

The two parameters (DMvi.75, OMd) are predicted according to the "Local" procedure described above on the collection of 811 fecal samples collected in the WTSA for the three main ruminant species bovines (BOV), sheep (OVI) and goats (CAP). 27 outlier values carefully selected either based on their spectral distance to the database and/or on the coherence of the predicted values with the results have been eliminated. The main statistical parameters of the results are detailed in table 2.7.

Table 2. 7. Statistical parameters of the predicted results of feed daily intake (DMvi.75) and digestibility (OMd) parameters for the three main ruminant species of the WTSA

	Species	**N**	**Mean**	**sd**	**VC** *(%)*	**Min**	**Max**
DMvi.75 (*g/kg MW*)	Cattle	375	70.86	11.72	16.53	44.44	108.83
	Goat	143	73.92	18.22	24.65	30.52	114.47
	Sheep	260	77.04	13.89	18.03	52.42	126.60
OMd *(%)*	Cattle	375	59.88	6.01	10.05	38.50	75.40
	Goat	143	67.08	6.81	10.15	47.32	80.94
	Sheep	260	63.42	7.11	11.21	47.58	76.36

N: Number of samples, sd: Standard Deviation, VC: Variation Coefficient, Min: Minimum value, Max: Maximum value.

Figures 2.8 and 2.9 describe the monthly evolution of the digestibility and intake for the three ruminant species. When they are calculated and expressed per unit metabolic weight, the daily intake for the month predicted from the faeces slightly differ between species. Indeed, year round averages range from 70.86 (sd =6.94) for cattle to 77.04 for sheep (sd =6.04) and 73.92 for goats (sd = 8.89). A clear seasonal dynamic appears for all three species with higher intake in WS. Yet this seasonal dynamic is more ample and start earlier (in May for goats, and June for sheep) for small ruminants. The increase of intake for cattle occurs later, in August, with less marked maximum spread from August to October.

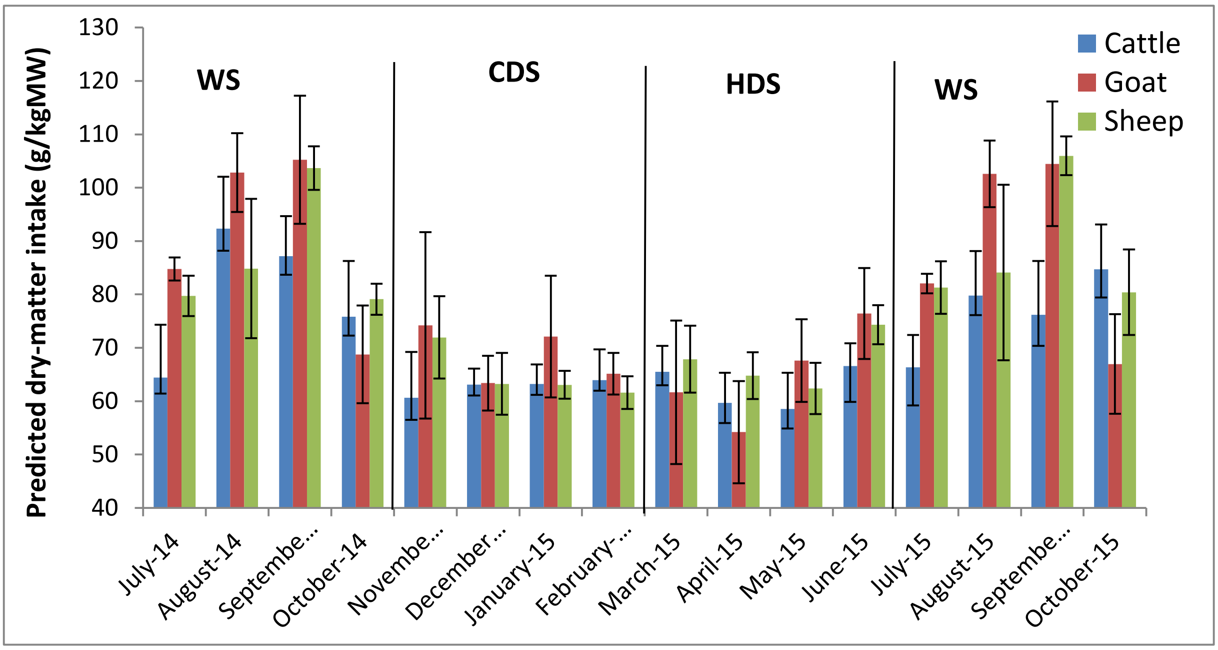

Figure 2. 8. Monthly evolution of feed intake (DMvi.75; g/kg MW) of the three main species, from July 2014 to October 2015, as predicted from faecal NIRS

The grazed diet digestibility (organic matter) is higher for goats (67.4 ±3.9%), followed by sheep (64.1 ±3.2%) and lower for cattle (59.3 ±3.8%) in average over the year (Figure 2.8). On the contrary the seasonal dynamics of the diet digestibility is larger for cattle than sheep and less marked for goats (Figure 2.9). Normally diet digestibility is higher during the wet season than during the dry season; however quite surprisingly for all three species digestibility also increases in the mid dry season from January to March for cattle and sheep and from December to April for goats. This increase is a bit too early to match the foliage renewal of main browses. It could correspond though to the availability of acacia's pods (*Acacia raddiana*, *Faidherbia albida*) and it may also be influenced by supplement feeding, at least for cattle and sheep.

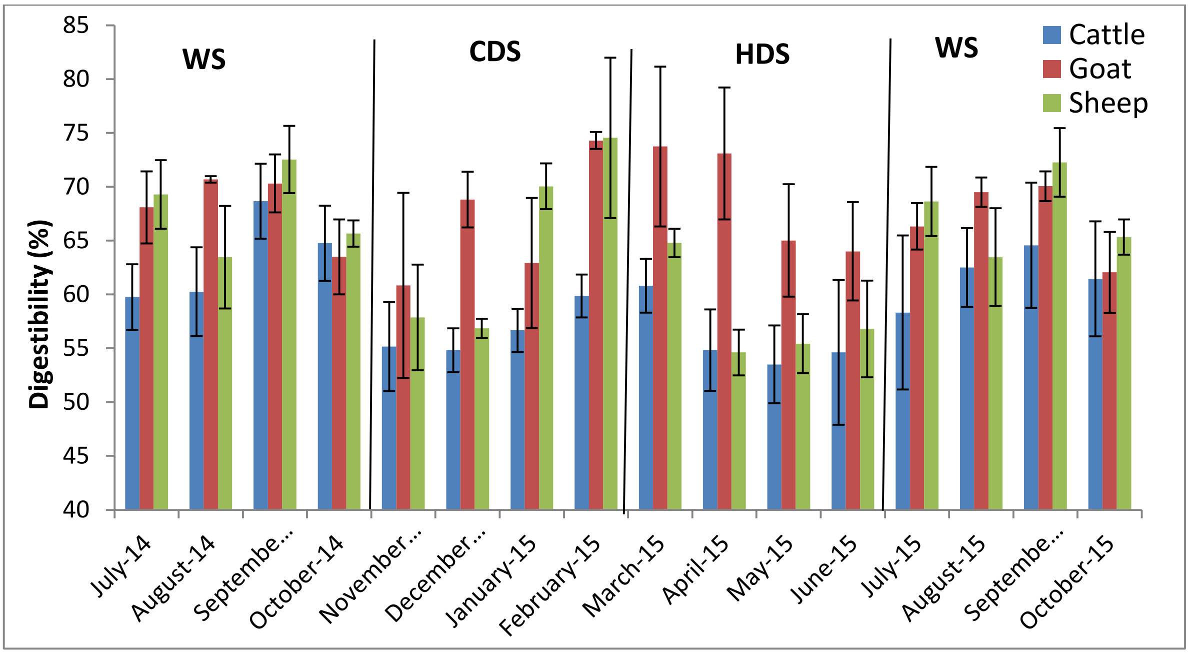

Figure 2. 9. Monthly evolution of the in vivo organic matter digestibility of the voluntary intake (C-OMviD) of the three ruminant species, from July 2014 to October 2015, as predicted by faeces NIRS

On a methodological point of view the comparison of the cattle intake estimates is summarized in table 2.8. The average values are in good coherence; the ranges are however larger for hand plucking approach which is quite normal for a method that remain subjective and uneasy to standardize.

Table 2. 8. Descriptive statistics of cattle intake (kg DM/hd/day)

Variable	**Mean**	**sd**	**cv**	**Min**	**Max**
Hand plucking	4.57	1.25	27.33	2.42	6.46
Fecal bags	4.80	0.95	19.76	3.68	7.07
On-floor collection	4.43	0.65	14.67	3.68	5.80

For cattle, the feed intake predicted from fresh faeces (345 samples over the year) collected on-floor in the rangelands compares well with the feed intake assessed with the fecal bags (Fig. 2.10) although these are slightly superior which could be expected from growing animals for (the 5 monitored animals are steers). These predictions are also close to feed intake simulations by hand plucking with similar seasonal dynamics (Fig. 2.10), only slightly higher for the simulations from hand plucking.

On the contrary, both predictions and simulations compare poorly with the standard intake generally considered for a TLU in Sahel, even when this standard is adjusted to the weight of the cattle as it is done for the 5 monitored steers. These standards over estimate in average by 33.07 % the annual intake (table 2.9 and figure 2.10).

Table 2. 9. Seasonal and annual variation of predicted and simulated forage intake by cattle

		Hand plucking		**Fecal bags**		**On-floor collection**	
		Value	*sd*	*Value*	*sd*	*Value*	*sd*
WS	kg DM/TLU/day	4.27	0.52	5.31	1.00	5.03	0.57
	g DM/kgMW/day	67.90	8.21	84.40	15.97	79.94	9.08
CDS	kg DM/TLU/day	4.18	0.50	4.32	0.42	3.94	0.27
	g DM/kgMW/day	66.52	8.01	68.76	6.75	62.72	4.33
HDS	kg DM/TLU/day	4.10	0.62	4.36	0.62	3.93	0.36
	g DM/kgMW/day	65.16	9.90	69.30	9.86	62.57	5.69
Annual	ton DM/TLU/yr	1.53	0.20	1.70	0.25	1.57	0.15
	Kg DM/kgMW/yr	24.28	3.18	27.07	3.96	24.97	2.32

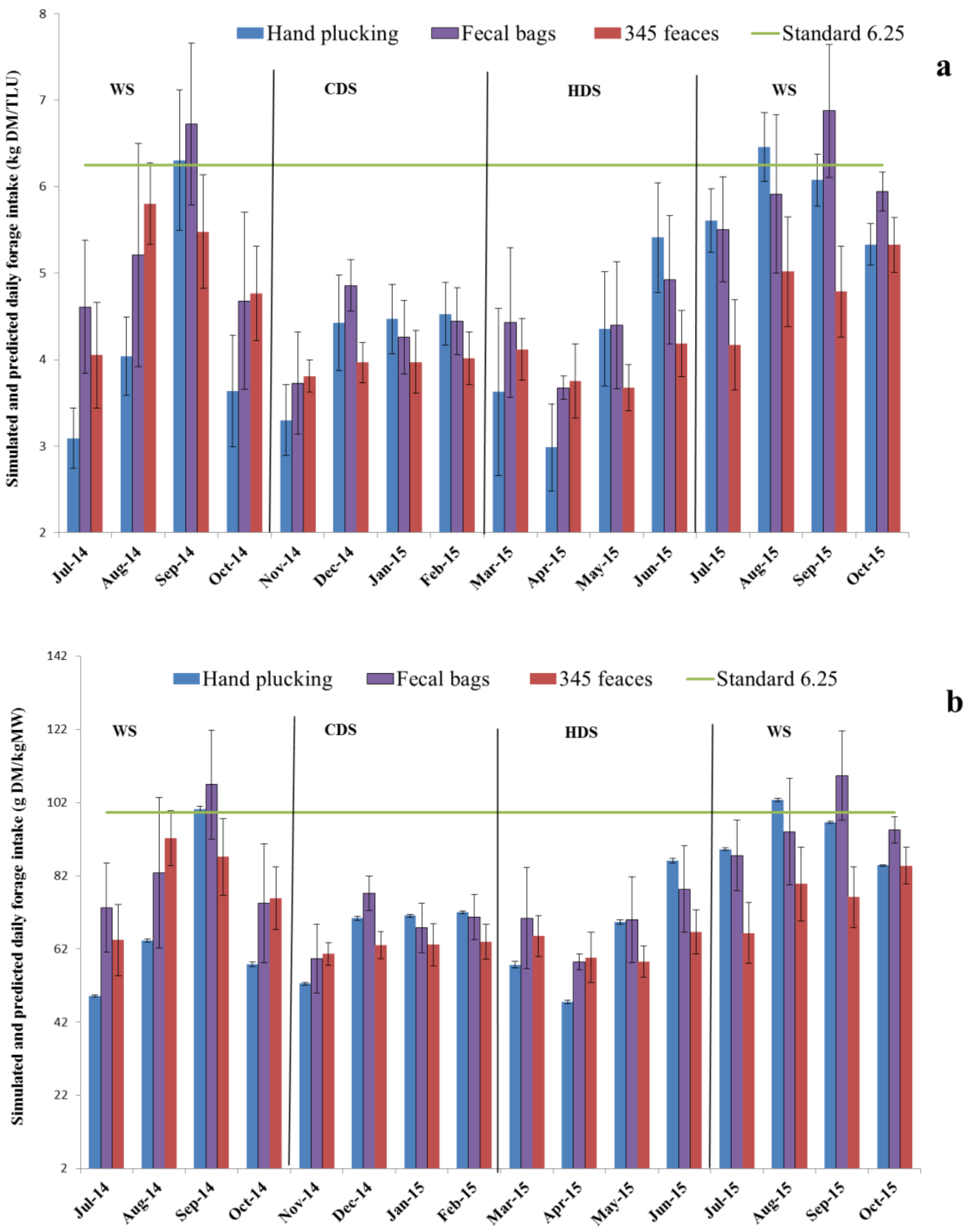

Figure 2. 10. Monthly variations of simulated and predicted daily forage intake for a cattle per TLU (a) and as per kgMW (b).

3.4. Methane emission

The enteric methane emission has been calculated along the Tier 3 IPCC method based on the monthly feed intake and the diet digestibility as predicted by faecal NIRS for the three main ruminant species. The live weight of these reference animals in each species are set to 250 kg for cattle, 40 kg for sheep and 35 kg for goats to keep with the general international standards used by (IPCC, 2006). Table 2.10 describes the variation of enteric emission throughout the year and the estimated total annual emission of a standard head. For cattle, methane emission varies from 1.49±0.02 in May to 2.84±0.02 kgCH_4/hd/month in September and the cumulated annual emission of 23.4±0.17 kgCH_4/hd/yr. The enteric methane emission of sheep ranges between 0.46±0.01 in May to 0.99±0.00 kgCH_4/hd/month in September cumulated annual emission is 7.37±0.06 kgCH_4/hd/yr. For the goats, the enteric methane emission is quite similar and ranges from 0.48±0.01 in April to 0.89±0.01 kgCH_4/hd/month in September and the cumulated annual emission reaches 7.34±0.10 kgCH_4/hd/yr.

Aggregated to the WTSA, the CH_4 emission by ruminant ranges from 0.30±0.01 kgCH_4/ha/month in hot dry season to 0.62±0.01 kgCH_4/ha/month during the wet season and cumulates at 5.54±0.03 kgCH_4/ha/yr.

Table 2. 10. Monthly variations and annual sums of enteric methane emissions for the three species from July 2014 to August 2015 (estimations based on the F- NIRS approach of intake and digestibility of resources)

		Cattle (kg CH_4/hd/month)		**Sheep** (kg CH_4/hd/month)		**Goat** (kg CH_4/hd/month)	
		Mean	*sd*	*Mean*	*sd*	*Mean*	*sd*
July	WS	1.83	0.02	0.73	0.01	0.70	0.01
August		2.64	0.01	0.71	0.01	0.88	0.01
September		2.84	0.02	0.99	0.01	0.89	0.01
October		2.33	0.02	0.68	0.01	0.53	0.02
November	CDS	1.59	0.01	0.55	0.01	0.54	0.00
December		1.64	0.01	0.47	0.01	0.53	0.01
January		1.70	0.01	0.58	0.01	0.55	0.01
February		1.82	0.01	0.60	0.01	0.58	0.01
March	HDS	1.89	0.01	0.58	0.01	0.55	0.01
April		1.56	0.02	0.47	0.01	0.48	0.01
May		1.49	0.02	0.46	0.01	0.53	0.01
June		1.73	0.02	0.56	0.01	0.59	0.00
Total (kg CH_4/hd/yr)		**23.07**	**0.17**	**7.37**	**0.06**	**7.34**	**0.10**

1 head of cattle=250kg of LW, 1 head of sheep=45kg of LW, 1 head of goat= 40kg of LW

The total enteric methane emission of the three main animal species at the whole year level ranges between 0.53±0.01 kt CH_4/yr and 0.67±0.01 kt CH_4/yr (table 2.11). Whereas the value would have been 0.73 kt CH_4/yr when considering a Tier 2 IPCC method and a standard intake of 6.25 kg DM /day with a 58% digestibility. Cattle is the main contributor whatever the base of estimation (59% using TLU and 43% using metabolic weight) followed by sheep and goat with 32-9% and 40-16% respectively on the base of TLU and MW respectively. Calculations on a ML basis give more importance to small ruminants.

Enteric methane emission intensities in the WTSA vary along species and products (table 2.11). For meat and milk cattle shows a higher emission intensity than the small ruminants when CH_4 emission was calculated per kg of CW or per kg of FPCM.

Table 2. 11. Contribution of the three ruminant species to the total enteric emission in the WTSA and emission intensities

	Estimation base	Cattle		Sheep		Goat		All species	
		Value	sd	Value	sd	Value	sd	Value	sd
Total Enteric methane emissions ***(kt CH_4/yr)***	TLU	0.31	0.00	0.17	0.01	0.04	0.01	0.53	0.01
	MW	**0.29**	**0.01**	**0.27**	**0.01**	**0.11**	**0.01**	**0.67**	**0.01**
Enteric methane emission intensity Meat ***(kg CO_2-eq/kg CW)***	TLU	16.77	0.12	8.16	0.04	7.62	0.08	10.71	0.07
	MW	**15.61**	**0.12**	**12.94**	**0.07**	**18.65**	**0.20**	**14.34**	**0.10**
Enteric methane emission intensity Milk ***(kg CO_2-eq/kgFPCM)***	TLU	1.75	0.01	0.85	0.01	0.79	0.01	1.31	0.01
	MW	**1.63**	**0.01**	**1.35**	**0.01**	**1.94**	**0.02**	**1.58**	**0.01**

4. Discussion

On a methodological point of view many methods have been used in the study to address the integrated assessment of the year round and seasonal livestock - forage balances, up scaled at the level of the WTSA ecosystem and to further discuss the consequences in terms of grazing efficiency, and resulting enteric methane emission. Regarding vegetation production and animal demography assessments, most of these specific methods are long-time established and discussed in the literature (Guerin, 1987; Hiernaux *et al.*, 2009a; Lesnoff *et al.*, 2013; Decruyenaere, 2015). The most relevant aspect to discuss is the consistency in combining these methods to bring the aggregated view.

4.1. Comparison of methods to assess voluntary feed intake and diet digestibility of grazing ruminants in the Sahel

In the approach of the interaction between vegetation and animals the most important variable still rather difficult to assess is the effective voluntary fodder intake in such free grazing pastoral systems. The originality of this study has been the concomitant use of assessment protocols on vegetation fodder and on animal feeding behavior. The comparison between "hand plucking", mimicking the animal behavior grazing in rangeland and the prediction of the quantities ingested according to NIRS calibration on the non-digested part of the resource shows that results match in terms of feeding level as well as in terms of diachronic variations. Correlation between hand plucking, faecal bags and F-Nirs datasets are not extremely high (+/-0.5) and standard error in regression between variables are large but this is in part due to the fact that the two measures are not really synchronic; faeces reflect the diet collected a few days before the hand plucking observation. In addition, each method has a quite large repeatability error. Averaged for each period, the results are however coherent between the different methods and with the observations made in other studies and environments (Bois *et al.*, 2014; Chirat *et al.*, 2014; Lecomte *et al.*, 2016). Regarding the field implementation of the protocols, F-NIRs offer real opportunities as the number of samples is not limiting being easy to collect and relatively cheap to analyse. Regarding the ecology of the fodder use in open rangelands, the combination of the two assessment methods allows a description of the main component entering in the diet and a good estimate of feed intake and thus of the diet nutritional value. Approaches on the value of the reconstituted diet are also a helpful tool to ex-ante characterize the nutritional value of the diet. It confirms the rapid decrease of the energetic and protein content of the diet during the DS. However, even if the NIRS predictions are cheap, the sampling, sorting, grinding of collected forages and diet reconstitution operations are highly time and manpower consuming.

4.2. Impact of the declining herbage quality on the intake behaviour of cattle, sheep and goats

The feed digestibility and nutritive values of diets simulated by hand plucking or predicted from faeces compare well with the literature for the SSA environments. Rainy and early dry season predictions of digestibility are close to estimates from experimental stations (Guerin, 1987; INRA, 1988; Ouédraogo-Koné *et al.*, 2008; Kouazounde *et al.*, 2015). However, forage intake predicted from faeces as well as assessed by hand plucking shows a general decline to very low values in mid and late dry season. These low values are comparable with the observations made by Ickowicz and Mbaye (2001) and Bois *et al.* (2014) using the same hand plucking methods, Fernández-Rivera *et al.* (2005) using oesophagal fistulae and faecal bags, and Schlecht *et al.* (1999) with faecal bags and markers.

Feed intake in the dry season lay far below the standard value of 6.25 kg DM/day for a 250 kg TLU recommended in Rivière (1991) to cover maintenance needs of grazing livestock (Figure 2.10) even when the standard is adjusted to cattle live weights. The cumulated discrepancy of the effective intake highlights the large seasonal feed gap of pastoral livestock in Sahel. As stated by Decruyenaere *et al.* (2009a) in her review on intake of grazing ruminants control of ingestion. It depends, at the same time, on plants characteristics (i.e. forage digestibility) in relation to the gut capacity, on the animal’s requirements and nutrient concentrations of forages, on the post-ingestive feedback of the intake and on the environmental such as climate (temperature, hygrometry), abundance and frequency of feed resources. The decreasing availability of the forage and the rapidly decreasing digestibility evidenced in the study are certainly highly conditioning factors.

These low feed intake values in the dry season should be considered when assessing annual feed balance of pastoral livestock, knowing that they stand lower than maintenance requirement as stated by (Grimaud *et al.*, 1998; Schlecht *et al.*, 1999; Atti *et al.*, 2004) and reveal seasonal under-nutrition conditions. With such feed intake and digestibility ruminants do not cover their maintenance needs during the mid and late dry season explaining seasonal weight losses in body reserve catabolism and the low productivity year round of pastoral livestock in Sahel.

The grazing pressure assessed by the ratio of feed intake to available forage (table 2.5) varies on a large range seasonally and between years, depending on both vegetation growth and stocking rates. In 2014-2015 grazing pressure increase assessed for the sole herbaceous above ground mass increased from about 5% in the wet season to 6-15% during the dry season and peaked at 76% in June. However, woody plant green leaf, and possibly pods, complemented the diet during the HDS. Over the year cycle, aggregated feed intake by all livestock within the WTSA remained less than a third of the sole herbaceous above ground production, and only account for a very small fraction (7.2%) of the woody plant leaf production.

4.3. Emission factors of enteric methane

According to literature biological processes are responsible for 55% to 70% of annual anthropogenic methane emissions at the world scale (Thorpe, 2009) with enteric fermentation from domestic ruminants as a major contributor to global emissions (39%) (Steinfeld *et al.*, 2006). Depending on the quantity and quality of the diet fed, ruminants release different quantities of methane into the atmosphere as by-products of an anaerobic digestion process. For cattle, sheep and goat, methane is directly related to the level of intake (Beauchemin *et al.*, 2009) and the digestibility of the forage consumed (Decruyenaere, 2015). It explains why in this study the daily emissions of methane vary highly between the seasons and appears to be 29.5% lower in late dry season compared to the rainy season.

Pooled over the year the emission of cattle expressed per TLU averages 23.07±0.17 kgCH_4/TLU/yr, far below the 46 kg default Tier 1 value of IPCC (2006) or the 39.5 kg recently estimated in Tier 2 for Benin cattle in Kouazounde *et al.* (2015) for standard animal of 250 kgLW. For small ruminants the annual emission value of 7.37±0.06 kg CH_4/hd/yr and 7.34±0.10 kg CH_4/hd/yr respectively for sheep and goat is slightly smaller than 5 kg CH_4/hd/yr proposed as default value by IPCC (2006) for standard animals of 45 and 40 kgLW for sheep and goat espectively. However, within the WTSA observed average animal weights are lower: 208.7kg, 38.5kg and 18.7kg respectively for cattle, sheep and goat. It induces even lower emission factors per head: 20.3±0.15 kg CH_4/hd/yr, 6.16±0.05 kg CH_4/hd/yr and 4.15±0.07 kg CH_4/hd/yr for cattle, sheep and goat respectively.

Emission of CH_4 in ruminants differs depending with animal species, breeds, pH of rumen fluid, ratio of acetate : propionate, methanogen population, composition of the diet and amount of concentrate fed (Sejian *et al.*, 2011). Small ruminants with 424.18±3.45 and 461.49±6.29 g CH_4/kgMW/yr respectively for sheep and goat have higher enteric methane emission per kg of metabolic weight than cattle (366.93±2.7 g CH_4/kgMW/yr).

When comparing to the most recent literature the WTSA enteric methane emissions intensity expressed per kg of product for the three ruminant species appear quite lower (table 2.12) than the estimation proposed by FAO (Gerber *et al.*, 2013). As annual livestock productivities are low, methane emission intensities per unit of animal product stay higher than in more intensive animal production systems of OCDE countries where methane emission intensity are averaged at 5.5 kg CO_2-eq/kg CW and 0.7 kg CO_2-eq/kgFPCM for cattle and 6.2 kg CO_2-eq/kg CW and 2.8 kg CO_2-eq/kgFPCM for small ruminants (Gerber *et al.*, 2013). Even if the efficiency gap is less large, margins of progress still exist.

Table 2. 12. Enteric CH_4 emission intensities for meat and milk production found in this study for the WTSA and compared to FAO estimations

	Estimation base	Cattle		Sheep		Goat	
		Gerber et al, 2013	WTSA	Gerber et al, 2013	WTSA	Gerber et al, 2013	WTSA
Enteric CH_4 emission intensity for meat ***(kg CO_2-eq/kg CW)***	*TLU*	*41*	*16.77*	*21.5*	*8.16*	*21.5*	*7.62*
	MW	**-**	**15.61**	**-**	**12.94**	**-**	**18.65**
Enteric CH_4 emission intensity for milk ***(kg CO_2-eq/kgFPCM)***	*TLU*	*5.2*	*1.75*	*4.9*	*0.85*	*4.9*	*0.79*
	MW	**-**	**1.63**	**-**	**1.35**	**-**	**1.94**

Estimations of enteric CH_4 emission intensities given by FAO where only calculated on a TLU basis.

When considering the spatial dimensions of the annual enteric emission intensity is 5.54±0.07 kgCH_4/ha/yr distributed between cattle (3.23±0.02 kgCH_4/ha/yr), sheep (1.73±0.01 kgCH_4/ha/yr) and goat (0.58±0.01 kgCH_4/ha/yr). In total, cattle contribute the most to the greenhouse effect through methane emission followed by sheep and goats respectively but cattle have the lowest emission per unit live weight as well as per metabolic weight (table 2.12.). The enteric emission estimated here on large field observations are in the range of 5.1 to 10 $kgCH_4/ha/yr$ estimated for Senegal by Herrero *et al.* (2008).

On the basis of data collected in the WTSA with the hand plucking and faces bad methods, we estimated that from the 31.52 kt DM ingested annually by the ruminants 15.79 kt DM are deposited under the form of excreta directly onto the soil. Similar results were obtained from F-NIRS approaches with a total annual intake of 34.47 kt DM and 13.93 kt DM excreted directly onto the soil. This restitution of organic matter participates to GHG emissions from soil and water. In the WSTA the cumulated soil and water CH_4 emissions were estimated at 17.4 $kgCH_4/ha/yr$ (Assouma et al, 2016 in press; Chapter 3). Soil and water CH_4 emissions are largely higher than the total enteric methane emissions estimated in this study (5.54 $kgCH_4/ha/yr$). However, the large restitutions of organic matter to the soils via the excreta deposition also has a positive impact on the vegetation ecosystem productivity and on soil carbon accumulation, two key ecological processes involved in climate change mitigation.

Conclusion

The integration of different methods to evaluate along time, at the scale of a large landscape, the available resources and their use by large numbers of animals of different species, managed under pastoralism practices is rather original for the Sub-Sahara African environments. The study illustrates the fact that stocking rates in Sahel pastoral systems are very dynamic in the course of the year cycle and are a quite complex indicator to manage when multiple species are present in the herds. The contribution of small ruminants is better accounted for the calculations based on metabolic weight. They give a more balanced evaluation of their contribution in the resources uses and impacts in the ecosystem. Stocking rates change seasonally in adaptation to rainfall and its effect on herbaceous resources availability and quality in the studied area. Herders move large part of the livestock out of the studied area when forage become more limited; this essential transhumance practice remain feasible because of the more or less formalized pastoral codes that guarantee the open access to communally managed rangelands. The practice often criticized against a general idea of sedentarisation of population and animals is a key factor of the maintenance of such large landscapes. Further general stocking rates rules developments on the monitoring of the dynamics of such indicator would be useful to better support herders and landscape managers decision.

The study describes an original application of the faecal NIRS (F-NIRS) methodology to estimate intake and digestibility of resources consumed by the animals and to derivate from both parameters the seasonal variation of enteric methane emissions. When confronted to the large faeces spectral database with in vivo references on multiple species issued in temperate, Mediterranean and tropical environments, even if it applies as an indirect method, F-NIRS and local calibration technique provides here an robust tool for description of the levels and variations of digestibility and intake in such particular SSA environment. Many similar approaches on F-NIRS already showed the relevance of the technique for such application in the humid tropics the study contributed to contextualize to dry situations. The large number of samples analyzed for a low cost at the different periods of the survey gives the opportunity to reasonably estimate relevant mean values and seasonal variations.

This research has been undertaken to provide a set of reference scaled from the level of the individual animal to the landscape scale and to contribute to the improvement of poorly documented estimates of the enteric emissions in SSA. On this important indicator of the livestock production in a country or a region the results show the large monthly variations of the emissions across the seasons. When summed up over the year these results differ from the default norms (Tier 1) generally attributed to cattle while they appear to stay close to those norms for small ruminants. The information provided here need certainly to be confirmed for additional landscapes and combination of practices. It however brings food for thought in the development of dedicated tools for monitoring and for the refinement of the national carbon inventories that each country needs to undertake in the coming years. Further work of the team (CIRAD, DP-PPZS) is actually on going on *in situ* direct measurement to validate and confirm the predicted values obtained in this study.

Conclusions intermédiaires et transition

Le Chapitre 2 essentiellement zootechnique permet de mieux comprendre comment l'animal se trouve au centre du fonctionnement des écosystèmes pastoraux en milieu semi-aride en contexte sahélien. Il permet d'aborder l'importante question de la gestion du chargement animal. Ce chapitre apporte également une vision originale sur les prélèvements de fourrages réels des animaux et la proportion de biomasse herbacée aérienne réellement utilisée. Cette dernière est largement en dessous des idées qu'on peut se faire de ces systèmes. Ce chapitre a permis de réévaluer les facteurs d'émission de méthane entérique qui constitue l'une des principales sources de GES des écosystèmes étudiés.

Le Chapitre 1 avait également souligné l'importance des émissions de GES depuis le sol du fait des restitutions de déjections animales, elles représentent 21% des émissions totales du GES du territoire. Elles font donc l'objet d'une attention particulière dans le chapitre suivant (Chapitre 3). Un suivi des émissions de CO_2, N_2O et CH_4 dans le temps et dans l'espace a donc été mis en place afin de mieux évaluer leur importance quantitative et leur variabilité dans le temps et l'espace.

Chapitre 3: Variabilité spatio-temporelle des flux de de Gaz à effet de serre (CO_2, N_2O, CH_4) depuis le sol et l'eau en territoire sylvo-pastoral

Ce chapitre se base sur un article accepté dans la revue « Journal of Arid Land » :
Assouma M.H., Serça D., Guérin F., Blanfort V., Lecomte P., Touré I., Ickowicz A., Manlay R. J., Bernoux M., Vayssières J. 2016. Livestock induces strong spatial heterogeneity of soil CO_2, N_2O, CH_4 emissions within a semi-arid sylvo-pastoral landscape in West Africa. In press in Journal of Arid Land.

Un poster intitulé « Impact of livestock on the spatial heterogeneity of CO_2, N_2O, CH_4 soil emissions in a sylvo-pastoral ecosystem in sub saharan west Africa » a également été présenté au « 6th Greenhouse Gas and Animal Agriculture Conference (GGAA2016) » à Melbourne en Australie du 14 au 18 février 2016.

Des données complémentaires produites dans le cadre de ce suivi font l'objet d'un autre article en cours de construction. Il s'agit de :
Assouma M. H., Serça D., Guérin F., Bernoux M., Blanfort B., Lecomte P., Ganglo J.C., Delon C., Tagesson T., Vayssières J. Modelling the spatio-temporal variability of greenhouse gas fluxes (CO_2, CH_4, NO_2) from soil and water in a sylvo pastoral semi-arid landscape in Africa. To be submitted to Agriculture, Ecosystems & Environment.

Abstract:

Greenhouse gas emissions (GHG) from the soil and surface water receiving animal excreta may be important components of the GHG balance of terrestrial ecosystems, but are poorly documented in tropical environments. A typical sylvo-pastoral landscape in the semi-arid zone of Senegal was investigated. The study area (706 km^2 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 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 CO_2 eq/(ha.yr) (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 1,148.2±91.6 mg/(m^2.d) in rangelands to 97,980.2±14861.7 mg/(m^2.d) from surface water in the vicinity of the borehole. N_2O fluxes ranged from 0.6±0.1 mg/(m^2.d) in forest plantations to 22.6±10.8 mg/(m^2.d) in the vicinity of the borehole. CH_4 fluxes ranged from -3.2±0.3 mg/(m^2.d) in forest plantations to 8,788.5±2,295.9 mg/(m^2.d) from surface water in the vicinity of the borehole. This study identified GHG emission "hot spots" in the landscape. Emissions from the soil 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.

1. Introduction

Climate change is among the most pressing sustainability challenges facing humanity today, and poses serious risks for ecosystem health. It is now widely accepted that concentrations of greenhouse gas (GHG) have risen at unprecedented rates since the industrial revolution (IPCC, 2013). After carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the two GHGs that contribute the most to anthropogenic and natural radiative forcing (IPCC, 2013). Together, these three GHGs contribute more than 90% of anthropogenic climate warming. The CO_2 fluxes 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). Our knowledge of the magnitude of GHG exchange between tropical ecosystems and the atmosphere is still limited (Wang et al., 2013; Ahlström et al., 2015). Large uncertainties also arise when soil-air fluxes of GHG in semi-arid lands (Ahlström et al., 2015) and water-air GHG exchanges are estimated due to the paucity of available data and to our poor understanding of underlying processes in tropical inland environments (Borges et al., 2015).

Extensive pastoral systems occupy most of the dry regions in the world where agricultural production is generally marginal (Nori et al., 2005) and a quarter of the total drylands of Africa (66% of the total continent land area) (Boval and Dixon, 2012). Because of climate change, pastoral systems are projected to expand in West Africa (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 in its two main forms, transhumance and nomadism, is a way of life that is still very common in arid and semi-arid zones, where very few rural activities other than raising ruminants are feasible (Turner et al., 2014). With their own way of managing space and time, based on mobility and "ancestral" knowledge (Manoli et al., 2014), pastoral communities have succeeded in making best advantage of the natural resources of vast, practically desert areas that are poorly conducive to the development of agriculture. In so doing, they have managed to develop and sustain an economic potential and an ecological and social system unique of its kind. Extensive pastoral systems contribute significantly to national economies and to the livelihoods of rural populations in sub-Saharan Africa; however, these systems 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 carbon cycle and their potential ecological and socio-economic vulnerability in the future, *in situ* measurements are still lacking (Tagesson et al., 2015a).

Soils in rangelands, combined with livestock production systems, are responsible for a large share of GHG emissions, but under certain conditions, these soils can also act as carbon sinks (Soussana *et al.*, 2010b). Most recent estimates of the net long-term carbon balance of African ecosystems based on observations including losses from fire disturbance gives a sink of the order of 0.2 Pg C /a with a large uncertainty around this number (Valentini et al., 2014). In pastoral ecosystems, the mechanisms driving the exchange of GHG between soil and water and the atmosphere are complex and knowledge on these ecosystems is lacking (Valentini et al., 2014), especially in tropical environments (IPCC, 2013). Under arid to semi-arid conditions, soil moisture is one of the main factor controlling emissions of CO_2 (Kuzyakov and Gavrichkova, 2010; Yemadje et al., 2016) and N_2O from the soil (Ussiri and Lal, 2013),while CH_4 emissions occur only in hydromorphic conditions (Serrano-Silva et al., 2014). In pastoral ecosystems, large amounts of manure are produced and deposited, thereby directly or indirectly affecting GHG emissions via modifications of the chemical and physical properties of the soil (Thangarajan et al., 2013). Different processes are involved including microbial processes (priming, methanogenesis, nitrification/denitrification) and modification of the physical characteristics of the soil (texture and moisture). Livestock, as a vector of organic matter, also plays an important role in the spatial redistribution of nutrients and carbon. This is particularly true in West African agro-pastoral ecosystems (Manlay et al., 2004a; Manlay et al., 2004b; Schlecht et al., 2006) and, due to the high mobility of herds and the importance of ruminants in the functioning of the ecosystem, a similar situation can be envisaged for pastoral ecosystems elsewhere. The resulting heterogeneous distribution of animal excreta in the landscape may affect the heterogeneity of soil properties and spatial variations in available nutrients as well as the distribution of plant roots. These factors significantly affect CO_2, N_2O via microbiological processes (Smith et al., 2003).

The purpose of this study was thus to evaluate the magnitude of the spatial heterogeneity of the emissions of CO_2, N_2O and CH_4 from the soil and surface water in a pastoral landscape, and to identify possible links between this variability and the important role played by livestock in ecosystem functioning. Our specific objectives were to: (1) quantify CO_2, N_2O and CH_4 fluxes in the different landscape units; (2) assess the spatial heterogeneity of GHG fluxes; and (3) link heterogeneity 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 of influence of the Widou borehole. This area is assumed to be representative of sylvo-pastoral ecosystems in northern Senegal.

2. Material and methods

2.1. Study area and sites

The study was carried out in the sylvo-pastoral Ferlo region of Senegal. Like in the whole Sahel region, the climate is tropical semi-arid. The Ferlo region is characterized by a high seasonal, annual and decadal rainfall variability and relatively high average annual temperatures

(Martínez et al., 2011). Three main seasons, each lasting four months, are usually distinguished: a wet season from July to October, a cold dry season from November to February and a hot dry season from March to June. Total annual rainfall is both low and highly variable, with an average of 296 mm/a, and 28% long-term rainfall variability (observations in the 1981-2007 period at the Widou weather station (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.*, 2014a).

The Ferlo region is organized around a network of boreholes at 30 km intervals, which 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 (Figure 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 survey activities of the group on pastoral systems and dry lands (French acronym PPZS) (Ancey et al., 2008; Bah et al., 2010), and the presence of enclosed experimental grazing plots hereafter referred to as 'enclosures' created over 30 years ago as part of a project implemented by the German agency for Technical Cooperation (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 (TLU/ha) depending on the seasonal movements of the herds.

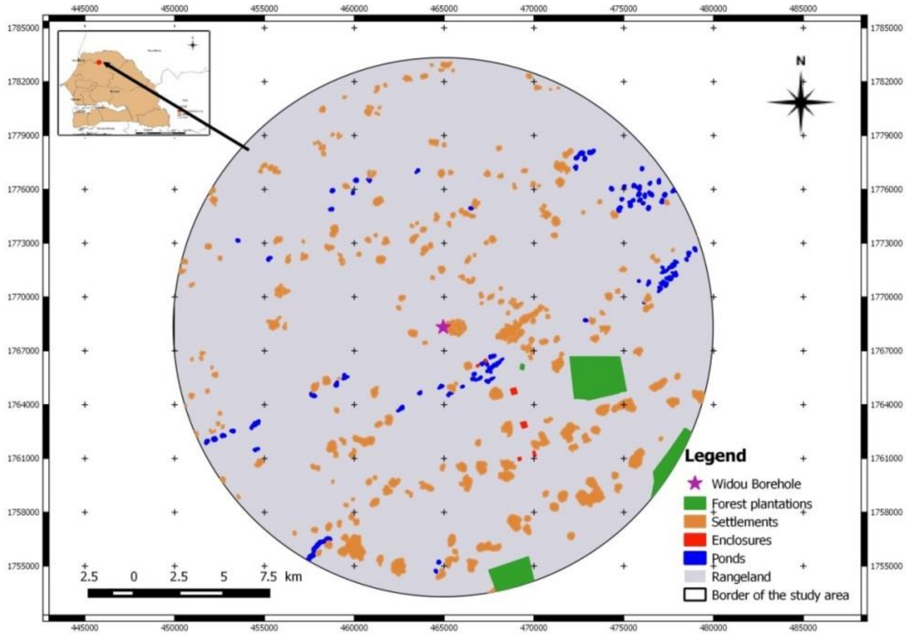

Figure 3. 1. Map of the study area around Widou borehole

A combination of GIS and field observations was used to define, map, and describe the main landscape units representing the spatial heterogeneity of the entire landscape (Fig. 1). Using a Landsat ETL+204-049 image acquired on November 3, 2010, six landscape units were defined based on land use and topography:

i. The **vicinity of the borehole** (<1 km², or 0.1% of the total 706 km^2 area), this corresponds to the part of the landscape in which the borehole is located, and includes the pump, the water tower and a tank. The borehole is used to water herds of cattle, goats, sheep, horses and donkeys and is where the animals rest after being watered. The soil close to the tank receives overflow water and is waterlogged all year round. We investigated both stagnant surface water and the soil around the tank.

ii. **Settlements** (44 km², 6.3%), these correspond to the land occupied by the herder's homestead and a corral for the herd. These areas are characterized by high SOM due to the accumulation of manure from the different livestock species during night corralling.

iii. **Natural ponds** (19 km², 2.7%), these correspond to areas of clayey soil where stagnant water accumulates temporarily during the wet season, but dries out two to three weeks after the last rainfall. The ponds are used by livestock to drink as an alternative to the borehole. We investigated both the water from the ponds and the soil in the shoreline of the ponds.

iv. **Forest plantations** (6 km², 0.9%), these were established by the government of Senegal as part of the Great Green Wall project. They are mainly planted with Acacia spp.

v. **Native rangelands** (635 km², 89.9%) correspond to the space occupied by natural vegetation (grass, shrubs and trees) actively pastured by livestock. This area is crossed by livestock pathways.

vi. **Enclosures** (<1 km², 0.03%) correspond to the six experimental enclosed plots described in (Miehe *et al.*, 2010).

2.2. Data collection

To investigate seasonal variability of greenhouse gases, field campaigns were conducted on six occasions between May 2014 and January 2015, once during the hot dry season (May 2014), once a month during the 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). This rational sampling took into account both the extent of the area occupied by each unit (n=5 corresponding to a sampling density of 0.01 measurement/km² on native rangelands which account for the largest of all the units) and the ability to have high emission units rates with high soil organic matter content (n=2 corresponding to a sampling density of 5.1 measurements/km² in the vicinity of the borehole, settlements and natural ponds).

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 gas chromatography (SRI 8610C equipped with ECD and a FID-methanizer).

The diffusive fluxes were calculated from the slope of the linear regression of the concentration of gas in the chamber versus time. 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 GHG 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 measurement sites in January 2015. Soil samples were used to determine soil total carbon (C), nitrogen (N), and phosphorus (P), NH_4^+, NO_3^-, bulk density and physical fraction sizes in the certified ISO9001 LAMA laboratory: 2008 by Euro-Quality System. The methods of soil analysis are described in full in (Pansu and Gautheyrou, 2006).

2.2.3. Collection of solid manure and monitoring of livestock

Each month, the solid manure deposited on the soil by livestock was collected manually in four 0.25 ha plots in all the landscape units. The total quantity of solid manure in each livestock category (cattle, small ruminants and non-ruminants) was weighed; samples were then taken and 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. Data analysis

2.3.1. Correlation between fluxes and environmental parameters

All statistical analyses were conducted with R software (RCoreTeam, 2015) using the ‘‘lme4’’ package for linear regression analysis and ‘‘ade4’’ (Dray and Dufour, 2007) for ANOVA. Data were checked for normality of residual 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 deposed on the soil.

2.3.2. Scaling up measurements for seasonal, annual and landscape 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 widely practiced simplified method (Valentini et al., 2014). It only takes into account emissions from rangelands, as the entire landscape comprises this unit (90% of the borehole territory is covered by native rangelands). The second approach, called “All landscape units” takes into account the spatial heterogeneity of GHG emissions. In both cases each flux measurement was weighted according to the length of the sampling season and to the relative surface area of the different landscape units in the landscape concerned to calculate the total GHG emissions at the year and landscape level.

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

3. Results

3.1. Spatial variability of manure deposition and GHG emissions

Table 3.1 lists the livestock stocking rate in a given landscape unit, the quantity of solid manure deposited on the soil per month and the physical-chemical characteristics of the soil in the different landscape units. The livestock stocking rate is expressed in tropical livestock units (TLU) per unit area (ha), where one TLU is equivalent to an animal of 250kg 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 where dung excreta are quantified in kilogram of dry matter (DM). The soils in the vicinity of the borehole were richer in nutrients and organic matter (total C, total N, mineral N and total P contents of the soil). However, there was more mineral nitrogen in the soil near settlements than in the vicinity of the borehole.

Table 3. 1. Livestock stocking rate, solid manure deposition, physical-chemical characteristics of the soil (0-10cm)

All data are mean ± standard deviation,

Landscape units	Stocking rate [1] (TLU/(ha.month))	Excretion rate [2] (kg DM/ (ha.month))	Soil total C content (g/100g)	Soil total N content (g/100g)	Soil mineral N content (µg N/ g)	Soil total P 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
Shoreline 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

[1] Is the instantaneous stocking rate (in tropical livestock units (TLU) per unit area (hm^2)), i.e. the allocation of the whole landscape livestock stocking rate among the different landscape units. It takes into account monthly variations of the whole landscape stocking rate and the relative surface area of each spatial unit.

[2] DM = Dry Matter

Table 3.2 lists soil GHG emissions in the different landscape units. Soil CO_2 fluxes ranged from 1148.2±91.6 mg/(m^2.day) in rangelands to 97,144.1±52,450.1 mg/(m^2.day) in the vicinity of the borehole. The mean CO_2 flux across all landscape units was 4,352.7±1,220.1 mg/(m^2.day). Soil N_2O fluxes ranged from 0.6±0.1 mg/(m^2.day) in forest plantation to 22.6±10.8 mg/(m^2.day) in the vicinity of the borehole. The mean N_2O flux across all landscape units was 2.5±0.9 mg/(m^2.day). Soil CH_4 fluxes ranged from -3.2±0.3 mg/(m^2.day) in forest plantations to 691.3±352.6 mg/(m^2.day) in the vicinity of the borehole. The mean CH_4 flux across all landscape units was 2.6±2.5 mg/(m^2.day).

Table 3. 2. Soil GHG emissions in the six different landscape units

All data are mean ± standard deviation, a superscript letter after the standard deviation indicates significant differences between landscape units (Tukey's HSD test; $p < 0.05$).

Landscape units [1]	CO_2 flux (mg CO_2/(m².day))	N_2O Flux (mg N_2O /(m².day))	CH_4 Flux (mg CH_4/(m².day))
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	17915.6±8602.8 ^{a}	6.2±3.4 ^{a}	277.9±72.3 ^{a}
Shoreline of the ponds	6898.5±4023.6 ^{b}	3.0±0.6 ^{ab}	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**

[1] Do not include data on water-atmosphere exchanges

CO_2 and N_2O fluxes exhibited similar trends. CO_2 and N_2O emissions from the soil 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 was no significant difference between CO_2 and N_2O emissions in the vicinity of the borehole and the settlements on the one hand, and between forest plantations, enclosures, rangelands and the shoreline of the ponds on the other hand.

The spatial pattern of CH_4 emissions from the soil differed slightly from that of CO_2 and N_2O. The highest CH_4 emissions were measured in the vicinity of the borehole and the shoreline of the ponds; they were 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 shoreline of the ponds, nor between forest plantations, enclosures, rangelands, the shoreline of the ponds, and the settlements.

Concerning GHG exchanges between water 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, so no N_2O fluxes could be calculated. CO_2 fluxes ranged from 5,855.1±970.5 mg/(m².day) in natural pond water to 97,980.2±14,861.6 mg/(m².day) 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±5,481.2

mg/(m².day). CH_4 fluxes ranged from 142.2±1.1 mg/(m².d) in natural pond water to 8,788.5±2,295.9 mg/(m².day) in the stagnant water around the borehole. The calculated overall mean (for both landscape units) of CH_4 fluxes was 3,170.8±659.4 mg/(m².day). CO_2 fluxes from ponds did not differ significantly from emissions from the soil, whereas fluxes of CH_4 from ponds were positive and significantly higher ($P<0.05$) than fluxes from the soil. On average, CH_4 fluxes from ponds were 45 times higher than fluxes of CH_4 from the soil.

3.2. Contribution of the different landscape units to total emissions from soil and water at landscape level

Figure 3.2 shows the contribution of the three GHGs to total GHG emissions from the soil and water at landscape level. CO_2 was the main contributor and accounted for 82% of total emissions. N_2O and CH_4 accounted for respectively 15% and 3% of total emissions (Fig. 3.2). Rangelands, which represent 90% of the entire territory, were the main contributors to CO_2 and N_2O emissions despite relatively low fluxes per unit area. However, rangelands contributed very little to CH_4 emissions. The vicinity of the borehole and the shorelines of the ponds were the main sources of emissions of CH_4 from the soil (93% of CH_4 emissions) even though this area accounted for less than 3% of the entire territory.

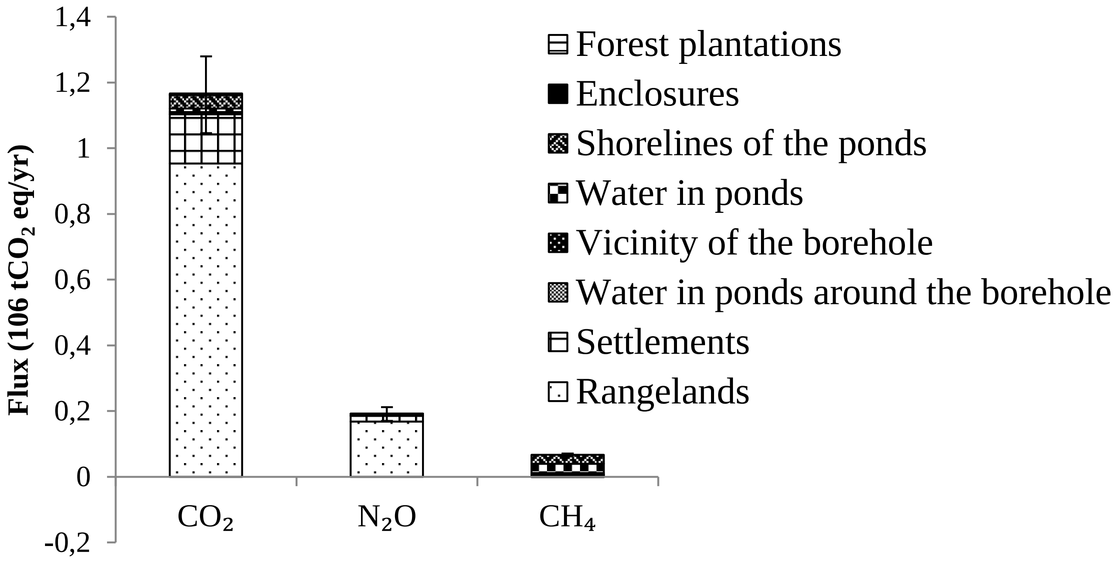

Figure 3. 2. Contribution of the three GHGs (CO_2, N_2O, CH_4) to total GHG emissions from soil and water at landscape level

Figure 3.3 shows the contribution of the three seasons (wet, cold dry and hot dry seasons) to average daily emissions of GHG from the soil and water at the landscape level. Most emissions (65%) occurred during the wet season. The cold and hot dry seasons represented 14% and 21%

of total emissions, respectively (Fig. 3.3). During the three seasons, rangelands were the main sources of GHG emissions, especially during the dry seasons when they accounted for more than 90% of total emissions. The contribution of settlements, ponds, and the vicinity of the borehole increased during the wet season mainly due to the higher CH_4 emissions rates during this season (see section 2.1).

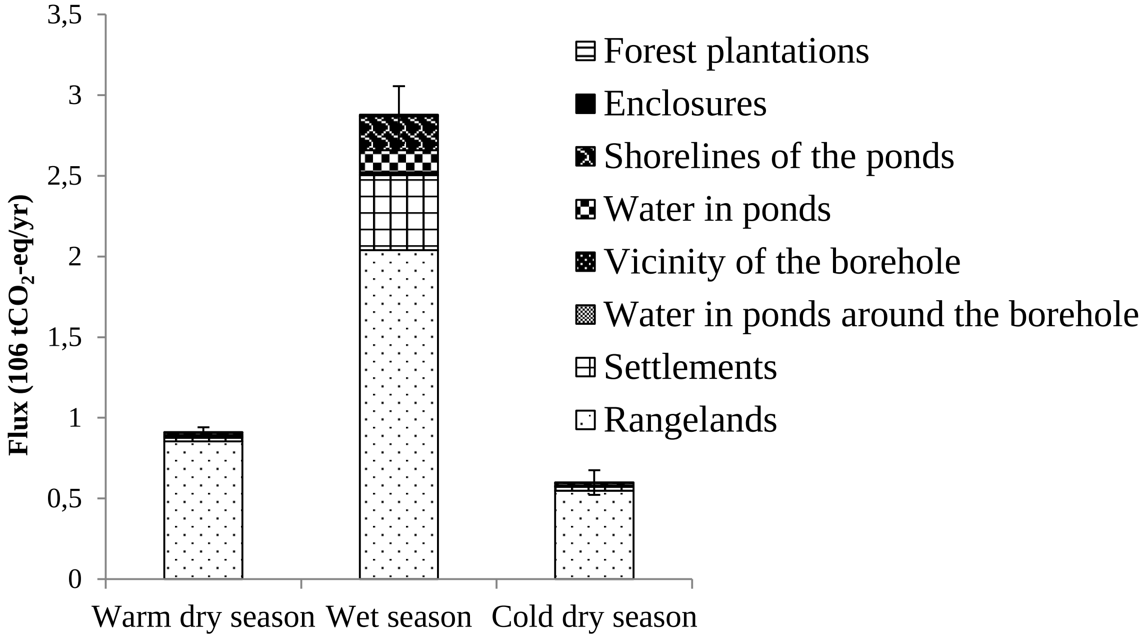

Figure 3. 3. Contribution of the three seasons (wet, cold dry and warm dry seasons) to total GHG emissions from soil and water at landscape level

4. Discussion

4.1. Impact of livestock on the spatial variability of GHG emissions

This study underlines the high spatial heterogeneity in GHG exchanges with the atmosphere. In the case of CH_4, the highest emissions per area were recorded in permanently or temporarily flooded landscape units (the borehole and ponds) where hydromorphic conditions favor methanogenesis (Serrano-Silva et al., 2014). These units are also highly frequented by animals (Table 3.1). 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/(m^2.day), 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/(m^2.day), respectively. 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 consistent with reports in the literature that consider non-flooded grassland soils to be sinks for atmospheric CH_4 (Mosier et al., 2004) and more generally, 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 is explained by the high inputs of manure (Table 3.1), which stimulate microbial activity. Figure 3.4 shows the relation between GHG emissions and the solid manure inputs observed in the sylvo-pastoral ecosystem studied here.

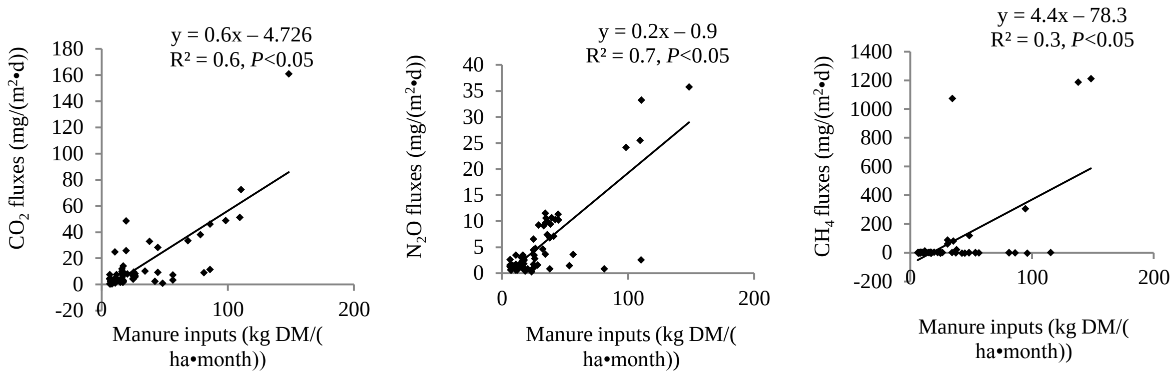

Figure 3. 4. Regression between soil GHG emissions and inputs of manure all landscape units considered

Figure 3.4 shows the positive effect of inputs of manure deposited on the soil on GHG emissions as reported by (Lin *et al.*, 2009). The correlation is stronger for CO_2 and N_2O fluxes ($R^2>0.5$ and $P<0.05$) than for CH_4. Manure is a direct source of CO_2 emissions (Clemens and Ahlgrimm, 2001) and of N_2O emissions (Yamulki et al., 2000). Manure deposition also represents inputs of large C and N and can consequently increase soil C and N contents (Hiernaux et al., 1999), as well as modify soil microbiological activity in such ecosystems (Chotte et al., 2012), especially in the case of long-term manure deposition (Petersen et al., 2013). Manure consequently also indirectly increases GHG emissions from the soil to the atmosphere (Yamulki et al., 2000; Li and Kelliher, 2007; Saggar et al., 2007).

The spatial organization of manure deposition certainly explains a large proportion of the spatial heterogeneity of the GHG emissions observed in this study. Quantification of the biomass, nutrients, and C flows resulting from the different uses of organic resources at the level of the landscape, done for wetter ecosystems than the one studied here, demonstrated the important role played by livestock in the spatial organization of soil nutrients and C stocks (Schlecht et al., 2004). In the Sudanian savanna agro-pastoral ecosystems, traditional practices like free grazing and night corralling lead to nutrient and C 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 C 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 observed by (Brümmer *et al.*, 2009) between rangelands and croplands in Sudanian savanna agro-pastoral ecosystems. Similarly in Sahelian drier sylvo-pastoral ecosystems, like the ecosystem studied here, the spatial heterogeneity of GHG emissions can be explained by livestock-related N and C transfers in the landscape. Animals mainly intake vegetal biomass in specific landscape units (rangelands, tree plantations) while excretion preferentially occurs in others while resting (in settlements) or drinking (stagnant water around the borehole and in natural ponds). Organic matter is consequently concentrated in particular landscape units (vicinity of the borehole, settlements and natural ponds). These hotspots account for only 9.1% of the total area of Widou landscape but for 21% of total CO_2 eq emissions from the soil and water at landscape level.

4.2. Taking spatial variability into account for more accurate assessment of total GHG emissions at the landscape level

Our results underline the marked spatial heterogeneity of GHG emissions. This variability should be taken into account when quantifying soil and water total emissions at landscape level. Figure 3.5 shows total annual emissions (in CO_2 equivalents) of the three main GHGs from the soil and water in the ecosystem. The two approaches described in section 1.3.2, i.e. including (i) all landscape units or (ii) only native rangelands, are compared. According to the "Only native rangelands" and the "All landscape units" approaches, soil and water in the Widou territory (706 km^2) emit between 1.2×10^6 and 1.4×10^6 t CO_2 eq/a, respectively.

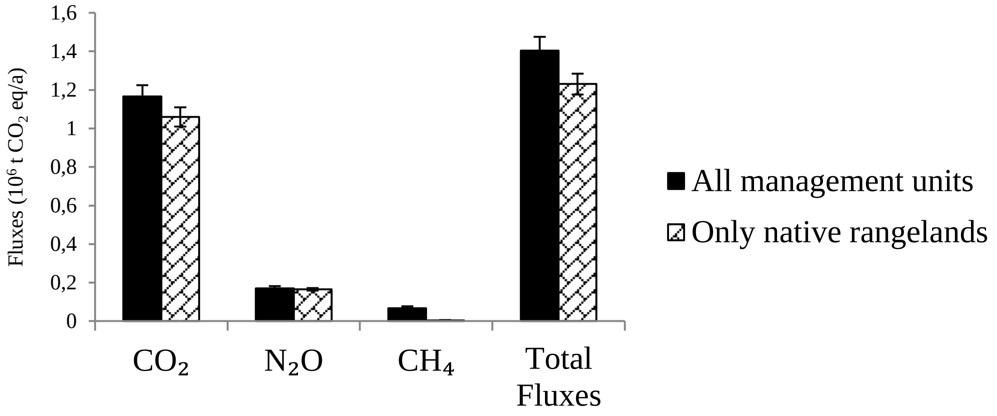

Figure 3. 5. Annual total GHG emissions from soil and water at landscape level calculated using two different approaches

If measurements were only made on rangelands, total emissions of CH_4 from the ecosystem would be underestimated by 94% because most of these emissions occur elsewhere than in rangelands. 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 underestimation of CO_2 emissions and the overestimation of N_2O emissions are less pronounced. The "only native rangelands" approach leads to +14% underestimation of the total emissions from the entire ecosystem despite the dominance of rangelands in the study area, where rangelands account for about 90% of the area. This can be explained by the fact that CO_2 emissions contribute most to global warming at the landscape level (Fig. 2), and, on the other hand, by the small surface area of CH_4 emission hotspots (ponds and the borehole, 2.8% of the area). This underlines the importance of taking the spatial heterogeneity of CO_2, N_2O and CH_4 emissions into account when assessing the GHG balance of sylvo-pastoral ecosystems characterized by high livestock stocking rates, mobile livestock systems, and a seasonal weather pattern. This study confirms that landscape level assessments of GHG require a combination of measurements across wide areas to enable extrapolations of GHG emissions (Harley et al., 2015). 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).

4.3. Taking temporal variability into account for more accurate assessment of total GHG emissions at the year level

Another way to increase the robustness of the assessment of yearly total GHG emissions from soil in tropical sylvo-pastoral ecosystems is the frequency of the GHG measurements. In the dry season, emissions fluxes are low and vary little over time because the soil is dry and the microbiological activity is considerably slowed down, justifying less frequent measurements (see section 1.2.). But during the wet season, microbiological activity and the resulting GHG fluxes are high. The occurrence of scaling up error is consequently certainly higher in the wet season despite the fact more frequent measurements were made in this season in the present study. Indeed the functioning of tropical soils is characterized by a dormant period during the dry season and mineralization flushes just after rainfall events at the onset of the wet season (Kim et al., 2012). It is consequently particularly difficult to capture the resulting variability of GHG emissions. It would require a dedicated monitoring program with very frequent measurements which was not the case in this study 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. The emission models usually used are hysteresis curves (Riveros-Iregui et al., 2007; Song et al., 2015). To date, modelling efforts have been limited by the lack of data for model parameterization and validation, due to the complex and often inaccessible nature of tropical rangeland ecosystems. Complementary *in situ* measurements under controlled watering across the wet season need to be planned to parameterize the hysteresis curves and better capture variations throughout the year (Krüger et al., 2013).

5. Conclusion

To our knowledge, the carbon dioxide, nitrous oxide and methane fluxes in northern Senegal we report here represent the first highly detailed data set on soil/water-atmosphere GHG exchanges in a tropical sylvo-pastoral ecosystem. Our results provide evidence for notable spatial heterogeneity of GHG emissions.

The spatial heterogeneity of GHG emissions is mainly explained by livestock behavior and movements within the study area, 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 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 to CH_4 emissions due to permanent or seasonal hydromorphic conditions. These 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 gas (83.1% of all GHG emissions) and native rangelands are the main landscape unit (78.8% of all GHG emissions) that contribute to total GHG emissions from the soil and from surface water. Not taking spatial heterogeneity into account when assessing total soil and surface water emissions at the landscape level can thus lead to a 14% error in estimation.

Further investigations are needed to refine the greenhouse gas footprint of sylvo-pastoral systems in the region including short-term monitoring of the transitions between seasons, with a focus on the onset of the rainy 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 undertaken to assess possible inter-annual variability of GHG emissions, since climate fluctuations can impact the presence, movements and excretion rates of livestock with major consequences for spatial heterogeneity and for the complete GHG balance of the pastoral system under study. Two important points that could improve the GHG balance of existing systems would be:

- To compare the magnitudes of the CO_2 and CH_4 flows measured here with that of the carbon stocks in the soil: if the flows are of the same order of magnitude as the stocks, that would suggest significant seasonal variations in stocks, as well as their vulnerability to global climate change;
- To identify the exact contribution of livestock to total landscape emissions, by comparing the emissions observed here with those from a baseline, animal-free landscape. This would enable a fair assessment of the environmental impact of animal products whose high C intensity is often criticized in extensive livestock systems.

Conclusions intermédiaires et transition

Le Chapitre 3 montre la forte variabilité temporelle et la forte hétérogénéité spatiale des émissions de CO_2, N_2O et CH_4 au niveau du sol et à la surface des eaux à l'échelle d'un écosystème sylvo-pastoral en milieu semi-aride. Le rôle des animaux dans la redistribution spatiale des biomasses ingérées à travers les dépôts de déjection au sol combiné à la forte variation de l'humidité saisonnière des sols expliquent en grande partie ces variabilités observées dans le temps et dans l'espace. On peut retenir que les unités paysagères recevant le plus de déjections animales par unité de surface (forage, campements, mares) sont les principales sources de CO_2 et de N_2O par unité de surface tandis que les mares et leurs berges sont les principales sources de CH_4 du faite de la présence d'eau stagnante combinée à des hauts niveaux d'apports de déjections animales.

Sur la base des résultats de ce dernier chapitre (Chapitre 3) et des connaissances zootechniques produites dans le Chapitre 2, un bilan GES du territoire a été repris dans le chapitre suivant (Chapitre 4) sur la base d'observations de terrain riches. En effet, le dispositif de suivi mis en place autour du forage de Widou a permis d'évaluer les niveaux d'émission et de séquestration dans les différentes six unités paysagères distinguées. Le Chapitre 4 évalue donc l'importance de l'hétérogénéité spatiale du bilan GES.

Chapitre 4 : Une forte hétérogénéité spatiale du bilan gaz à effet de serre en territoire sylvo-pastoral

Ce quatrième chapitre se base sur un article qui sera prochainement soumis dans la revue « Agriculture, Ecosystems & Environment » :

Assouma M. H., Hiernaux P., Barthès B., Lecomte P., Ickowicz A., Bernoux M., Bourgouin J., Vayssières J. Do spatial transfers of organic matter and nutrients by grazing livestock jeopardize carbon sequestration in Sahel pastoral ecosystems? To be submitted to Agriculture, Ecosystems & Environment.

Abstract

Rangelands, grasslands, steppes and savannas occupy around 40% of the terrestrial land surface. The GHG balances for these ecosystems are commonly calculated at plot or regional scales. In an original way, this study describes and explains the spatial heterogeneity of the GHG balance in a typical sylvo-pastoral landscape in northern Senegal based on a detailed description of the functioning of the ecosystem over a full year.

The landscape concerned is the area surrounding the Widou borehole (15°59'N, 15°19'W, 706 km²), a circular zone with a radius of 15 km from the borehole. The case study covers an area of 706 km² within the influence of the Widou borehole where six different landscape units were defined: the land in the vicinity of the borehole, natural ponds, natural rangelands, forest plantations, settlements, and enclosed plots. The area is representative of the semi-arid sylvo-pastoral ecosystems in this region.

An original measurement protocol was implemented from May 2014 to October 2015 to estimate GHG emissions and all carbon accumulation in each landscape unit. Thus, methane emission from livestock enteric fermentation was evaluated using an indirect approach based on estimated intake and digestibility of resources consumed by the animals using near infrared spectroscopy analysis applied to faeces (F-NIRS). Nitrous oxide (N_2O) and methane (CH_4) emissions from the soil and the water due to manure deposition were measured using static chambers. The other sources of emissions (CH_4 from termites, CO_2 from fuel consumed by the borehole motor pump and CH_4 & N_2O from burning plant biomass) were evaluated using emissions reported in the literature. Total carbon accumulation in the aboveground and belowground biomass of trees was evaluated in an *in situ* survey and specific allometric equations available for the study area. In the soil, net carbon exchange was quantified using soil *in situ* sampling and a 5(CHN) elemental analyzer. Observed yearly weight gains of animals were used to evaluate carbon sequestrated in livestock.

At the landscape level and over one full year, the full GHG balance was -0.09 tCO_2-eq. This negative value for the GHG balance indicates that the GHG emissions are compensated for by total carbon accumulation in the soil, trees and animals. The GHG balances of the different landscape units ranged from -3.41 tCO_2-eq /ha/year in the enclosures to +127.1 tCO_2-eq /ha/year in the vicinity of the borehole. The GHG balance was negative in landscape units which receive little or no manure (rangelands, enclosures and forest plantation) whereas the balance was positive in units receiving high rates of manure deposition but which contributed little to fodder intake (the vicinity of the borehole, ponds and settlements). This study underlines the role of livestock in the spatial heterogeneity of the GHG balance.

Key words: GHG balance, livestock, ecosystem functioning, sylvo-pastoral, Senegal.

1. Introduction

Over the last century, modern industries and changing lifestyles have rapidly increased greenhouse gas (GHG) concentrations in the Earth's atmosphere. The majority of scientists studying this issue assume that these increasing concentrations contribute to global warming. The main greenhouse gases in the atmosphere are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Bernoux and Paustian, 2013). Animal production systems are major sources of greenhouse gases, especially methane (CH_4) and nitrous oxide (N_2O) (de Oliveira Silva *et al.*, 2016). Using a life cycle analysis approach, the relative contribution of global livestock production to anthropogenic GHG emissions has been estimated to be 14.5% (Gerber *et al.*, 2013). Extensive pastoral production systems are characterized by high GHG emissions per unit of protein produced due to the combination of low feed digestibility and high methane conversion factor in pastoral systems (Steinfeld *et al.*, 2006).

Pastoralism refers to the extensive production of livestock in rangelands, in which managed herd movements are necessary for sustainability (McGahey *et al.*, 2014). Pastoralism plays a major role in safeguarding natural capital across a quarter of the world's land area (White *et al.*, 2000). Pastoralism is usually practiced on land with a low production capacity (contrasted climate and low soil fertility) and low stocking rates. Rangelands are extensive pastures in which investments are generally limited (except for access to water through boreholes). In this ecosystem, livestock also plays an important role in the reorganization of nutrient and carbon cycles (CC) and in the spatial distribution of organic matter, soil nutrients and C stocks (Petersen *et al.*, 2013). Livestock graze freely in rangelands and excrete while grazing and also while resting close to the settlements, the ponds or a borehole. Livestock return about 50% (55% in the dry season, 45% in the wet season) of the dry matter consumed as forage to the soil through their faeces and urine (Schlecht *et al.*, 2004). The organic matter in the deposited faeces boosts vegetative growth, improves pasture productivity and also promotes C sequestration in the soil and also accelerates decomposition. Animal excreted nitrogen (N) deposited as urine and faeces onto pastoral soils during grazing has been identified as an important source of nitrous oxide (N_2O) (Luo *et al.*, 2007).

The majority of Sahelian livestock graze under the guidance of a herder or freely in communally exploited grazing areas. Due to the high mobility of herds in this landscape, livestock play an important role in the spatial reorganization of organic matter in agro-pastoral ecosystems in West African savannas (Schlecht *et al.*, 2006). The spatial distribution of faeces and urine across the different landscape units is closely correlated with the proportion of time spent there (with the exception of water points which increase the frequency of urination). This creates the significant spatial heterogeneity which characterizes sylvo-pastoral as well as agro-sylvo-pastoral ecosystems in sub-Saharan Africa.

For this ecosystem, information is lacking on the effects of grazing on CO_2, CH_4, and N_2O emissions from rangeland soils (Chiavegato *et al.*, 2015). Furthermore, to date, there is still a lack of reliable data on GHG from sylvo-pastoral ecosystems in semi-arid regions and on the spatial heterogeneity of the GHG balance in landscapes. There is also considerable uncertainty concerning the default emissions factors used in National Inventory Report for sub-Saharan African Greenhouse Gas Inventory still largely based on IPCC coefficients. These IPCC Tier 1 coefficients are increasingly called into question, see for instance Pelster *et al.* (2016) for cattle excreta in an East Africa pasture.

In the present study, the GHG balance of herbivore livestock takes into account both greenhouse gas emissions from sylvo-pastoral ecosystem functioning (CO_2, CH_4, and N_2O) and carbon accumulation in the rangeland. This makes it possible to calculate a net carbon balance and hence the effective contribution of grazing areas to the greenhouse effect. Many recent studies in temperate climates showed that grassland is the component that stores carbon within the ruminant livestock production system and that it may compensate for the greenhouse gas emissions produced by the livestock production system (Allard *et al.*, 2007; Soussana *et al.*, 2007).

The central hypothesis of this study is that landscape units with low stocking rates, offset the GHG emissions from all sources through C sequestration. The objective of this study was to calculate a greenhouse gas (GHG) balance at landscape level considering the different landscape units in relation to sylvo-pastoral management. To achieve this objective, GHG balances were assessed in different landscape units within the region of influence of the Widou Thiengoly borehole: land in the close vicinity of the borehole, ponds, rangelands, forest plantations, settlements, and experimental enclosures. The fluxes and balances were then weighted by the area of each land unit and averaged over the region of influence of the Widou borehole.

2. Material and methods

2.1. Description of the study area

2.1.1. Study Site

The area under investigation is the Ferlo region (Senegal) covering 70 000 km² (more than a third of the territory) (Thiam *et al.*, 2015). The study area is located in the northern part of the Sahelian bioclimatic zone of Senegal between latitudes 14°30′N and 16°15′N and longitudes 12°50′W and 16°W (Cissé *et al.*, 2016). The climate is a monsoonal tropical, semi-arid, with strictly monomodal rainfall distribution in summer from July to mid-October. Summer rainfall is highly variable between years. Rainfall events feed a large number of small temporary ponds (Diop *et al.*, 2004; Soti *et al.*, 2013).

Economic and social lives in the Ferlo region are organised around the network of boreholes dug in the 1950s and 1960s at a intervals of between 5 and 30 km (Manoli *et al.*, 2014). This study focuses mainly on the area surrounding the Widou borehole (15°59'N, 15°19'W, 706 km²). A secondary study site located near the village of Dier Biran (15°21'N, 15°28'W) was also used for complementary measurements like the assessment of C accumulation in trees (Figure 4.1).

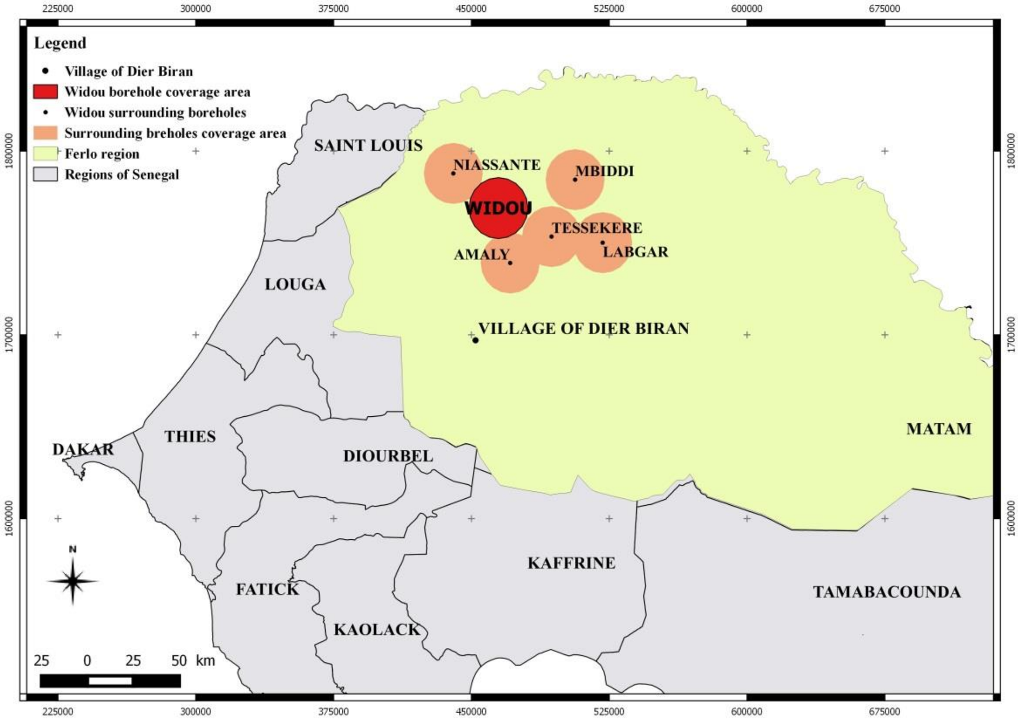

Figure 4. 1. Location of the study area and the secondary study site in the Ferlo region.

The study area is a circular zone with a diameter of 30 km centered on the Widou borehole (Miehe *et al.*, 2010). Total annual rainfall in Widou averaged 277 mm year^{-1} from 1981-2007, with a coefficient of variation of 28% (Olsen *et al.*, 2015). Mean annual temperature oscillates around 27.7 ˚C and fluctuates between a maximum average of 30.2 ˚C in October and a minimum of 24.5 ˚C in January (Ndiaye *et al.*, 2014a). The vegetation consists of annual herbaceous plants dominated dry savanna or steppe vegetation. Woody plants are scattered and the overall canopy cover averages 35% (Brandt *et al.*, 2016). The herbaceous layer consists almost exclusively of annuals, and is usually dominated by grasses.

The secondary study site is located 12 km from Dahra, on the ranch belonging to the Zootechnical Research Centre (CRZ) of the Senegalese Institute for Agricultural Research. It is still in the Sahelian region, only 72 km from Widou, and is characterised by a dry tropical climate; data for the past 50 years showed that mean annual precipitation is 422.6±126.8 mm (Ndiaye *et al.*, 2014b). Again there is not much difference between the CRZ and Widou dry savanna or steppe with annual herbaceous dominated by grasses, scattered shrubs and low trees. There are a number of tree plantations, the ranch is partially fenced but most of it is managed with free grazing. A short herbaceous layer remains at the end of the dry season. A detailed soil map in (Audry, 1962) indicated the site is characterized as sandy, reddish and have been classified as ferralic Arenosols and vegetation map of the Dahra CRZ by Raynal (1964).

2.1.2. Landscape units in Widou borehole coverage area

A geographic information system (GIS) was specifically designed for the study to design the sampling strategy. The GIS was based on a Landsat ETL+204-049 image acquired on November 3, 2010, and a digital elevation model. Six landscape units (Figure 4.2) were defined on the basis of the topography, geomorphology, soil types, vegetation cover and land-use criteria:

- *The close vicinity of the borehole*

The close vicinity of the borehole corresponds to the portion of land where the pump, the water tank and the water tower are located, and the place where herds stand during watering, waiting before, and resting after watering. The area is characterized by high soil organic matter (SOM) due to the accumulation of faeces and urine deposited by all the different herds (cattle, goats, sheep, horses and donkeys). In all seasons, the heavily trampled soils around the borehole are waterlogged due to tank spillovers. Both the resting area for herds and the artificial pond were investigated during this study. At Widou Thiengoly, what we refer to as the 'close vicinity of the borehole' extends over 0.78 km², and represents 0.1% of the study area.

- *Ponds*

Large numbers of small temporary ponds are formed during the summer monsoon (from July to mid-October) which dry out in the first part of the dry season. Small ponds of less than 0.5 ha dominate whatever the time period and account for nearly 65% of the total ponds during the peak of the rainy season, and up to 90% at the end of the same season (Lacaux *et al.*, 2007). These ponds are widely distributed and organised in clusters of all sizes. The edges of the ponds are delineated by a belt of trees which corresponds to the maximum water extension. There are also cisterns, tanks, shallow and deep wells which are essential for life in the semi-arid Sahel region of Africa. Besides hosting considerable biodiversity, these water bodies are filled during the rainy season, and are the primary water supply and often the only one (Gourma in Mali, part of Hodh in Mauritania) for human and animal consumption (Soti *et al.*, 2010). The vegetation cover includes trees such as *Acacia sp.*, *Mytragena inermis*, *Diospyros mespiliformis, Anogeissus leiocarpa* and *Balanites aegyptiaca*. GHG emissions from both the water and soil were investigated during this study. Within the area covered by the Widou borehole, the ponds and their surroundings extend over 19.34 km², and represent 2.7% of the whole landscape.

- *Experimental enclosures*

The experimental enclosures were established as part of the grazing control experiment at the PAPF project (GIZ funded) and have been maintained ungrazed and unburned since 1982. The composition of herbaceous plants in the enclosed plots deviated markedly from those of the surrounding grazed rangelands, with a significant increase in the magnitude of non-graminoid herbs and high-quality forage species (Miehe *et al.*, 2010). Substantially higher end of season standing biomass (ESSB) was observed in Widou (Olsen *et al.*, 2015). Within the Widou borehole coverage area, the experimental enclosures cover 0.24 km², and represent 0.03% of the whole landscape.

- *Forest plantations*

The Great Green Wall (GGW) programme was set up in in the 2000s to start forest plantation in the Sahel. New forest plantations have been taking place in Widou borehole coverage area as part of this program since 2008. The forest plantations vary in age and are planted with *Acacia Senegal, Acacia raddiana and Acacia seyal* and a few other species such as *Sclerocarya birrea* and exotic species such as *Prosopis juliflora.* They are fenced and kept ungrazed during the first three years. At the study site, the forest plantations cover 6.23 km², and represent 0.9% of the whole landscape.

- *Settlements*

Ferlo is a dry expanse of savanna with only pastoral settlements scattered at a distance from the boreholes and a small village that was established just next to it. In the coverage area of Widou borehole 354 settlements were counted during a survey conducted in December 2013. In fact, pastoral families live in semi-sedentary settlements (Adriansen, 2006) organised in one or several houses (*galle* in Fulani) (Manoli *et al.*, 2014). The families in the settlements have different ways of managing their herds, from individual to collective management. In this study, the pastoral settlements include the herder's houses and corrals for the herd. Pastoral settlements are also characterised by heavy trampling and high SOM due to the accumulation of manure from all the livestock species. In our study site, the settlements extend over an area of 44.46 km², and represent 6.3% of the whole landscape.

- *Rangelands*

The semi-arid rangelands of the Ferlo form a vast zone where livestock breeding is the main source of income and is essential for local food security. The main animals kept are cattle (Zebu), sheep and goats. The vegetation in the rangeland consists of tree and shrub savanna dominated by *Sclerocarya birrea*, *Balanites aegyptiaca*, *Acacia spp. and Boscia senegalensis*, with the woody vegetation covering an average of < 40% (Brandt *et al.*, 2016). The herbaceous layer almost exclusively comprised of annuals and usually dominated by grasses, with highly varying proportions of forbs, depending on the microhabitat (shade provided by woody plants, depressions, etc.), the rainfall regime, grazing intensity and fire events. The rangelands comprising the study site extend over an area of 635.45 km², and account for 89.9% of the landscape.

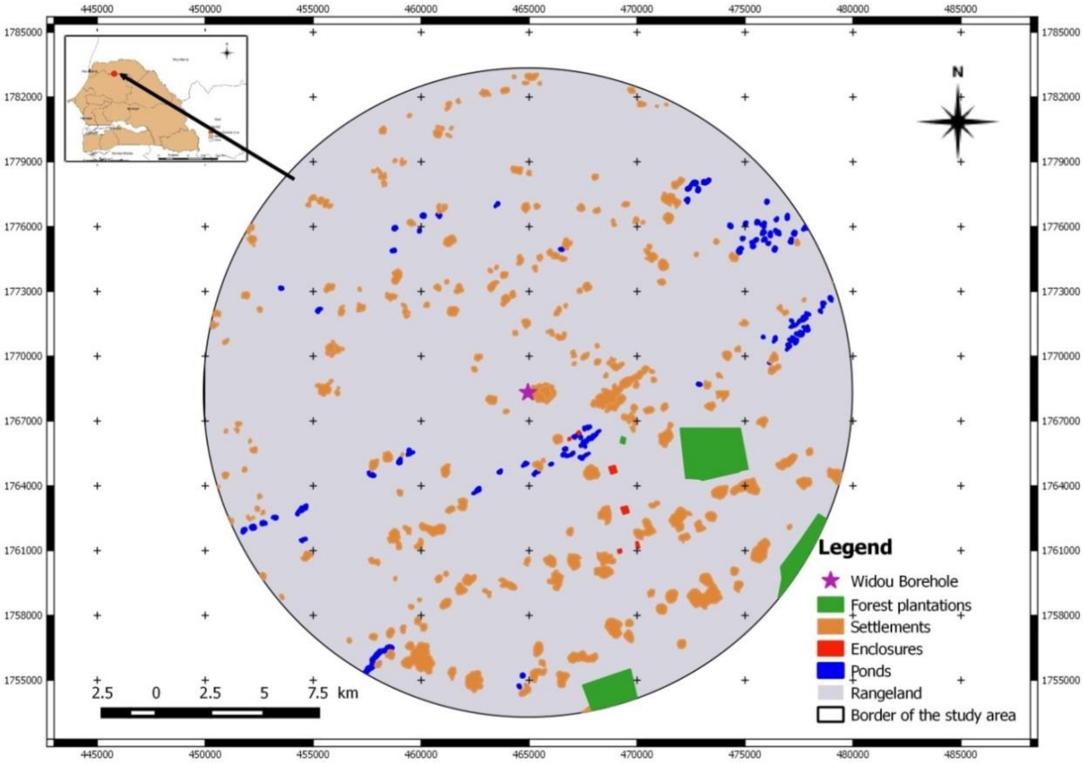

Figure 4. 2. Landscape units in the Widou borehole coverage area

2.2. Data collection

2.2.1. Sampling strategy

Observations lasted from May 2014 to October 2015. They included a full year cycle from July 2014 to June 2015, and an additional wet season (July to October 2015). The sampling strategy targeted the seasonal variability and spatial heterogeneity of the different landscape units encountered in the study area (Table 4.1).

To assess the spatial heterogeneity of GHG emissions, measurement sites were selected to cover the different landscape units: rangelands, ponds, settlements, forest plantations, experimental enclosures and the land in the close vicinity of the borehole (Table 4.1). The number of sample sites within each landscape unit took into account the extent of each landscape unit within the study area (i.e. more observations were made on rangelands which account for over 89.9% of the study area) and the probability of high emission rates in relation with high manure deposition such as in the close vicinity of the borehole, the settlements and ponds. The aim of the observations was to calculate the GHG balance at the scale of each landscape unit. The GHG balance takes into account both total emissions and total carbon accumulation within the landscape unit to obtain the complete GHG balance and underline the real impact of the livestock on GHG emissions.

Table 4. 1. Sampling strategy accounting for both spatial heterogeneity and temporal variability

	Rangelands	Settlements	Ponds	Vicinity of the borehole	Forest plantations	Enclosures	Dahra Research station	Observation frequency
Enteric methane		5						Once a month during the whole study period
Soil GHG emissions	5	2	2	2	1	1		Once a month during the warm wet season and twice during the dry season
Water GHG emissions			2	2				Once a month during the warm wet season and twice during the dry season
Soil carbon accumulation	8	6	6	4	4	2	233	Once during the cold dry season
Livestock carbon accumulation		40						Once a month during the whole study period
Tree carbon accumulation	5	2	2	2	2	2	1	Once during the cold dry season

2.2.2. GHG emissions

The main GHG emission sources taken account in the GHG balance were enteric CH_4 from livestock and termites, N_2O and CH_4 emissions from the soil and the water due to manure deposition, CO_2 from fuel consumed by the motor pump and caused by bush fires, as described in Assouma *et al.* (2014) (chapter 1).

- *Enteric CH_4 emissions and analyses*

Methane production in the digestive tract of ruminants due to enteric fermentation, is one of the main sources of global methane emissions. Enteric CH_4 emissions were estimated based on forage intake and digestibility assessed by near infrared reflectance spectroscopy (NIRS) of sample faeces. Faecal NIRS is a suitable non-invasive method (Li *et al.*, 2007) to predict feed intake and diet digestibility (Boval *et al.*, 2004; Fanchone *et al.*, 2007). More recently, (Decruyenaere *et al.*, 2009b) demonstrated that the organic matter voluntary intake (OMVI) of ruminants was successfully predicted by faecal NIRS equations with R^2 ranging from 0.80 to 0.90, and low relative standard error of calibration RSEC (8%). The survey involved five growing male cattle (because males are required for the use of fecal bags) weighing between 115 and 140 kg monitored over a period of 17 consecutive months as described in (Schlecht *et al.*, 2006). The daily grazing itineraries of each animal were followed and simultaneously tracked by a GPS for 24 or 48 h depending on the watering frequency (once or twice a day). The hand plucking method developed by (Guérin *et al.*, 1986) was used to sample the daily forage intake of each animal (Chirat *et al.*, 2014). During livestock tracking, specific diapers were fitted onto the male cattle to collect all daily solid excretion. The collected faeces and forage intake samples were weighted immediately after collection and subsamples were dried in a forced-air oven at 65 °C for 72 h to determine the DM content. They were then ground to pass through a 2 mm screen and stored in closed plastic boxes before NIRS scanning. All samples were scanned at 1 nm intervals over the 350 – 2500 nm wavelengths by an ASD Inc LabSpec® 4 Standard-Res lab analyzer (N° 28022). The samples were scanned in triplicate using open cells, and NIR absorbance data were recorded as mean log 1/reflectance values (log 1/R). Mathematical treatment of the spectral data was performed using WinISI III software (Shenk *et al.*, 1997) to evaluate the standardized Mahalanobis distance (H). Before scanning, calibration and validation were performed, mathematical pretreatments, standard normal variate and detrending, and different derivative pretreatments were applied to the spectral data. The best derivative (2.5.5.1) for each component was kept for the final calibration.

Organic matter digestibility (OMD) and intake (OMI) were predicted according to a faecal NIRS reference database and equations published by Gembloux University (Belgium) and CIRAD laboratory (France) databases. The spectral library used was the one initiated and described by (Decruyenaere *et al.*, 2012). It contains spectral data related to ruminant diet characteristics collected in several temperate and tropical contexts and has been completed with a recent set of 90 local field faeces referenced for daily dry matter intake. A data set including 3,394 diet-faecal pairs from these large databases was used to perform local calibrations for the prediction of diet intake, quality, and digestibility. The local technique, described by (Shenk *et al.*, 1997), is a procedure which searches through a wide sample database to select samples spectrally similar to the sample analyzed. The subset spectra are then used to write a specific calibration equation to predict the unique unknown sample by using PLS regression. An independent validation data set was built with 20 diet-faecal NIRS pairs of monthly spectra. The new data set included local references which were used to develop local equations, whereas the monthly spectrum data (20 individual diet-fecal pairs) were used to validate the accuracy and the robustness of this local equation. The statistical parameters used to evaluate the predictive performance of the calibration and validation data set were standard error of calibration (SEC), standard error of prediction (SEP), relative standard error of calibration (RSEC), relative standard error of prediction (RSEP), R^2, and ratio performance deviation (RPD) (Tran *et al.*, 2010).

Based on the predicted digestible organic matter voluntary intake (DMOI in %) with the F-NIRS approach, the enteric methane production (EMT in gCH4/kgBW) was estimated using an appropriate equation for tropical conditions developed by (Archimède *et al.*, 2011):

$$\mathbf{EMT = 0.082 + 0.28\ DOMI}$$

- *GHG fluxes from soil and water measurements*

GHG fluxes from the soil were quantified using rectangular stainless steel static chambers as described in (Serça *et al.*, 1994). All the measurements taken at each site were made in duplicate. 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 as described in (Guérin *et al.*, 2007). Samples for CH_4 and N_2O analysis were stored in serum vials initially filled with a salt-saturated solution as described in (Deshmukh *et al.*, 2014). The analyses were carried out using gas chromatography (GC).

The diffusive fluxes were calculated from the slope of the linear regression of the gas concentration in the chamber versus time (Karki *et al.*, 2015a). Fluxes were discarded when the correlation coefficient was $r^2 < 0.8$ (Deshmukh *et al.*, 2014).

For measurements of the concentrations of dissolved GHG in ponds, water samples were collected and sterilized according to Guérin and Abril (2007). They were then analyzed by GC after the creation of a headspace with N_2. Concentrations of dissolved gas were computed using 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.

- *Other sources of GHG emissions at the whole landscape level*

The other GHG emissions described in (Assouma *et al.*, 2014) were not directly measured in the *in situ* survey but were quantified using emission factors reported in the literature.

For instance, methane is produced in the termite digestive tract by symbiotic micro-organisms during the breakdown of cellulose or hemicellulose (Seiler *et al.*, 1983). In this study, the methane flux from termites was estimated using the emission factor (mean CH_4 fluxes ranged from 4444 µg CH_4–C m^{-2} h^{-1} in the wet season to 558 µg CH_4–C m^{-2} h^{-1} in the dry season) proposed by (Jamali *et al.*, 2011) and the density of termite mounds proposed (218.9.19m^2/ha) by (Traoré *et al.*, 2008).

The CO_2 fluxes from the fuel used by the borehole motor-pump were evaluated using the method and the emission factor fuel (2.6 kg CO_2/L of fuel) proposed by ADEME (2010). The total quantity of fuel used during this study was quantified in collaboration with the borehole supervisory committee on a monthly basis.

Biomass burning is a significant global source of greenhouse gases including carbon dioxide, methane and nitrous oxide (Koppmann *et al.*, 2005; Castaldi *et al.*, 2010) particularly in tropical and subtropical regions (Scholes *et al.*, 1996; Fearnside, 2000; Rossi *et al.*, 2016). In this study, no GHG emissions from the burning of biomass were taken into account as no fires were observed during the 2014-2015 study period. This is an unusual year because such fires are common in Ferlo region, especially in years with higher rainfall and forage yields (Mbow *et al.*, 2000).

2.2.3. Carbon accumulation

There has been growing interest in including soil carbon (C) sequestration as an offset to greenhouse gas (GHG) emissions in rangelands. The potential of semi-arid pastoral ecosystems to store carbon in soils and vegetation has been acknowledged in many studies (Dabasso *et al.*, 2014; Yusuf *et al.*, 2015). In the present study, carbon stored in the soil and trees, and carbon accumulation in livestock bodies were assessed.

- *Soil carbon accumulation*

Soil carbon sequestration is a process in which atmospheric CO_2 is absorbed and stored in the soil C pool indirectly through the wilting and decomposition of plants and deposition of manure excreted by the livestock on the soil. To obtain precise estimates, a sampling design was implemented in both Widou borehole coverage area and Dahra research station. In Dahra, soil was sampled in 2009 and 2015 from 233 randomly distributed points among the grazed pastures. In the Widou borehole coverage area, soil was sampled at 30 sampling points distributed in all landscape units with five replicates at each point. Soil samples were collected at three soil depths (0–10, 10–20 and 20–30 cm) in the top 30 cm layer of the mineral soil according to IPCC recommendations (IPPC, 2003). Soil cores were extracted using manual coring devices with a diameter of 8 cm. Taking care not to disturb the soil surface or sub-surface, the sample site was cleared of living plants, plant litter and surface rocks prior to sampling. The coring devices were cleaned after each soil core was collected to ensure no cross-contamination of soil cores. In this way, 450 samples were collected in the Widou coverage area and 1,398 in the grazed pastures at Dahra research station.

All the 1,848 soil samples were air dried, ground to pass through a 2 mm sieve and scanned with a spectrometer. Combined visible and near infrared reflectance spectroscopy and chemical measures were used to determine the C and N contents. The soil samples were scanned and diffuse reflectance was measured from 350 to 2500 nm at 1 nm intervals using a portable spectrophotometer ASD Inc LabSpec® 4 Standard-Res lab analyzer (N° 28022). Three spectra were acquired for each core. The three spectra acquired per soil sample were then averaged. After each spectral acquisition, the window of the contact probe was cleaned with lens paper. The white reference standard, with zero absorbance, was a disk made of Spectralon (compressed polytetrafluoroethylene powder) and its reflectance was measured every 20 acquisitions. Spectral data were recorded as absorbance, which is the logarithm of the inverse of reflectance (log(1 / reflectance)). Standard laboratory analyses were carried out on 177 samples from the Dahra research station taken in 2009 and on 180 samples taken in 2015, and on 125 samples from the Widou coverage area. The C and N concentrations in the soil samples were determined with an Elemental Analyzer (CHN) as described in (Pansu and Gautheyrou, 2006). Samples from the Widou coverage area were used to calibrate and validate C and N prediction equations. Samples from the Dahra research station analysed in 2009 and 2015 were compared to assess variations in mean annual carbon content at the three soil depths.

Spectrum analysis consisted in fitting the VNIR spectra to the conventionally determined soil organic carbon content. Data analysis was conducted using WinISI III-v.1.61e software (Infrasoft International, LLC, State College, PA, USA). First, VNIR spectra were pre-processed, which consists of mathematically transforming the signal to amplify its useful parts (e.g. related to chemical properties) and to reduce irrelevant information (e.g. resulting from light scattering) (Cambou *et al.*, 2016).

Seven pre-processing methods were tested: none (no transformation), standard normal variate (SNV) transformation, detrending (D), SNVD (i.e. both SNV and D) and standard, inverse or weighted multiplicative scatter correction (MSC, IMSC and WMSC). These seven spectral transformations were combined, or not, with first derivation. Using principal component analysis (PCA), we identified and deleted six outliers of spectra data. The calibration subset including the 80 samples and a validation subset of 35 samples were selected randomly.

Next, a prediction model was built using NIR data to extract the C concentration of the samples that had not been analysed using standard methods. NIRS predictions of soil carbon content were considered accurate when $\text{RPD} \geq 2.0$, acceptable when $1.6 \leq \text{RPD} < 2.0$, and poor when $\text{RPD} < 1.6$ (Chang *et al.*, 2001). The three best pre-processing methods were selected based on RPD validation and applied on a global dataset (115 samples) to calibrate equations which were then validated with cross-validation. Thus soil carbon was obtained by averaging the six predicted values.

These soils are carbonate free; soil organic carbon concentration is consequently considered as the total concentration of carbon; and soil particles >2 mm were disregarded. Therefore, SOC stocks at each soil depth interval were calculated with the following equation (Don *et al.*, 2007):

$$\mathbf{SOC_{stocks}} = \sum_{i=1}^{n} BD_i \times SOC_{conc,i} \times depth$$

where n is the number of sampled soil depth intervals i, SOC_{stock} ($MgC.ha^{-1}$) is soil organic carbon stock. BD (g.cm3) is the soil bulk density; SOC_{conc} ($mgC.g^{-1}$) stands for soil organic carbon concentration measured from

NIRS and CHN in the layer i, and depth (cm) is the thickness of each soil layer (the same thickness applies to the three soil layers considered here).

Estimating the rate of annual change in soil C stock was necessary to calculate the GHG balance for the whole landscape. To assess soil carbon dynamics over time, the survey conducted in 2009 at 233 points located in the Dahra research station was repeated in 2015 at the same geo-referenced locations. Mean annual changes in carbon content were estimated from 174 duplicate analysed samples out of the 699 samples collected in grazed pastures at the Dahra research station. Changes in soil carbon in the Widou borehole coverage area were obtained using regression equations established for each depth interval (figure 4.3) between the carbon stock measured in 2015 in the different landscape units and the mean annual carbon variation in the soil.

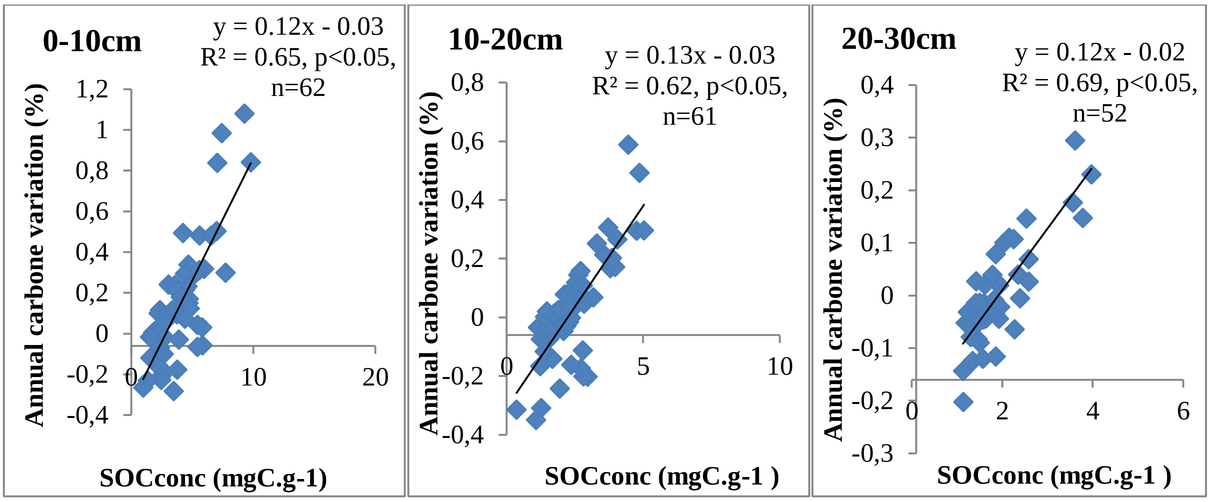

Figure 4. 3. Regression between soil organic carbon measured in 2015 and the mean annual soil organic carbon variation measured between 2009 and 2015 at three soil depths in Dahra

- *Carbon accumulation in trees*

Like for soils, trees sampled in June 2009 in pastures belonging to the Dahra research station were resampled in June 2015, whereas sampling was only performed once at sites in the Widou borehole coverage area.

At the Dahra research station, trees were sampled in a 92 x 52 m plot. The plot contained 24 trees (18 *Acacia senegal*, five *Balanites aegyptiaca* and one *Commiphora africana*), tree density in the plot was thus 50.2 plants/ha. The four corners of the plot were geo-referenced and physically marked by wooden poles. The following dendrometric parameters were measured at both dates: maximum height of the canopy, trunk circumference at a height of 1.30 m, and the diameter of the tree crown. The differences in trunk circumference measured between 2009 and

2015 were used to estimate mean annual carbon accumulation in the wood mass assessed by specific allometric functions (Henry *et al.*, 2011).

The distance from point centred quadrant method (PCQ) proposed by Clark and Evans (1954) was used in Widou borehole coverage area to describe the woody population in all the landscape units. In the PCQ method, the plant density of individual species or plant type is estimated by the mean distance between the closest individual and the sampling points (20 or 10) measured systematically at 50 or 100 m intervals along the transect, depending on plant density (Hiernaux *et al.*, 2009b). In this study, this method was used at 15 sites with observations made at 50 m intervals along the 500 m transects. At each sampling point, the mean distance was calculated between the shortest distances measured for each four quadrants defined by the linear transect and the line perpendicular to transect line at the sampling point. The four individuals with their top crown height equal to or higher than 4 m for which the distance is measured are described by their species name, height, crown perpendicular diameter, base circumference of the trunk. The woody plant density (D) i.e. the number of individuals per unit area (ha) was estimated using equation proposed by (Pollard, 1971):

$$\boldsymbol{D = 1000 \times \frac{4(kn-1)}{\pi \sum_1^n \sum_1^k d_{ij}^2}}$$

where d_{ij} is the distance (m) in the k (j = 1 to 4) sectors, and n (I = 1 to n) is the number of sampling points.

The aboveground biomass sequestered in all landscape units was estimated using the allometric equations per species described in (Henry *et al.*, 2011) and annual variation in circumference of each species was obtained using the regression equation described above. The increase in belowground biomass per species was deduced using the convertor factor of 38% proposed by Woomer *et al.* (2004). The sequestered biomass was converted into carbon equivalent using the convertor factor of 0.48 proposed by Hughes *et al.* (1999).

- *Carbon accumulation in livestock bodies*

During the monitoring of the five male cattle, their monthly weight was estimated using the equation proposed by Njoya *et al.* (1997). The annual increase in weight was estimated after the one year survey by taking into account the succession of weight losses and gains over a period of year. The annual mean of this increased weight was used to estimate total carbon sequestrated by livestock in the Widou borehole coverage area. A monthly survey was performed to assess the herd population structure according to species and to evaluate the size of the herd present in Widou borehole coverage area over a period of one year. Thus, a retrospective survey of 40 randomly-selected settlements was conducted monthly with the owner of the herd from May 2014 to September 2015. The study questionnaire was structured and designed to collect quantitative data on three general topics: size of each category (male, female, young and adult) per species (cattle, sheep, goats, donkey or horses), mortality rate and growth rate for each category, size of transhumant herd per species and the number of animals sold monthly according to species during the survey. The survey and annual mean of increased weight made it possible to estimate the live biomass stored in herd bodies. For this purpose, C sequestrated in live biomass was obtained using a convertor factor on 0.22 and 0.29 gC/kgLW (live weight) respectively for small ruminants and cattle proposed by (Garnier-Laplace *et al.*, 1998).

2.3. Data Analysis

2.3.1. Allocation of the GHG emissions and C sequestration to the different landscape units

A complex monitoring and survey system was set up to evaluate all the components of the GHG balance in the different landscape units. Concerning the components directly monitored in each landscape unit, all the measurements were averaged for each unit. Concerning the components not directly monitored in each landscape unit, estimations were spatially allocated on the basis of knowledge of the ecosystem functioning. C accumulation in livestock and CH_4 from enteric fermentation was allocated using the time spent by the herds in the different landscape units assuming that enteric emissions are constant over a 24 h period. Methane from termites was allocated on the basis of available herbaceous biomass on the soil as litter and loss of tree leaves due to senescence in each landscape unit. CO_2 emissions from the motor-pump were allocated to the whole landscape unit in which the borehole is located.

2.3.2. GHG balance at the landscape unit level

The GHG emissions balance for each landscape unit was calculated by subtracting the total C accumulation in each landscape unit from total GHG emissions at the level of the whole landscape unit. Total GHG emissions were determined as the sum of the emissions of the three GHGs, where methane and nitrous oxide were converted into C dioxide equivalent units (CO_2-eq). The global warming potential of each of these gases at the 100-year time horizon proposed by (IPCC, 2013) was used. These GWP are 1, 34, and 298 respectively for CO_2, CH_4 and N_2O. C accumulation in the soil, in trees and in livestock were also converted into CO_2-eq on the basis of the molar mass of CO_2.

2.3.3. Scaling up emissions and sequestration to the whole landscape level

In this study, both total GHG emissions and C accumulation were weighted according to the surface area of the different landscape units in the study area and summed over time to calculate total GHG emissions at year and landscape scale.

3. Results

3.1. Soil chemical properties

The distribution of organic matter contents in the three top layers of the soil samples taken from the landscape units assessed using the most appropriate pre-processing method (in terms of RPDval) revealed contrasted profiles among the landscape units (Table 4.2). The best predictions of organic C content in soil samples were most often obtained with a complete range of wavelengths (350–2500 nm) with D0011, MSC1441 and MSC2441 pre-processing (Table 4.3) with RPDval>2.6. Removing or retaining the spectral and/or calibration outliers did not affect the accuracy of the prediction.

The soil carbon content in the top 10 cm soil layer ranged from 2.77±0.50 g C kg^{-1} dry soil in the rangeland to 13.87±10.04 g C kg^{-1} dry soil in the close vicinity of the borehole. In the following soil layer (10-20 cm), soil carbon content ranged from 1.93±0.42 g C kg^{-1} dry soil in the enclosures to 9.12±2.87 at the vicinity of the borehole. Deeper in the soil profile (20-30 cm), the soil carbon content was still highest in the close vicinity of the borehole with 7.14±3.43 gC kg^{-1} dry soil and lowest in forest plantations, with 1.20±0.25 gC kg^{-1} dry soil.

The mean C content in top 30 cm of the soil ranged nicely from the landscape units in which livestock was concentrated (borehole, settlements and ponds), to long term and short term enclosures (forest plantations) and finally rangelands. The profiles differed between the three categories. In the rangelands, soil carbon content values increased with depth in contrast to enclosures and forest plantations.

Table 4. 2. Distribution of soil organic carbon content in the landscape units at the three depths between 0 and 30 cm

Landscape unit	Soil carbon content in gC kg^{-1} dry soil sieved to 2 mm						
	0-10 cm		10-20 cm		20-30 cm		n
	Mean	SD	Mean	SD	Mean	SD	
Rangelands	2.77	0.50	2.42	1.14	3.15	2.55	40
Settlements	4.90	3.35	8.07	5.26	3.36	2.37	20
Vicinity of borehole	13.87	10.04	9.12	2.87	7.14	3.43	20
Ponds	6.78	2.74	3.91	1.95	3.68	1.36	20
Enclosures	6.63	1.81	1.93	0.42	2.05	0.17	10
Forest plantations	4.64	2.89	2.85	0.59	1.20	0.25	10

Table 4. 3. Cross-validation and statistic validation using pre-processing methods that produced the best predictions of the soil carbon content at a depth of 0–30 cm

	Calibration						Validation							
Pre-processing[a]	Outlayer	Ncal[b]	Mean	SD[c]	SECV[d]	R²cv	N Val[b]	Mean	SD[c]	Biais	SEPC[e]	Slope	R²Val	RPD Val [f]
D0011	0	75	3.76	3.54	0.86	0.94	35	3.25	2.72	-0.07	1.01	0.94	0.86	2.68
MSC1441	0	75	3.76	3.54	1.12	0.9	35	3.25	2.72	-0.08	0.98	0.92	0.88	2.76
MSC2441	0	75	3.76	3.54	1.15	0.89	35	3.25	2.72	-0.17	0.92	0.97	0.89	2.96
MSC2441	0	110	3.60	3.39	1.13	0.88	-	-	-	-	-	-	-	-
D0011	0	110	3.60	3.39	0.91	0.92	-	-	-	-	-	-	-	-
MSC1441	8	102	3.07	2.73	0.52	0.96	-	-	-	-	-	-	-	-

[a] See Section 2.2.3 for details of the pre-processing methods

[b] Size of the calibration and validation subset, respectively

[c] Standard deviation of the calibration and validation subset, respectively

[d] Standard error of cross-validation (in the unit of the variable)

[e] Standard error of prediction corrected for bias (in the unit of the variable).

[f] Ratio of validation subset SD to SEPc (unitless).

3.2. GHG emissions according to the category of emission

3.2.1. Enteric methane

Table 4.4 shows the time the livestock spent in each landscape unit, the mass of herbaceous fodder intake, and enteric methane emitted by livestock related to the herbaceous yields and the mass of wood and leaves of the woody plants in each landscape unit. Livestock spent most of their time in settlements and rangelands (more than 75% of the time on average over the year) mostly resting (including ruminating) and grazing (including walking). The two landscape units most frequented by the animals contributed substantially to livestock feeding (91.8%) and produced the bulk of herbaceous and woody biomass of the landscape as a whole. These two landscape units also produced most of the CH_4 emissions originating from herd enteric emissions due to the length of time spent by animals in these units. However, when CH_4 emissions are expressed per unit area, the smaller landscape units often visited by animals like the close vicinity of the borehole had very high CH_4 emissions rates per unit area.

Table 4. 4. Time spent by the livestock, production of plant biomass and enteric methane in each landscape unit

Landscape unit	Area (km^2)	Time spent % 24h	Fodder intake mass (tCO_2-eq/year)	Herbaceous production (tC-eq/year)	Woody plant production (tC- eq/year)	Enteric Methane (tCO_2-eq /year)
Settlements	44.46	42.70	1569.42	7499.93	168.94	8401.78
Ponds	19.34	9.12	1436.10	3647.80	120.06	1793.89
Vicinity of the borehole	0.78	4.12	86.53	182.82	5.59	810.62
Forest plantations	6.23	8.09	849.44	1033.46	64.42	1591.59
Rangeland	635.45	35.97	22662.11	102582.04	5507.97	7077.03
Enclosures	0.24	0.00	0.00	31.01	0.86	0.00
Landscape level	706.50	100.00	26,603.59	114,977.06	5,867.85	19,674.95

3.2.2. GHG emissions from soil and water

Table 4.5 shows the quantity of cattle manure deposited on the soil per unit area (ha) and total soil and water GHG emissions over a period of one year in the different landscape units. The rates of deposition of cattle manure ranged from 0.16±0.04 tDM/ha/year in rangelands to 0.82±0.3 tDM/ha/year in the vicinity of the borehole. Soil total CH_4 emissions ranged from -6.71 tCO_2-eq /year in forest plantations to 47,624.41 tCO_2-eq /year on the pond shoreline with a total annual emission of 57,319.64 tCO_2-eq /year at the level of the ecosystem. Soil total N_2O emissions ranged from 19.23 tCO_2-eq /year in the enclosures to 94,184.62 tCO_2-eq /year in the rangelands, with a total annual emission of 107,470.86 tCO_2-eq /year at the level of the whole landscape. CO_2 and CH_4 emissions from the natural ponds were higher than the emissions from the ponds in the vicinity of the borehole. In the settlements, N_2O emissions from the soil are the highest of all the emissions due to high rates of manure deposition per unit area. The ponds were the main sources of CH_4 emissions from the soil and water due to temporary water logging of the soil during the rainy season. In the close vicinity of the borehole CH_4 and N_2O emissions from soil and water were the highest per unit area due to combined effect of permanent soil water logging and very high rates of manure deposition.

Table 4. 5. Deposition of manure, soil and water GHG emissions in each landscape unit

Landscape unit	Dung deposition rate (tDM/ha /year)	Soil CH_4 (tCO_2-eq /year)	Soil N_2O (tCO_2-eq /year)	Pond water CO_2 (tCO_2-eq /year)	Pond water CH_4 (tCO_2-eq /year)
Settlements	0.63±0.1	350.55	9588.56	0.00	0.00
Ponds	0.37±0.09	47624.41	3051.34	11637.53	34524.67
Vicinity of the borehole	0.82±0.3	5810.97	275.49	824.61	2973.40
Forest plantations	ND	-6.71	351.62	0.00	0.00
Rangelands	0.16±0.04	3540.18	94184.62	0.00	0.00
Enclosures	0	0.23	19.23	0.00	0.00
Landscape level	0.19±0.05	57319.64	107470.86	12462.14	37498.06

3.2.3. Other sources of GHG emissions

Table 4.6 lists other sources of GHG emissions in the ecosystem assessed per landscape unit. Enteric emissions from termites ranged from 1.48 tCO_2-eq /year in enclosures to 3,960.30 tCO_2-eq /year in rangelands with total annual emissions of 4,368.88 tCO_2-eq /year for the whole landscape. CO_2 emissions from the motor-pump totaled 124.54 tCO_2-eq /year in the vicinity of the borehole. These two sources of emissions accounted for 2% of total GHG emissions at the level of the whole landscape.

Table 4. 6. GHG emission from termites and the motor pump in each landscape unit

	Termite (tCO_2-eq /year)	Motor pump (tCO_2-eq /year)
Settlements	282.76	0.00
Ponds	108.10	0.00
Vicinity of the borehole	4.72	124.54
Forest plantations	11.52	0.00
Rangelands	3,960.30	0.00
Enclosures	1.48	0.00
Landscape level	4,368.88	124.54

3.3. Carbon sequestration

3.3.1. C sequestration in the soil

Annual C accumulation in the top 30 cm soil layer ranged from 0.37 tC/ha/year in the rangelands to 1.69 tC/ha/year in the close vicinity of the borehole resulting in a mean C accumulation of 0.42 tC/ha/year at the level of the whole landscape. The annual rate of carbon accumulation in the soil was highest in the landscape units with high rates of manure deposition. For instance, annual C sequestration in settlements and ponds was 0.94 tC/ha/year and 0.78 tC/ha/year respectively. In forest plantations and enclosures, soil carbon accumulation was lower (0.55 and 0.64 tC/ha/year respectively). Annual soil carbon accumulation per landscape unit ranged from 56.57 tCO_2-eq /year in the vicinity of the borehole to 87,266.69 tCO_2-eq /year in the rangeland, with a total annual accumulation of 139,980.87 tCO_2-eq /year at the landscape scale (Figure 4.4). The landscape units which contributed most to total soil C sequestration at the level of the whole landscape were rangelands and settlements, which accounted for respectively 79% and 14% of total C accumulation in the soil.

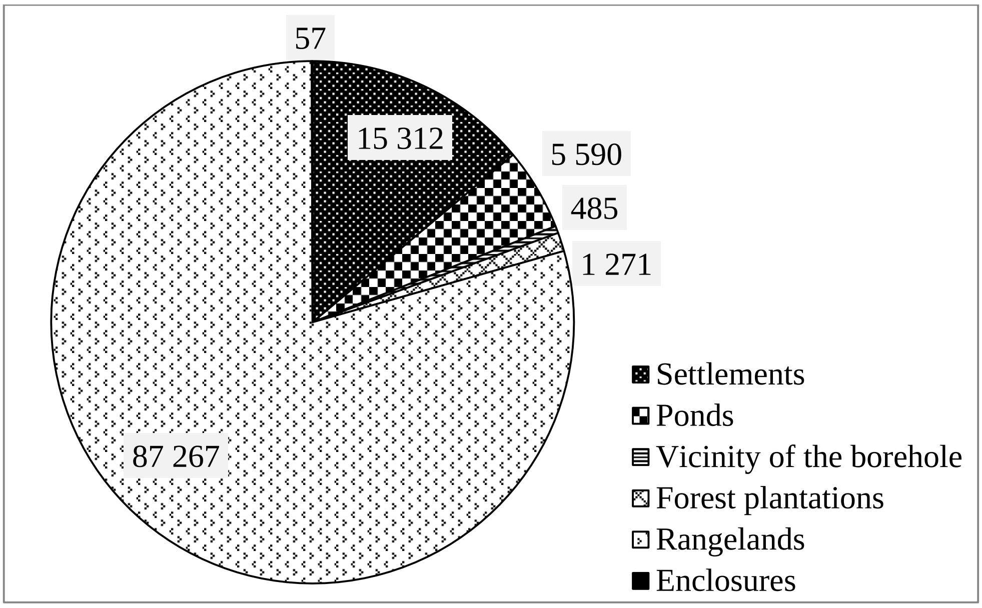

Figure 4. 4. Soil carbon accumulation in each landscape unit (in tCO_2-eq /year)

3.3.2. C sequestration in trees

Annual mean diameter growth recorded over the study period (2009-2015) was 3 mm/year for all species and trunk sizes. The corresponding annual carbon accumulation in aboveground and belowground woody biomass per landscape unit ranged from 42.6 tCO_2-eq /year in the vicinity of the borehole to 119,394.9 tCO_2-eq/year in the rangelands with total annual emissions of 109,980.87 tCO_2-eq /year (Figure 4.5). The landscape units which contributed most to total tree C sequestration at landscape scale were rangelands and ponds, which accounted for respectively 89% and 7% of total C accumulation in trees.

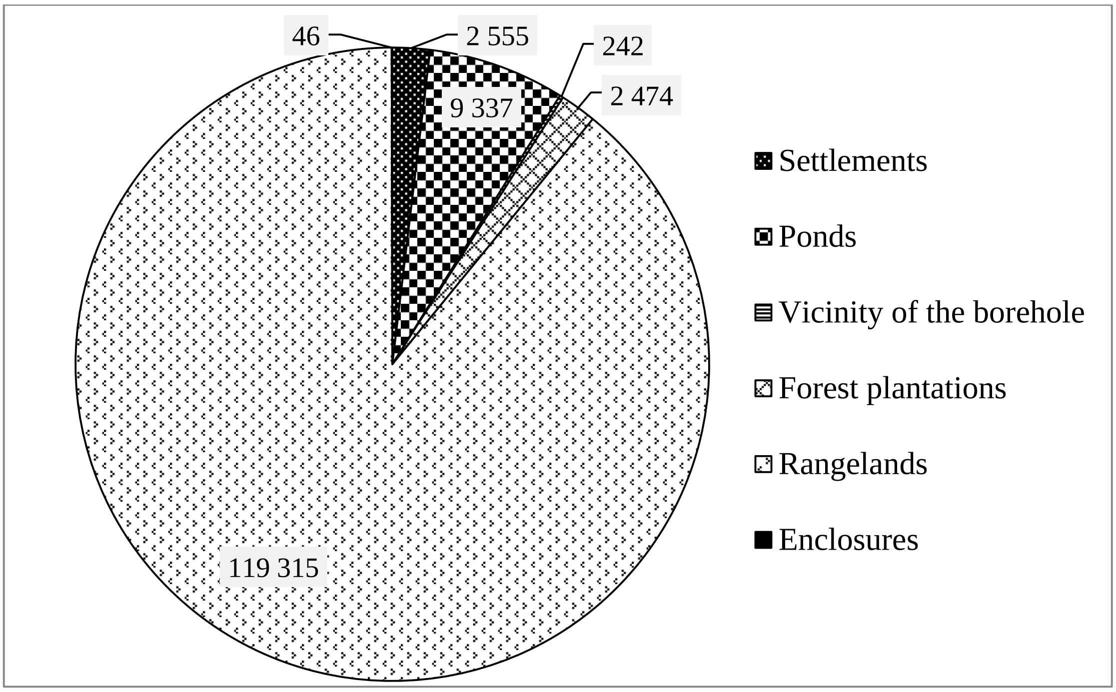

Figure 4. 5. Tree carbon accumulation in each landscape unit (in tCO_2-eq /year)

3.3.3. C sequestration in livestock

The survey of the weight of the herd during livestock monitoring indicated an average daily body weight gain of 16.9±4.3 kgLW/animal/year. Figure 4.6 shows the contribution of each landscape unit to the total carbon accumulation in livestock live biomass at the level of the whole landscape. Total annual carbon accumulation in livestock bodies per landscape unit ranged from 62.7 tCO_2-eq /year in the vicinity of the borehole to 650.1 tCO_2-eq /year in the rangeland, with a total annual C accumulation of 1,522.3 tCO_2-eq/year at the level of the whole landscape. The landscape units which contributed most to total C sequestration in livestock at the landscape scale were settlements and rangelands, which accounted for respectively 42% and 35% of total C accumulation in livestock bodies. Carbon stored in livestock bodies contributed very little (less than 1% relative contribution) to total carbon sequestration at the level of the whole landscape.

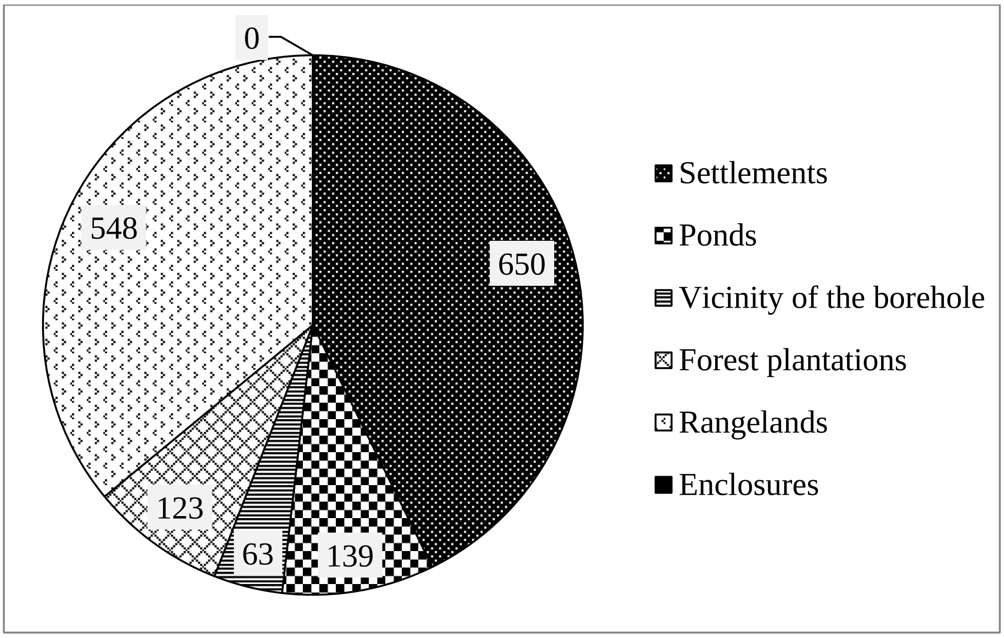

Figure 4. 6. Carbon sequestration in livestock bodies in each landscape unit (in tCO_2-eq /year)

3.4. GHG balance of the different landscape units and at the whole landscape level

Both components of the GHG balance, GHG emissions and carbon accumulation, are presented for the six landscape units and for the whole ecosystem in Figure 4.7. A negative value of the GHG balance means that C accumulation offset GHG emissions. The GHG balance of each landscape unit ranged from -3.41 tCO_2-eq /ha/year in the enclosures to +127.1 tCO_2-eq /ha/year in the close vicinity of the borehole. Three landscape units had a negative GHG balance (rangeland, forest plantations and enclosures) and the remaining units (the vicinity of the borehole, the settlements and the ponds) had a positive balance. The net GHG balance at the whole landscape level was -0.09 tCO_2-eq/ha/year.

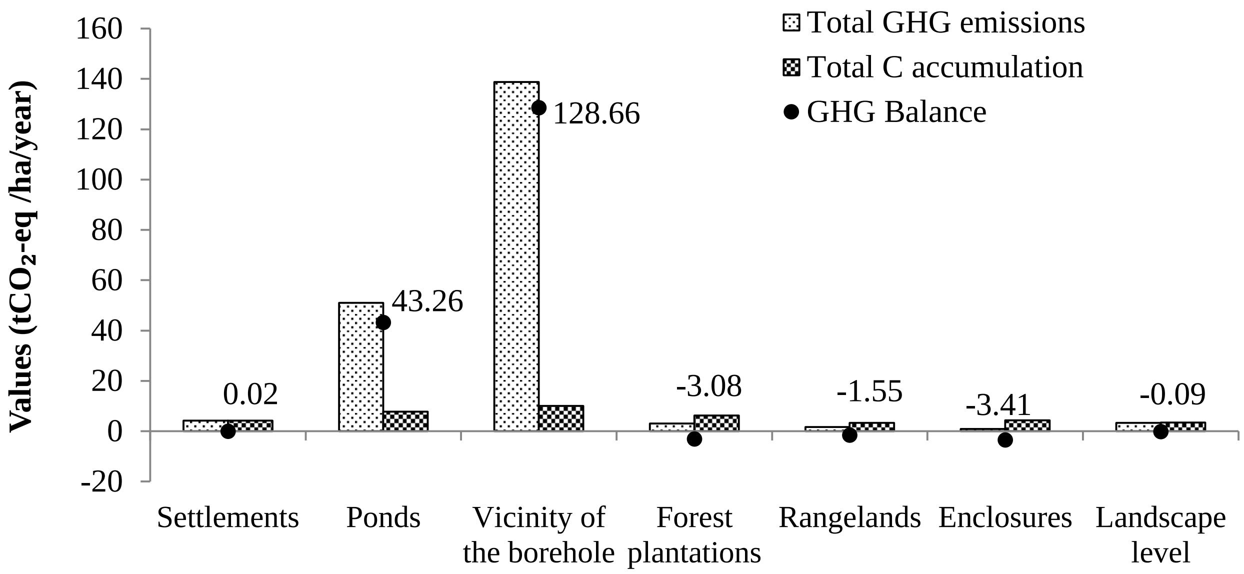

Figure 4. 7. GHG balance in each landscape units and at landscape level

4. Discussion

Our results underline the **high spatial heterogeneity** of the GHG balances (see figure 4.7). Landscape units can be classified in three groups according to the time spent by the livestock in each unit, the quantity of forage consumed and manure deposited on the soil by livestock. Thus, settlements, ponds and the borehole vicinity can be clustered in “Group 1” with high manure deposition but limited contribution to annual forage intake. Rangelands and forest plantations can be clustered in “Group 2”, with low manure deposition rates and a high contribution to annual forage intake. The last category, “Group 3”, contains enclosures with no livestock effect (zero intake and excreta). This study showed that landscape units which receive little or no livestock excreta have negative GHG emissions (Groups 2&3) and landscape units which receive large quantities of livestock excreta and contribute little to fodder intake have positive balances.

Most of the spatial heterogeneity of GHG emissions and C accumulation is certainly **explained by the spatial transfers and the concentration of nutrients and C** in specific landscape units due to forage intake and manure deposition by livestock. In fact, grazing animals mainly consume biomass in the landscape units in Group 2 (rangelands, forest plantations) and manure is mainly excreted in the units in Group 1 during resting (in settlements) and watering (in the vicinity of the borehole and on the shoreline of the ponds). When animals graze pastures, they consume forage and gain body weight, and also leave behind a large quantity of excreta. Manure represents high nutrient and C inputs to the soil which indirectly increase vegetation growth (*C* *accumulation in trees*). Excreta are major sources of the two most limiting elements (P and N) to the growth of vegetation in the Sahel (Turner, 1998). The positive effect of excreta deposition on *C accumulation in soils* content was originally demonstrated by Hiernaux *et al.* (1999) for sandy soils in a comparable Sahelian rangeland. C sequestration in soils is especially important in the case of long-term applications (Zhang *et al.*, 2008; Bhattacharyya *et al.*, 2013). Animal excreta are also sources of direct emissions of GHG, in particular of N_20 and CH_4 (Lin *et al.*, 2009; Mulbry and Ahn, 2014). The deposition of excreta results in biological processes in the soil (i.e., priming effect, methanogenesis, nitrification, and denitrification) which cause high indirect GHG emissions from the soil (Thangarajan et al, 2013). Excreta deposition consequently also indirectly increases GHG emissions from the soil to the atmosphere (Yamulki *et al.*, 2000; Li and Kelliher, 2007; Saggar *et al.*, 2007).

Similar nutrient and C transfers have also been reported for Sudanian savanna agro-pastoral ecosystems (Manlay *et al.*, 2004a; Manlay *et al.*, 2004b). In **agro-pastoral ecosystems**, traditional practices like free grazing and night corralling lead to nutrient and C transfers from the periphery to the core of the landscapes, i.e. from rangelands to fields located close to dwellings (Manlay *et al.*, 2004a; Schlecht *et al.*, 2004). Consequently marked heterogeneity of the GHG balance can be expected at landscape level for this type of ecosystem in West Africa.

Beyond the marked spatial heterogeneity of the GHG balance, the full GHG balance at the whole landscape level was slightly negative: -0.09 tCO_2-eq/ha/year (see Figure 4.7). Total GHG emissions from livestock, termites, soil, water, fires and the motor-pump were balanced by C accumulation in soil, trees and livestock at the whole landscape level. This means that tropical sylvo-pastoral ecosystems in the Sahel are potentially C sinks, in agreement with the figures for temperate grazing ecosystems reported by Allard *et al.* (2007) and Soussana *et al.* (2007), ranging from 2.75 tCO_2-eq/ha/year to 3.12 tCO_2-eq/ha/year. The results of this study suggest that there are reasons to be optimistic about the potential of grazing ecosystems to sequester C under semi-arid tropical conditions and to offset part of global anthropogenic GHG emissions.

5. Conclusion

This chapter presents new data on the GHG balance and the functioning of a typical tropical sylvo-pastoral landscape in the Sahelian region of Africa. The following main conclusions can be drawn:

- This study revealed **strong spatial heterogeneity** of the GHG balance. The spatial heterogeneity of the GHG balance is mainly explained by livestock habits and movements within the territory, which affects the spatial distribution of forage intake and manure deposition thereby creating hotspots of GHG emissions. The GHG balance is negative in landscape units which receive little or no livestock manure (enclosures, forest plantations, rangelands) whereas the balance is positive in units with high rates of manure deposition which contribute little to fodder intake (the vicinity of the borehole, settlements and ponds).

- At the whole landscape level, the yearly GHG balance was shown to be slightly negative. GHG emissions from livestock, termites, soil, water, fires and the motor-pump are globally compensated by carbon accumulation in soil, tree and animals. This figure argues for an **"in equilibrium" state of the ecosystem**.

This "in equilibrium" state of the ecosystem now needs to be confirmed through more detailed analysis of the long-term dynamics of the different components of the ecosystem studied here. This more detailed analysis needs to complete the quantification of the biomass/nutrient/carbon flows/stocks proposed in this study by other ecological indicators such as changes in the land cover and the relative abundance of the different plant/animal species in the ecosystem. This type of study may argue for including tropical semi-arid rangeland ecosystems in payment for environmental services schemes.

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Conclusions intermédiaires et transition

Cet avant dernier chapitre (Chapitre 4) montre la forte hétérogénéité spatiale du bilan GES du territoire étudié. Le rôle de l'élevage dans la construction de cette hétérogénéité est majeur. Les troupeaux par le jeu des prélèvements-déplacements-restitutions des animaux créent des « zones d'extraction » (parcours, plantation) et des « zones d'accumulation » de nutriments et de C (campements, forage, mares). Ainsi les unités paysagères avec de forts niveaux d'apports de déjection au sol par unité de surface et de temps ont un bilan GES positif tandis que celles ayant de faibles niveaux d'apports ont un bilan négatif.

Les mêmes résultats exploités dans le Chapitre 4 sont repris dans le chapitre suivant et ré-analysés sous l'angle de la variabilité temporelle du bilan GES. Ce dernier chapitre (Chapitre 5) offre à partir d'un suivi d'un peu plus d'un an une vision dynamique et saisonnière du bilan GES.

Chapitre 5 : Une forte variabilité saisonnière du bilan Gaz à effet de serre en territoire sylvo-pastoral

Ce cinquième chapitre se base sur l'article suivant :
Assouma M. H., Hiernaux P., Lecomte P., Ickowicz A., Bernoux M., Ganglo J.C., Vayssières J. A neutral carbon balance over the year achieved through contrasted seasonal balances in a Sahel pastoral ecosystem. To be submitted to Journal of Arid Environments.

Une communication courte de 2 pages intitulée « Intra-annual variability of the greenhouse gas balance of a sylvo-pastoral ecosystem in semi-arid West Africa » a également été présentée à l'occasion du « 10th International Rangeland Congress » à Saskatoon au Canada du17 au 22 Juillet 2016.

Abstract

Greenhouse gas (GHG) emission inventories for agricultural systems are usually calculated on an annual basis. This study puts forward, in an original way, a dynamic vision of the functioning and GHG balance of a West African sylvo-pastoral ecosystem with a very seasonal climate and a semi-arid monsoon climate, and characterized by high herd mobility.

The study territory was the area under the influence of the Widou borehole, conventionally a circular zone with a diameter of 30 km centred on the borehole, covering 706 km². In terms of pastoral practices, this territory is typical of the Ferlo region, the sylvo-pastoral area in the North of Senegal. The GHG balance described here integrates the main sources of carbon emission and accumulation of the ecosystem. Methane emissions arising from animal enteric fermentation were indirectly evaluated by rations monitoring and a spectral analysis of faeces. Soil emissions were measured with static chambers and analysed by gas chromatography. Emissions in pond water were evaluated with water samples by assessing the concentration of dissolved gas and using chromatography. Other emissions (termites, motor pump) which were less significant were evaluated from emission factors found in the literature. Changes in animal weight and herd composition parameters were used to calculate the carbon stock growth represented by the herd. C accumulation in wood and woody roots was evaluated by observing tree diameters (2009-2015 period) and using allometric equations specific to each species involved. At soil level, C accumulation was estimated by balancing incoming (biomass) and outgoing (gaseous) C fluxes.

The annual net GHG balance of the ecosystem was -0.01±0.03 tC-eq/ha/year. Thus, the sylvo-pastoral ecosystem would be offsetting the overall GHG emissions with carbon accumulation in trees, soil and animals at the end of a complete annual cycle. The results showed great seasonal variability for this balance with a positive monthly balance in the rainy season (July to October) and a negative monthly balance in the hot and cold dry seasons (November to June). This balance varied from +0.19 tC-eq/ha/month in the rainy season to – 0.16 tC-eq/ha/month, on average, in the cold dry season. In the wet season, emissions exceeded sequestration due to high soil humidity and a large number of animals in the study territory. In the dry season, the negative balance could be explained by the gradual departure of animals for transhumance and soil micro-organisms reducing their biological activity (quick drying on the surface). This period was characterized by C accumulation in the soil (through an accumulation of animal excreta and landfill litter burying) and in active woody vegetation for at least the first part of the dry season thanks to its capacity to explore deep down for water in the soil. It is most likely that this high intra-annual variability for GHG goes hand in hand with high inter-annual variability.

Keywords: Ecosystem functioning, Animal-soil-plant interactions, Landscape, Senegal

1. 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 (CO_2), methane (CH_4) and nitrous oxide (N_2O). In parallel, international reports and review studies draw attention to the contribution made by livestock breeding activities to GHG emissions (CO_2, CH_4, N_2O) and to climate change. They evaluate the contribution of the world's livestock sector to GHG emissions at 14.5% (Gerber *et al.*, 2013; Caro *et al.*, 2014). The environmental impact of intensive versus extensive livestock systems is a matter of debate in the scientific community (Herrero and Thornton, 2013). Extensive pastoral ecosystems are said to be major contributors to global warming. In sub-Saharan Africa, they are assumed to be responsible for the highest rates of greenhouse gas (GHG) emissions per unit of animal products (Steinfeld *et al.*, 2006). The main reasons put forward are herds with low productivity, low management levels in pastures and the high methanogenic potential of feed intakes. Pastoral rangelands cover more than 25% of terrestrial ecosystems (Boval and Dixon, 2012; Rouget, 2015) and more particularly about 40% of Africa's land mass, where semi-arid rangelands dominate (Tagesson *et al.*, 2015a). 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, 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) (Chapter 3).

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 Sahelian climate is characterized by low rainfall varying between 100 mm/year in the North and 600 mm/year in the South (Nicholson, 2013), high seasonal variation in rain events and high inter-annual variability (Hiernaux and Le Houerou, 2006). Precipitation is naturally a rare occurrence and predominantly occurs over 3 or 4 months between July and October. There is also high heterogeneity of the spatial distribution of rainfall at local level (Sanogo *et al.*, 2015). Water availability is the main limitation to the functioning of this ecosystem due to its impact mainly on processes that control the functioning and productivity of the ecosystem, such as soil biological activity (Delon *et al.*, 2015), the presence and growth of vegetation, particularly forage grasses (Hiernaux *et al.*, 2009a; Brandt *et al.*, 2016) and indirectly, the feeding, growth and reproduction of animals (Chirat *et al.*, 2014).

These processes also control the majority of nitrogen (N) and carbon (C) flows in the ecosystem via the degradation of litter and the mineralization of soil organic matter (Wu *et al.*, 2010), N assimilation and C fixation by plants (Maseko and Dakora, 2015), and their consumption by animals with a partial return to the soil of these elements in the form of animal excreta (Schlecht *et al.*, 2006). In pastoral ecosystems, livestock animals, particularly ruminants, play a major role in the organization of C&N cycles because they digest plants mainly composed of cellulose, with slow degradation (Petersen *et al.*, 2013) and they produce faeces (urine and dung) with high N concentrations, providing the soil with C and N in available forms for micro-organisms and plants (Whitmore, 2001). The C & N cycles both very strongly determine the processes of greenhouse gas (GHG) emissions and C sequestration (Soussana *et al.*, 2004). It is thus highly likely that the large seasonal variation in rain and resource availability induces strong temporal variability in GHG emissions and strong seasonal variations in C sequestration. This study proposes a dynamic vision of sylvo-pastoral landscape functioning by investigating the impact of intra-annual variability in the GHG balance. The **objectives** of this study were to describe the functioning of the sylvo-pastoral ecosystem over a full year and propose a first assessment of the intra-annual temporal variability in the GHG balance of a study case located in the sylvo-pastoral Ferlo Region (northern Senegal) in the Sahelian zone of West Africa. The studied landscape was a circular area of 15 km radius centred on the Widou borehole (15°59'N, 15°19'W, 706 km^2). For this study, an original measurement protocol was implemented from May 2014 to October 2015 to estimate full GHG emissions and carbon accumulation in the studied landscape. This study was original through its capacity to integrate the various components of the ecosystem (animals, soil and vegetation) and to bring a dynamic vision of various stocks/fluxes. The study was based on a new original dataset on this ecosystem which has been little described. The high level of complexity in this type of ecosystem explains the lack of data and the difficulty in producing reliable data concerning N&C exchanges between the ecosystem and the atmosphere (Galy-Lacaux and Delon, 2014). Indeed, the strong animal-soil-plant interactions, high spatial heterogeneity (Chapter 4) and strong temporal variability in the biophysics processes (this chapter) render these systems particularly complex. The access restrictions related to their isolation and a high level of insecurity (terrorism in the Sahel) do not facilitate the production of references for these territories (De Haan *et al.*, 2016). This paper also provided the opportunity to identify sources of uncertainty and gaps in knowledge that need to be addressed in order to consolidate the variability in the GHG balance of this ecosystem.

2. Material and methods

2.1. Description of the study area

2.1.1. Physical and climatic characteristics of the study area

Located between the latitudes 15° and 16° 30' North and the longitudes 13°'30' and 16° West, Ferlo corresponds to a large part of the Senegalese pastoral zone (Ndiaye *et al.*, 2014a). It occupies around 70,000 km^2, i.e. slightly over a third of the Senegalese territory (Wane *et al.*, 2010). The main way of life in this region is pastoral, characterized by shared access to its land, forage (herbaceous and woody) and water resources (Leclerc and Sy, 2011). Ferlo is situated in the Sahel bioclimatic domain and is characterized by spatio-temporal variability in rainfall, whose incidence on the level of the pond filling and rangeland development has often made settlements difficult, favouring the pastoral system, on the one hand, and, on the other hand, explaining the migration regimes (big and small transhumance) as an option for adapting to these sometimes very restrictive situations in some years (Sy, 2010). Prior to the 1950s, it was a zone exploited almost exclusively in the rainy season by Fulani transhumance farmers in that region. In the dry season, due to a lack of available water (very deep Maastrichtian fossil water), livestock farmers moved to the rangelands of the Senegal River valley floodplains in the North and East or to the savannahs of the Southeast of the country. An ambitious programme to install deep pastoral boreholes with mechanical pumping was developed from the 1950s based on a very regular grid of around 20 to 30 km between neighbouring boreholes, further completed in recent years (Manoli *et al.*, 2014). Since then, in Ferlo, land occupation by pastoralists has been organized concentrically around the main water point formed by the borehole. This has created spatial units which we call **borehole coverage areas** here; they comprise "the land and all the resources centred on a pastoral borehole". Our case study was centred on the Widou Thiengoly borehole located at 15° 59' latitude North and 15° 20' longitude West (Sagna *et al.*, 2014). This borehole was chosen due to the existence of a large database resulting from the monitoring of ecosystem dynamics undertaken by the Ferlo Pastoral Self-Promotion project within the Widou experimental zone (André, 2001) and the Pastoral Systems and Dry Lands platform (PPZS) since 2000 (Ancey *et al*., 2008; Bah *et al*., 2010), and also due to the existence of small deferred grazing plots in which grazing had been prohibited for over thirty years of intervention by German development programmes (Miehe *et al*., 2010). By convention, the study site corresponded to the circular territory with a radius of around 15 km centred on the Widou borehole. It occupied an area of around 706 km².

The study zone exhibited the typical traits of a semi-arid Sahelian type monsoon climate (Niang *et al*., 2014b) with the alternation of two seasons: a dry season lasting from 8 to 10 months (October/November to June-July) and a rainy season of 2 to 4 months depending on the years (Figure 5.1). The dry season could be divided into two seasons of four to five months each, the first being the cold dry season from November to February and the second being the hot dry season from March to June. The data gathered between 1973 and 2015 at the Widou forestry centre indicated strong inter-annual variability in rainfall and in the number of rainy days. The coefficient of variation was 36.7% for total annual rainfall and 24.1% for the number of days' rain. On average, annual rainfall amounted to 285.8 ± 84.2 mm distributed over 19 ± 4 days with more than 2 mm of rain (mean of 42 years: 1973-2015).

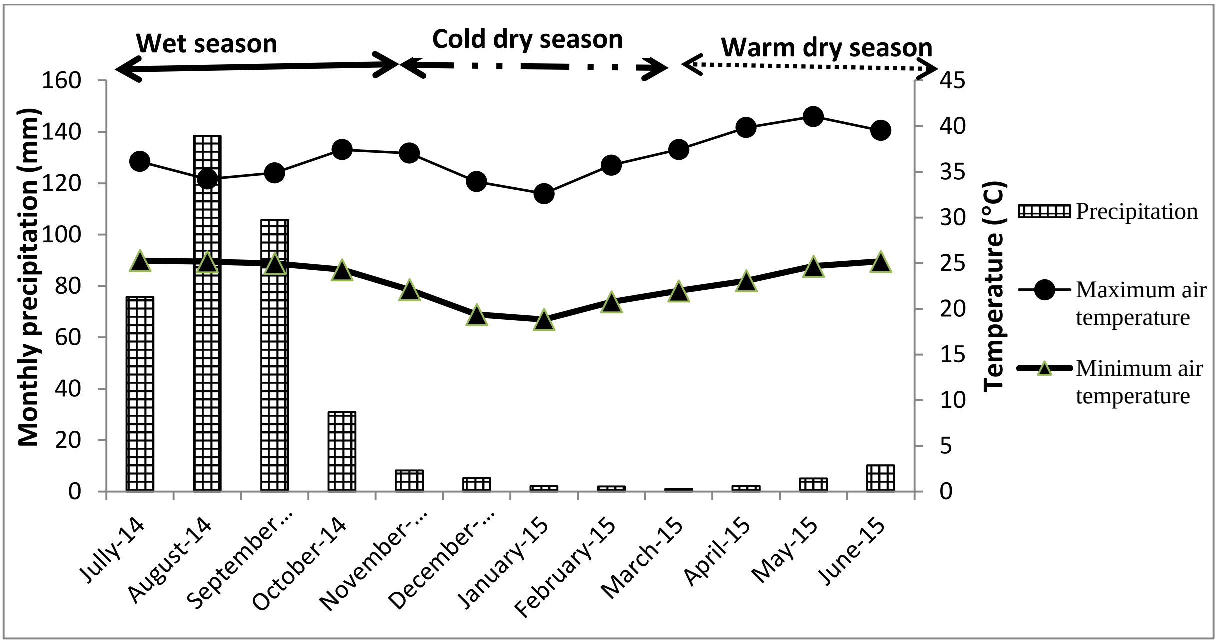

Figure 5. 1. Monthly maximum and minimum air temperature and precipitation during the period of the study at the Linguère weather station (15,38°N, 15,12°W)

Inter-annual variability in rainfall is quite strong with, for example, annual rainfall in 2005 (478.4mm) that was 4 times greater than in 1983 (105.4mm). The relative humidity of the air was very low (annual mean of around 43% varying between 27% in March and 72% in August) and the temperature high (annual mean between 25 and 30°C) with high evaporation followed by precarity in the soil water reserves.

The soils are sandy, of the leached tropical ferruginous type (Tappan *et al.*, 2004) characterized by a succession of dunes and gentle depressions with a different type of soil depending on whether at the top of a dune or the bottom of a slope (Ndiaye *et al.*, 2014a). In fact, the bottomlands had a higher clay rate than the dune tops. The plant cover was of the steppe or savannah type with sparse annual herbaceous or woody plants, particularly thorny plants (*Balanites aegyptica*, *Acacia senegal*, *Acacia raddiana*, *Acacia seyal*, etc.) (Niang *et al.*, 2014a). The herbaceous vegetation was mainly based on annuals, among which grasses dominated (*Schoenefeldia gracilis*, *Cenchrus biflorus* and *Aristida mutabilis*), and rarely exceeded 40 cm in height (Vincke *et al.*, 2010). Among the dicots, legumes were mostly represented by *Zornia glochidiata*, *Alysicarpus ovalifolius* and *Indigofera senegalensis*.

2.1.2. Landscape organization of the study territory

Based on reference spatial data describing the soil occupation and landscape of the Widou borehole area (Assouma et al, 2016 in press), the study environment was subdivided into six landscape units based on soil occupation. Remote sensing tools (Landsat scene image TM 204-049 dated 3 November 2010) and field observations (GPS point to mark out the boundaries of the units and identify particular points) led to the following six landscape units being defined (presented here in decreasing order of occupancy by animals):

- **Rangelands** (635.45 km², 89.9%) corresponding to steppe-like plant formations on which animals go to graze.
- **Settlements** (44.46 km², 6.3%) corresponding to the zone occupied by farmers' dwellings, along with the animal night paddocking and resting areas.
- **Forest plantations** (6.23 km², 0.9%), set up since 2005 by the Senegalese government as part of the Grande Muraille Verte project (Diallo *et al.*, 2015). This landscape unit is only accessible to animals 3 years after planting.
- **Natural ponds** (19.34 km², 2.7%) located in the low-lying areas of inter-dune depressions (bottomlands), which form a string of ponds in the wet season and are the main watering places for herds in that season and in the early months of the dry season.
- The **borehole** (0.78 km², or 0.1%) is the only watering place for herds when the ponds dry up, thereby constituting a very strong pole of attraction for animals (cattle, sheep, goats, donkeys, horses) and for pastoral farmers for more than 6 months of the year.

- **Enclosures** (0.24 km², 0.03%) consisting of 6 plots where grazing has been integrally prohibited since 1981 (Miehe *et al.*, 2010).

2.2. Survey of C stocks and GHG fluxes

2.2.1. The conceptual model guiding data collection

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 choice of fluxes to be monitored was based on the conceptual model presented in Figure 5.2. This figure describes all the fluxes between the main components of the sylvo-pastoral ecosystem (animals, soil, plants) and between its components and the atmosphere.

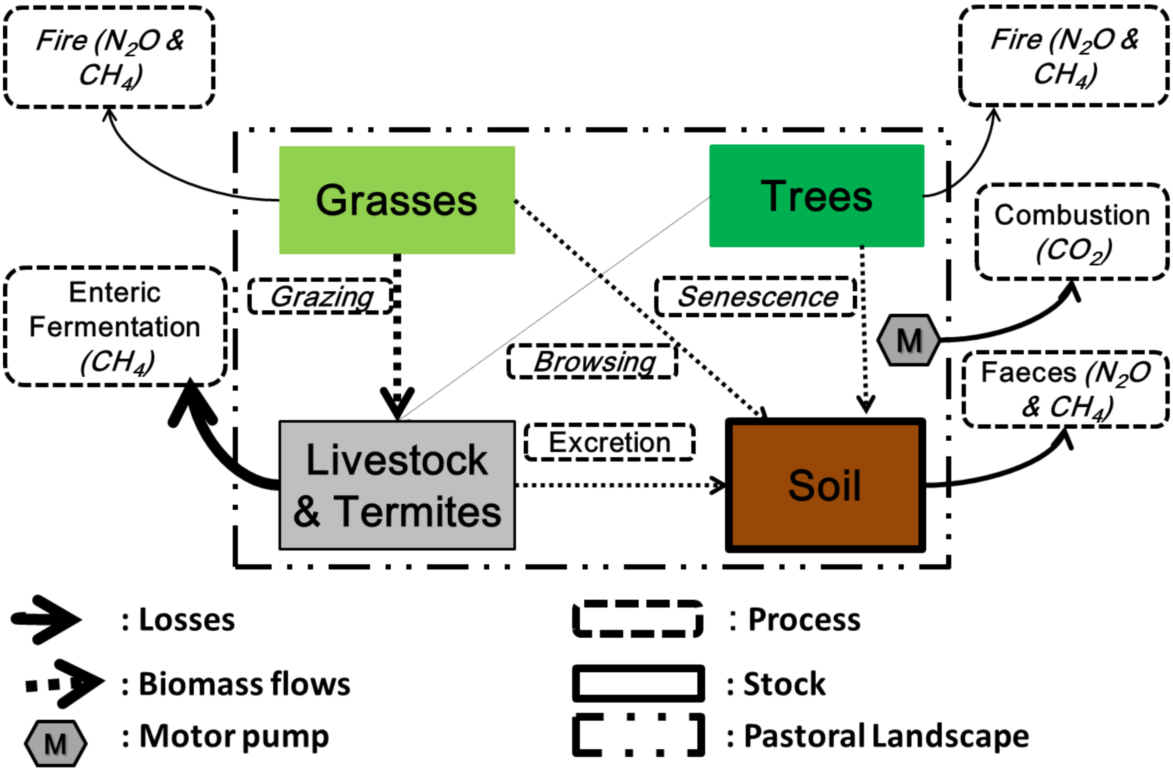

Figure 5. 2. Simplified conceptual model of the functioning of a sylvo-pastoral ecosystem in terms of nitrogen and carbon stocks-fluxes (the thickness of the box outlines for stocks and of the arrows for fluxes are proportional to their importance).

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. During annual monitoring, only gas emissions from soil and water (CO_2, N_2O and CH_4) were measured directly. The other fluxes were estimated by monitoring biomass flows/stocks, and subsequently converting that biomass into C or CO_2 equivalents according to contents and emission factors that were either observed or found in the literature.

2.2.2. Sampling strategy

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). This 18-month observation period was chosen to guarantee measurements were taken over 1 full year (July 2014 to June 2015) and to account for a degree of inter-annual variability in certain key items such as enteric emissions from ruminants (table 5.1).

Table 5.1 indicates the number of observations and direct measurements in the field carried out per flux/stock type and per landscape unit over the study period (May 2014 to August 2015). The set of direct measurements in the field was carried out at 13 common sites covering all the landscape units in the territory. The choice of the number of sites (table 5.1) per landscape unit also took into account the extent of the unit and the probability of encountering strong GHG emissions there due to higher animal occupancy.

Table 5. 1. Timetable of observations per component of the ecosystem with an indication of the number of measuring sites per landscape unit at Widou (W) and Dahra (D)

Fluxes/Stock	May-14	Jun-14	Jul-14	Aug-14	Sep-14	Oct-14	Nov-14	Dec-14	Jan-15	Feb-15	Mar-15	Apr-15	May-15	Jun-15	Jul-15	Aug-15	Sep-15	Oct-15	Landscape Unit
			← Period covered by the GHG balance →																
Enteric Fermentation		**W**	**W**	**W**	**W**	**W**	**W**	**W**	**W**	**W**	**W**	**W**	**W**	**W**	**W**	**W**	**W**	**W**	5 animals of 3 herds across all landscape units
Soil and Water GHG fluxes	**W**		**W**	**W**	**W**	**W**			**W**										Rag(5), Set(2), Pon(2), Bor(2), Pla(1), Enc(1)
Livestock carbon accumulation	**W**	**W**	**W**	**W**	**W**	**W**	**W**	**W**	**W**	**W**	**W**	**W**	**W**	**W**	**W**	**W**	**W**	**W**	5 animals and 40 herds across all landscape units
Tree carbon accumulation									**W**					**D**					Rag(5), Set(2), Pon(2), Bor(2), Pla(2), Enc(2)
Herbaceous biomass	**W**		**W**	**W**	**W**	**W**	**W**		**W**		**W**								Rag(5), Set(2), Pon(2), Bor(2), Pla(2), Enc(2)
Soil carbon accumulation									**W**										Rag(5), Set(2), Pon(2), Bor(2), Pla(2), Enc(2

W: Measurement carried out in the Widou coverage area, **D:** Measurement carried out at the Dahra Research station

Rag: Rangelands, **Set:** Settlements, **Pon:** Ponds, **Bor:** Borehole, **Pla:** Forest plantations, **Enc:** Enclosures

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. Some additional measurements were taken in June 2015 in a small plot located in a rangeland area (15° 21' latitude North and 15° 28' longitude West), at the Dahra research station (Ndiaye et al., 2014b). These additional observations were needed to assess the annual growth in C stock in trees, as the geo-referenced measurements of tree circumferences had been carried out at the same site six years earlier (in June 2009), which was not the case at Widou.

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. They were completed by an estimation of the weight of the animals in the 3 monitored herds to estimate enteric emissions (see below). Variations in animal weight were estimated from barymetric measurements (Njoya *et al.*, 1997).

Emissions of **enteric CH_4** were assessed by monitoring biomass fluxes generated by the animals (ingestion, defecation) in 3 herds of three different settlements on a monthly basis from June 2014 to October 2015. The three herds chosen represented the three categories of livestock farmers (small-, medium- and large-scale) present in the study territory (Section 2). In each herd, one or two bull calves were chosen to be monitored using the hand-plucking method. In all, 5 bull calves were monitored. Each animal was monitored for 24 h or 48 h depending on the animals' rhythm of activity, which greatly depended on the watering frequency of the animals (1 or 2 times per day depending on the season). The biomass ingested and its composition were determined by the "hand-plucking" technique (Chirat *et al.*, 2014). The biomass excreted was measured by the "faeces bag" technique (Guerin, 1987). The quantities ingested daily by the monitored animals were sorted to reconstitute the composition of the ration consumed each day by the animals.

Lastly, **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 hot dry season (May 2014). The GHG fluxes in soil were measured by the static chamber method (Serça *et al.*, 1994). 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 water points were natural ponds in the bottomlands and ponds created around the borehole by animal watering and the filling of water carrying containers by the livestock farmers.

2.2.3. Complementary data to explain intra-year variations in the GHG balance

The sampling strategy described above made it possible to quantify the main GHG fluxes and C stocks. It was also used to collect certain additional information useful for understanding the functioning of the studied ecosystem and explaining the time variability of the elements of its GHG balance. One of the strong hypotheses in this study was that the availability of forage biomass and herd movements linked to rainfall distribution in time were key elements in constructing the time variability of the GHG balance.

Herbaceous biomass was monitored at the same 15 sites chosen to assess C stocks in woody plants and soil. In all, 8 consecutive measurements were taken over time to cover the temporal dynamics of biomass production in all the landscape units (table 5.1.). The measurements were taken each month in the wet season (from July to October 2014) and every two months in the dry season (from November 2014 to May 2015). When the different measurements were taken, the aboveground and root biomass in the first 30 cm of soil were quantified.

Monitoring of the 40 herds as previously described enabled an assessment of the numbers present in the Widou borehole coverage area, or having left for transhumance, and the length of time the animals were present per landscape unit, along with the time spent each day on each activity (watering, feeding, standing rest, lying rest).

2.3. GHG flux measurement and estimation

2.3.1. Enteric methane

Enteric methane arising from the fermentation of feeds in the rumen of ruminants is one of the main sources of GHG in livestock systems (Cottle *et al.*, 2011; Chung *et al.*, 2013). **Enteric methane** emissions in the pastoral ecosystem was assessed by an indirect method based on the digestibility of the predicted ration with the spectral analysis of faeces samples (Tran *et al.*, 2010). The method can be summed up in two main stages: faeces sampling stage (and reconstitution of dietary regimes) and a spectral analysis stage.

- *Reconstitution of dietary regimes and collection of faeces samples*

In the Ferlo sylvo-pastoral system, rangeland management is primarily based on herd grazing by day and night. Cattle herds are on communal rangelands throughout the year, without any permanent cowherd to manage them, since they are free in their movements, while small ruminants are managed by young herdsmen throughout the year (Section 3).

The biomass ingested, and its composition, were determined by the so-called "hand plucking" technique developed by Guérin *et al.* (1986) and used by (Chirat *et al.*, 2014) in agro-pastoral zones. It involves mimicking biomass uptake by grazing animals (Bonnet *et al.*, 2011; Chirat *et al.*, 2014). The grazing orbit of cattle, sheep and goats was also described by the time spent in the landscape units and simultaneously by the orbit traced using a GPS (GPS MapGarming 62S) as described in Schlecht *et al.* (2006). Each animal was monitored for 24 h or 48 h depending on its rhythm of activity. The duration of each monitoring operation was determined by the watering frequency of the animals (once or twice a day depending on the season). The quantities ingested daily by the monitored animals was sorted to reconstitute the composition of the ration consumed each day by the animals, making a distinction between grasses, legumes and biomass from woody plants.

Excreted biomass was measured by the "faeces bag" technique (Guerin, 1987). In all, 5 bull calves were fitted with a harnessed bag enabling the collection of all the faeces excreted by the animal. The faeces bag was emptied every 12 hours to avoid overloading the animal. On each monitored animal, the zoo-technical parameters were measured on each monitoring operation. This involved the body condition score (BCS), height at withers, and chest girth, parameters used in the formula of Njoya *et al.* (1997) to estimate animal weight.

- *Sample preparation phase and NIRS processing of dietary regimes and collected faeces*

Near infrared spectroscopy (NIRS) is an analytical technique based on the principle of (infrared) radiation absorption by organic matter. As such absorption is linked to the chemical composition of the samples; the latter can be estimated by simple measurements of light absorption by the sample. Many studies have shown that NIRS can be used to estimate the chemical composition of forage samples (Boval *et al.*, 2004) but also directly their digestibility and rate of intake (Fanchone *et al.*, 2007), then predict the quantities ingested during grazing from a spectral analysis of faeces (Decruyenaere *et al.*, 2009b).

Each forage and faeces sample was dried in an oven at 65°C for 72 h then ground to 2 mm and analysed by NIRS. For the dietary ration, a ration was reconstituted for each animal and for each monitoring operation based on the results of the ration composition estimated from the hand plucking collection. It was this reconstituted ration and the corresponding faeces samples that underwent NIRS analysis. Spectra were taken on powders, presented in cups (diameter = 20 cm) in diffuse reflection between 350 and 2 500 nm on an ASD 28022 spectrometer (LabSpec® 4 Standard-Res lab analyzer). Three spectra of each of the samples were measured, averaged and mathematically pre-processed.

The NIRS approach called for a calibration phase based on reference measurements obtained in the laboratory and the establishment of mathematical models making it possible to link the infrared spectrum to the parameters to be estimated. In order to increase prediction quality, we enriched a database comprising 3,394 spectra taken on faeces samples from various places (tropical and temperate zones) with some reference values produced from observations of herds in the Widou borehole zone. In all, 90 new spectra of faeces-reconstituted ration pairs from monitoring operations were added to the database to integrate some observations from pastoral systems in a tropical semi-arid environment. For each of the 90 samples, the quantity of voluntarily ingested dry matter (DMvi075) was calculated based on field measurements. A validation set (18 samples) was created from mean spectra representing each month of monitoring. Then the calibration equations were developed using partial least squares (PLS) regression techniques. The spectral data acquired for each sample, pre-processed in Standard Normal Variate Detrend (SNVD) and first derivative 1,5,5,1, were calibrated and cross-validated in the software (Winisi, Infrasoft) for each of the two variables dOM (digestibility of organic matter) and DOMI (digestible organic matter ingested voluntarily). The local calibration technique described by Shenk *et al.* (1997) was used. The resulting validation set was used to validate the local calibrations. To validate the model, the coefficient of determination (R^2), the standard error of cross-validation (SECV), standard error of prediction (SEP) and ratio of performance to deviation (RPD) were calculated.

Monthly methane emissions (gram of methane per kilogram of live weight) were then computed using the formula proposed by Archimède *et al.* (2011):

$$\mathbf{CH_{4\ (g/kgLW)} = 0.083 + 0.025\ DOMI}$$

These monthly values were then multiplied by the size of the herd actually present in the study environment to produce the balance.

2.3.2. Soil and water emissions from manure

For GHG emissions from soil, the method of static chambers (40*20*20 cm) described by (Khalil *et al.*, 1998) was used. Two chambers were thus installed per measuring site in order to have replicates and ensure the representativeness of the measurements. The chambers were placed on the soil taking care to position them outside areas with termite nests. For each measurement, 4 samples were taken half an hour apart, over a period of 90 minutes, using 20-cc syringes and 10 cc vials. Two different samples stored in two different vials were taken for each sampling operation. Vials containing saturated saline solutions were used for the samples used to quantify N_2O and CH_4. Some vials rinsed beforehand with gaseous nitrogen N2 (Guérin *et al.*, 2007) were used for the samples used to quantify CO_2. For GHG emissions from water, water samples taken from ponds were sterilized on sampling with Mercury Chloride (0.01ml/vial) to halt any biological activity, as suggested by Guérin and Abril (2007). On arrival at the laboratory, a vacuum was created in the vials by expelling some of the water and replacing it with gaseous nitrogen.

In both cases (emissions from soil and water), the air samples were analyzed on an SRI 8610C Gas Chromatograph. Each sample was injected twice into the chromatograph for each gas to be quantified. For emissions from soil, fluxes were calculated from the GHG contents of the different air samples using the slope of the linear regression of the concentrations as a function of sampling time (Deshmukh *et al.*, 2014). For emissions from water, the GHG concentrations dissolved in the water were calculated using the coefficients of solubility proposed by Weiss (1974), Yamamoto *et al.* (1976) and Wanninkhof (1992) for CO_2, CH_4 and N_2O, respectively. The fluxes exchanged between the water surface and the atmosphere were then calculated as described in (Borges *et al.*, 2015).

2.3.3. Other sources of GHG emissions

It was not possible to measure the other sources of emissions by direct observations in the field but they were assessed using some emission factors found in the literature.

Termites produce a large share (around 12%) of global methane emissions of natural origin through the digestion of cellulose in their gut by micro-organisms (Bousquet *et al.*, 2006). The enteric methane emissions linked to the activity of termites were estimated from the means of coefficients found in the literature, which gave seasonal mean emissions (wet season and dry season) per unit area (Jamali *et al.*, 2013), and the description of soil occupation by termites in a tropical semi-arid context (Traoré *et al.*, 2008).

For emissions linked to fuel combustion, the quantity of diesel oil consumed each month by the motor pump was obtained from the Borehole Management Committee, which keeps a management logbook for that purpose. The quantity consumed was then converted into the quantity of CO_2 emitted monthly using the emission factor (2.8 kg of CO_2 per litre of diesel) proposed by (IPCC, 2006).

Plant biomass combustion is acknowledged to be a source of GHG emissions (Koppmann *et al.*, 2005; Castaldi *et al.*, 2010) especially in tropical and subtropical regions (Scholes *et al.*, 1996; Fearnside, 2000; Rossi *et al.*, 2016). Vegetation fires are a typical trait of many graze land ecosystems, lit to promote the development of grasses to the detriment of woody species, in order to improve rangeland fodder (Mapiye *et al.*, 2008). In our study, due to one year characterized by low rainfall and low standing fodder biomass availability, no vegetation fires were inventoried in the Widou borehole area over the period concerned by the balance.

2.4. C sequestration in animals, plants and soil

2.4.1. Variations in the C stock in livestock biomass

In sub-Saharan Africa, traditional livestock farming is of the extensive breeder type. Its meat production function and economic profitability are not a priority. On the contrary, this livestock farming has more of a strong social and cultural function (Ancey *et al.*, 2008). This dimension of social capital accumulation is fairly coherent with the ecological approach taken here, which leads us to consider the herd as a more or less stable biomass and C stock in the same way as the other compartments of the ecosystem (soil, plants) described in the conceptual model described above. In order to assess the variation in this stock, it was a matter of estimating the numbers of animals present, sometimes seasonally, in the territory of the Widou borehole area. Some inventories of the numbers were made by monthly surveys from June 2014 to October 2015 on the composition of the herds of a sample of 40 settlements. This sample was reasoned on the basis of the composition of the herds in each settlement (Table 5.2) using data from an exhaustive census carried out in December 2013 in the 354 settlements occupying the Widou borehole area (Assouma *et al.*, 2014).

Table 5. 2. Distribution of surveyed settlements by category according to herd size (in heads).

		Cattle				Total
		NONE (=0)	SMALL (≤20)	MEDIUM ([21-50]	LARGE (≥51)	
Small ruminants	NONE (=0)	0	1	1	0	2
	SMALL (≤20)	1	1	0	0	4
	MEDIUM ([21-100]	3	5	2	0	13
	LARGE (≥101)	1	4	7	9	21
Total		5	11	10	9	**40**

These surveys were used to describe how the composition of the herd evolved per animal species, by gender category and age. The inventories were validated by zoo technical monitoring enabling the quantification of incoming fluxes (purchases, births, loans and returns from transhumance) and outgoing fluxes (deaths, sales, gifts, loans and transhumance departures) also on a monthly basis in the same 40 settlements. The variations in animal numbers completed by the variations in animal live weight (observations described in section 2.3.1) made it possible to assess the gain in live weight stock in the form of livestock animals.

2.4.2. Variations in C stock in woody biomass

- *Inventory of woody plants and of their biomass in the study territory*

Estimation of the density of woody plants in semi-arid ecosystems is a necessary stage for studying the total or net production of plant formations. The “point-centred quadrant” (QCP) vegetation study method, also known as the “distance method” Clark and Evans (1954), was used to assess the woody density in each landscape unit. The method was implemented along a transect of 500m at each of the 15 sites (see § 2.2.2). For each site, the observations were made from 11 points 50 m apart along the transect. The so-called “distance method” consists in measuring the distance Qi between a sampling point and the nearest tree, i, located in each of the four sectors defined by the transect and its perpendicular for the woody plant inventory (Figure 5.3). The distance was measured (with a 50 m tape measure) for each woody plant measuring over 2 m at the top of its crown.

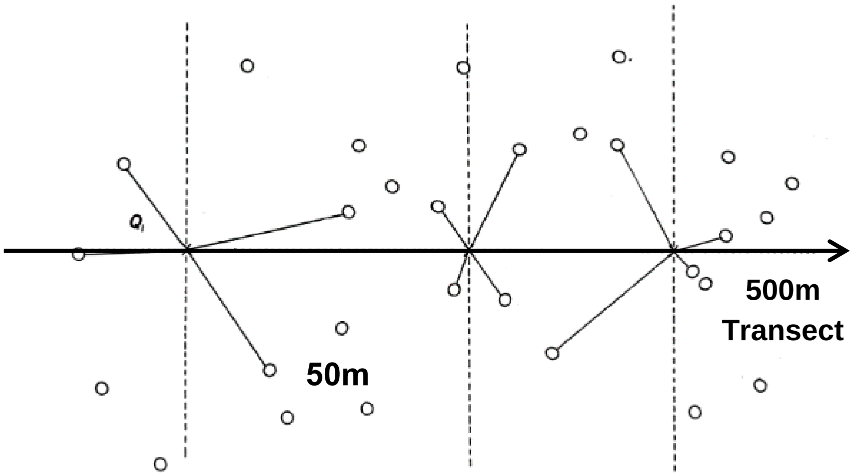

Figure 5. 3. Diagrams of QCP implementation

The density per hectare D(ha) was calculated using the formula of Pollard (1971), from the sums of squares of the distances measured for the 4 individuals of the n measuring points by the following formula:

$$D(ha) = (10000) * 4 * (4*n-1)/(\pi*\Sigma dist^2)$$

The standard error of the density was calculated as follows:

$$Sdens = (Dens^2)/(4*n-2)$$

On each tree present at each of the 15 sites, the following parameters were measured:

- The circumference of the trunk 30 cm from the ground, in the case of single stem species or the base of the bunch of stems in the case of multiple stem species.
- The height of the tree with a clinometer for trees over 4 m, or a tape measure for trees under 2 m in height. For leaning trees, the height measured was that from the base of the trunk to the upper limit of the crown and not the perpendicular height from the ground.
- The diameter of the crown with a 25-m tape measure, in 2 perpendicular directions, in order to take into account, the shape of the crown (rarely circular) and thereby enable as correct as possible an estimation of the tree's projection.

Leaf mass (Mleaf) was estimated using a specific allometric function giving the leaf mass from the circumference of each trunk. The following power type function was used:

$$\mathbf{Mleaf = oo * Cir^{ex}}$$

The coefficients oo and ex were taken from the overview by Henry *et al.* (2011) for each species (except for *Adansonia digitata*) and Cir was the circumference of the measured tree.
Wood volume was calculated like the leaf mass by a power type function from the circumference. The mass was then obtained by multiplying by the wood density. For both the wood and the leaves, the coefficients and the density were determined by species.

- *Estimation of the annual growth of woody biomass*

The measurements needed to estimate the annual growth of woody plants were carried out at the complementary site located at the Dahra research station (cf. section 2.2.2). It was a small 92*52m plot for which dendrometric data were collected in June 2009 and for which the trees were marked and geo-referenced. To have a value of the mean annual increment in the main dendrometric parameters in the biomass estimation, a new measuring campaign was organized in June 2015. The annual increase in circumference was calculated by putting forward the hypothesis of a uniform variation over the full period of 6 years. This mean value for the annual increase in circumference was used to assess total wood production from the aboveground part of each measured tree in the Widou borehole area using some allometric equations for each species proposed by Henry *et al.* (2011). Total production per site was obtained using the density of each site. Root biomass (main roots) was estimated on the basis of the aboveground biomass assessment using a conversion factor of 38% of the aboveground biomass proposed by Woomer *et al.* (2004).

2.4.3. Soil C sequestration

- *Variation of the soil C stock*

With a view to lessening the greenhouse gas emissions of livestock farming systems, pastoral ecosystems can play a major role through the C accumulation potential of their soils (Blanfort *et al.*, 2010). To assess such C accumulation, we assessed all soil C inputs and outputs, with the difference between the monthly inputs and outputs constituting the monthly variations in C stock in the soil. The incoming and outgoing fluxes considered in the soil C balance are summed up in figure 5.4. Only the fluxes affecting the C stock in the soil compartment are considered; for example C fixation by chlorophyllous plants is therefore not represented.

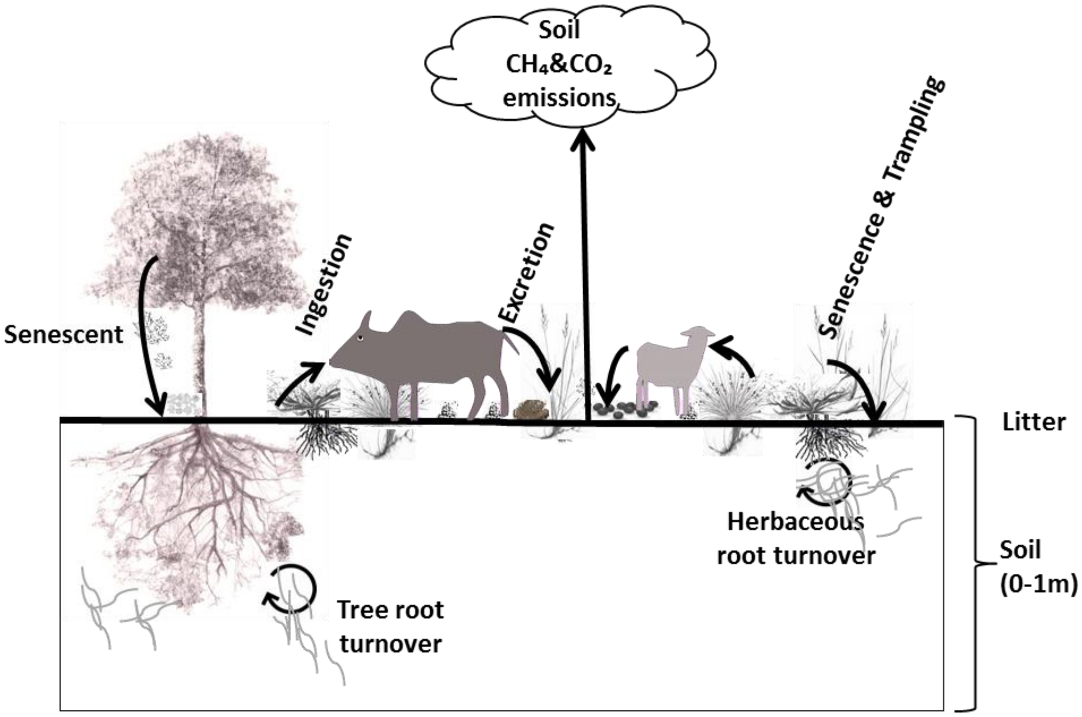

Figure 5. 4. Aboveground-belowground and belowground-atmosphere exchanges affecting soil carbon accumulation in a typical sylvo-pastoral ecosystem.

- *C inputs*

The return of animal excreta to the soil, along with plant litter of woody and herbaceous origin and the fine root turnover of plants, were the main incoming biomass considered.

To assess faecal deposits on the soil, four small 0.25 ha plots were marked out per landscape unit, inside which the quantities of faeces were collected and weighed each month from July July 2014 to September 2015. Each plot was completely cleared on each observation, so it could be estimated that the total quantities of faeces weighed each month corresponded to the monthly applications. For the months of the wet seasons, the collection rate was less frequent (every 3 days) to adapt to the dung burying rhythm of dung beetles (Rougon, 1987).

For herbaceous plants, the return to the soil was assessed through the quantities of litter buried in the soil and root turnover. This evaluation was based, among other things, on the quantification of aboveground biomass and that of the belowground biomass at the 15 sites chosen for woody biomass (cf. section 2.2.2). At each site, the biomass of herbaceous plants was measured using a destructive approach like the one proposed by Schlecht *et al.* (2006). At each of the sites, the herbaceous stratum was divided into four groups according to the coverage of the herbaceous: bare soil (O), low density (B), medium density (M) and high density (H). After classification metre-by-metre of the herbaceous stratum along a 500-m transect, 12 places were randomly chosen (at a rate of 3 per L, M and H stratum) along the transect to assess the aboveground biomass. A 1m*1m quadrat was positioned at each point and all the herbaceous plant mass present was harvested and sorted between litter and stubble. The belowground biomass was then assessed using a cylinder 7 cm in diameter pushed 30 cm into the soil of each quadrat. All the excavated soil was sieved to 2 mm for root extraction. The subsamples of stubble, litter and roots were dried in an oven at 65°C for 72 hours before weighing again to determine the dry matter content. The subsamples were used to assess the quantity of herbaceous mass buried in the soil each month. In order to have a complete annual series, arithmetic interpolations were carried out from the values of adjacent months for the missing dry season months (December, February, April and June). For the biomass buried in the soil, senescence was very low (annual herbaceous plants) in the mid rainy season and the litter reaching the soil was therefore disregarded between August and September. From October to May the quantity of herbaceous mass buried in the soil was calculated using the following formula:

$$\textbf{Buried mass}_{\textbf{mi}} = \textbf{total aboveground mass}_{\textbf{mi-1}} - (\textbf{total aboveground mass}_{\textbf{mi}} + \textbf{total ingested mass}_{\textbf{mi}})$$

Where mi= the month in question and mi-1= the previous month.

For the root turnover of herbaceous plants we started from the hypothesis that root turnover only occurs when roots are alive, i.e. in the wet season for herbaceous plants (from July to October). The conversion factor used for root turnover in the wet season was 0.53% of the root production of the month (Gill and Jackson, 2000). An equivalent root turnover rate was applied to the remainder of the biomass existing at the end of the wet season and constant between November and June.

For woody plants, the inputs comprised leaf and branch fall and root turnover. For the leaves of woody plants, whatever the phenological regime (6 types proposed), all the leaves produced in one year were recycled over a complete year in accordance with the method below. For each phenological type, the breakdown of this leaf recycling (Appendix 4) proposed by (Hiernaux *et al.*, 1999) over the 12 months of the year was used to assess the quantity of leaves from woody plants returned to the soil each month.

For root biomass, the turnover was a fraction (0.56%) (Gill and Jackson, 2000) of the annual increment of root mass itself, determined as a fraction of the wood mass (0.38%). The mass of the branches returned to the soil was assessed as being a fraction of the total wood mass. The latter was estimated on the basis of allometric relations specific to each species (Henry *et al.*, 2011) and from field records. The fraction used here was estimated at 5.4% of annual production (Marion *et al.*, 2015).

- *C ouputs*

Carbon outputs at soil level are mostly in the form of CO_2 and CH_4. These GHG emissions at soil level were assessed taking a classic approach with static gas chambers described in section 2.3.2. These measured gas fluxes were converted into C equivalent using the molar mass of the 2 elements.

2.5. Full GHG balance per season at whole landscape level

2.5.1. Conversion of biomass stock variations into C sequestration and GHG emissions

All the emissions of the three GHGs were converted into eq-CO_2 using the global warming potentials proposed by the IPCC (2013) which is 1, 34 and 296 for CO_2, CH_4 and N_2O respectively. To assess carbon accumulation in the main compartments, the quantities of biomass (animal, faecal or plant) sequestrated were converted into C equivalent then converted into CO_2 equivalent to establish the balance using the conversion factor of 3.67.

Carbon accumulation in the main reservoirs was assessed using some conversion factors making it possible to switch from animal and plant biomasses into carbon equivalent (table (.3).

Table 5. 3. Conversion factors of biomass into carbon equivalent

	Animal live biomass	Wood biomass	Herbaceous litter	Tree leaves	Dead wood	Faeces
Conversion factor	2.2 - 2.9	480	450	470	490	490
Units	*gC/kgLW*	*gC/kgDM*	*gC/kgDM*	*gC/kgDM*	*gC/kgDM*	*gC/kgDM*
Sources	(Garnier-Laplace *et al.*, 1998)	(Hughes *et al.*, 1999)	(Hughes *et al.*, 1999)	(Hughes *et al.*, 1999)	(Hughes *et al.*, 1999)	(Achmad *et al.*, 2011)

LW. live weight, DM. dry matter

2.5.2. Distribution of C sequestration and GHG emissions per month and per season

The different elements of the balance (GHG fluxes and variations in C stocks) were distributed monthly to facilitate the establishment of the GHG balance for the observations that were not carried out monthly in all the months of the balance period.

For instance, the total production of aboveground and belowground mass of woody plants was distributed over the entire year to have a monthly estimation of accumulation per landscape unit and on a whole ecosystem scale. This wood production was distributed over each month of the year according to the monthly foliation status (dimensionless coefficients given in Appendix 3) for which seasonal dynamics differ depending on leaf phenology types (Hiernaux *et al.*, 1999; Brandt *et al.*, 2016).

At soil level, the root turnover of woody plants was also distributed monthly according to leaf mass. For the monthly breakdown of this stock of branches returned to the soil, there is no reason to follow the breakdown of leaf fall and, failing any particular data, a simple uniform monthly distribution was adopted.

2.5.3. A GHG balance calculated per season and per year

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 hot dry season). The balance, the sum of emissions and the sum of variations in C stock were expressed per unit area to facilitate comparison with other territories and other types of ecosystems.

3. Results

3.1. Livestock-related biomass fluxes and stocks

A census was carried out around the Widou borehole area where 354 settlements and a population density of 7 inhabitants per km² were recorded. The total herd size around the borehole was 33,095 tropical livestock units (TLU), which were divided up into several species: cattle 49%, sheep 23%, goat 9%, donkeys 15% and horses 4%. Figure 5.5 describes seasonal variations in animal stocks in the Widou borehole area. In 2014-2015 the average animal stocking rate was 0.39, 0.43 and 0.31 TLU/ha, in the rainy season, cold dry season and hot dry season, respectively. This variation in stocking rate was explained by poor rainfall records in the study area during the monitoring period. Livestock farmers started the transhumance early that season (from December 2014) in order to cope with limited pastoral resources.

Most of the transhumance, i.e. the moving of a part of the cattle herds for large livestock farmers, started in the middle of the cold dry season. This was a gradual departure which continued until the end of that season. More than 70% of the cattle and sheep herds left. Most of the herd that remained in the Widou borehole area in the hot dry season was composed of goats which are hard to lead for transhumance, and non-ruminants (horses and donkeys) kept for animal draught power, especially for human and water transportation.

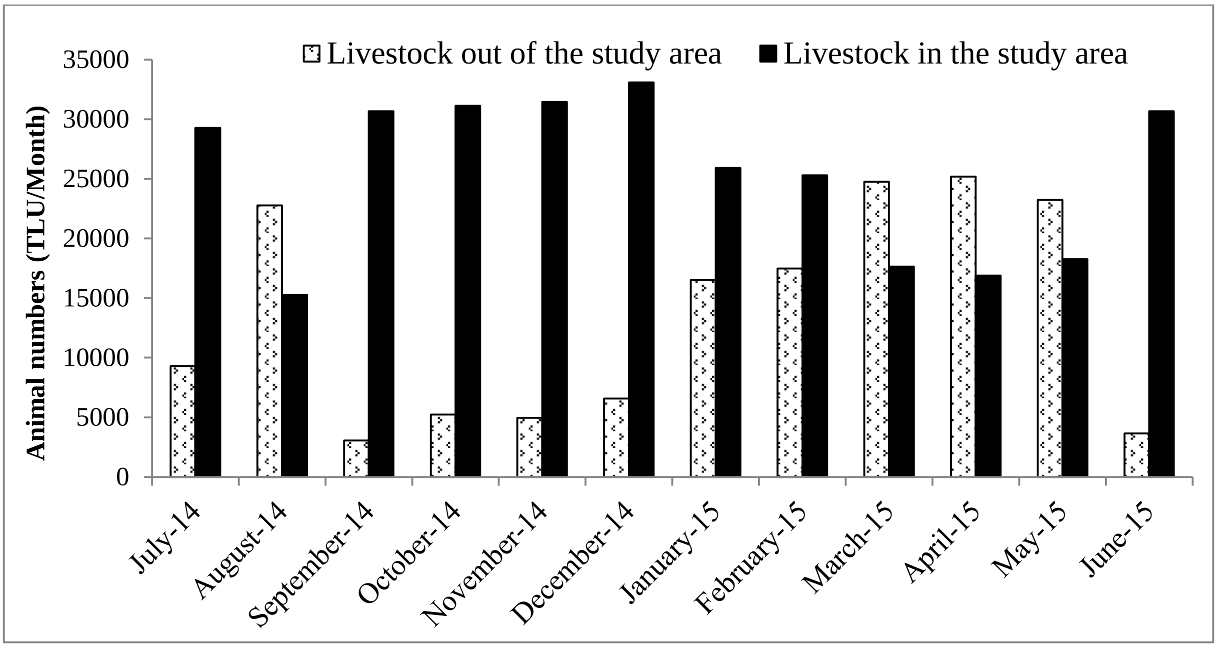

Figure 5. 5. Monthly variations in livestock presence in or out of the studied landscape.

Figure 5.6 shows animal localization in terms of presence times per landscape unit (a), and duration per activity (b) in one day (24 hours) over the monitoring period. On average annually, animals spent more than 75% of their time on rangelands and settlements, which were the largest landscape units in terms of surface area. During the rainy season (from August to September 2014), animals did not graze around the borehole but rather around ponds filled with water at that period. Animals rested around 60% of their time, either lying down, or standing up, especially for rumination. Over the year, 5.4±1.8h of a 24h-day on average were dedicated to feeding by grazing. This duration varied between 8.1±1.9h in the rainy season and 4.8±0.5h in the hot dry season.

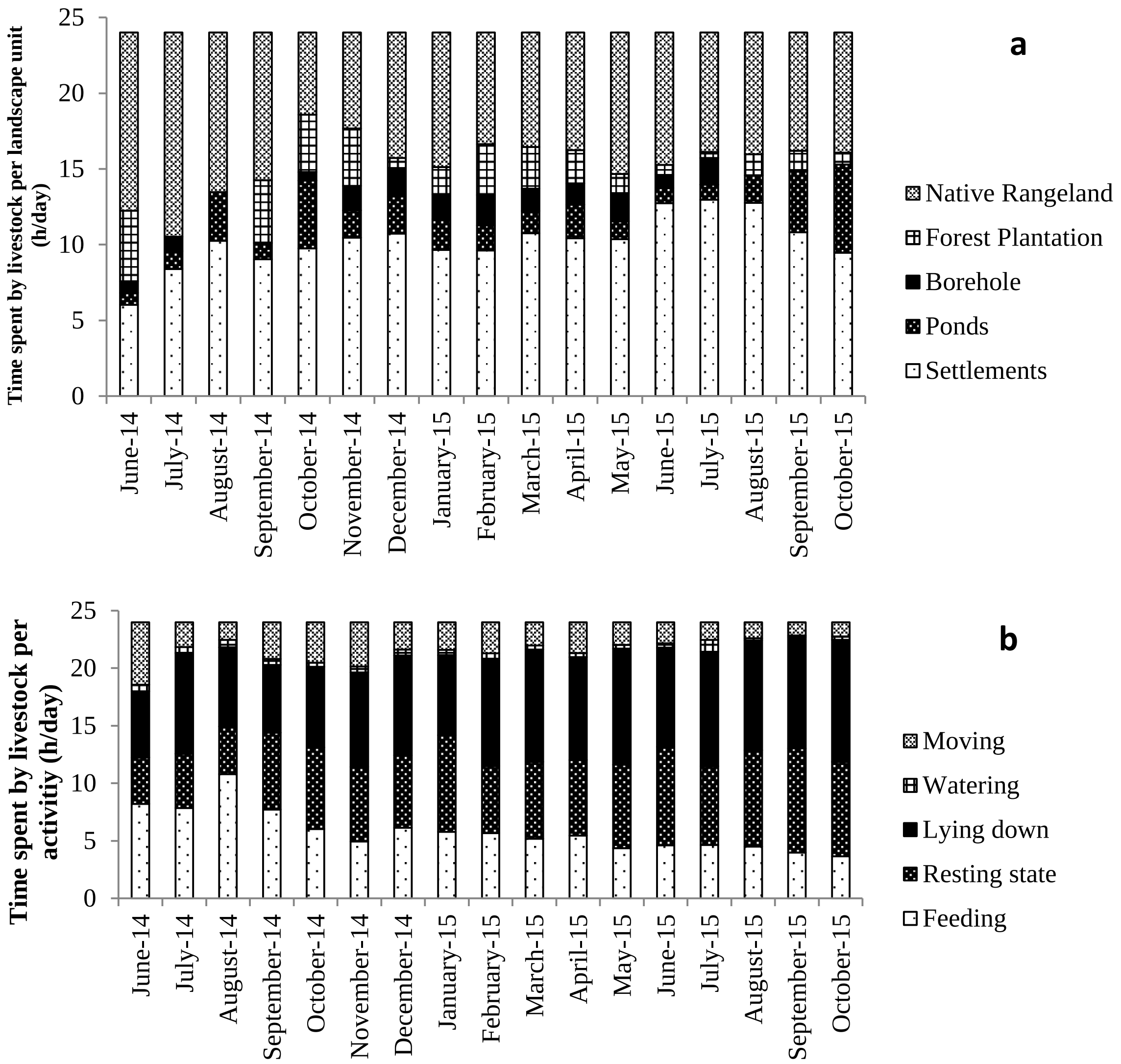

Figure 5. 6. Daily time spent by livestock in the different landscape units (a) and per activity (b)

Figure 5.7 shows aboveground and belowground herbaceous biomass production and its evolution over time during the monitoring period. The abundance peak was observed in September with aboveground biomass production of 1.49tDM/ha and root biomass of 0.22tDM/ha in the first 30-cm top layer of soil, i.e. 15% of aboveground biomass. Late and low rainfall (204.3 mm in 2014 vs. an annual average of 284.6 mm/year) was the cause of this relatively low production. Available aboveground biomass rapidly decreased on the one hand because of cattle grazing, and on the other hand because of animal trampling during grazing.

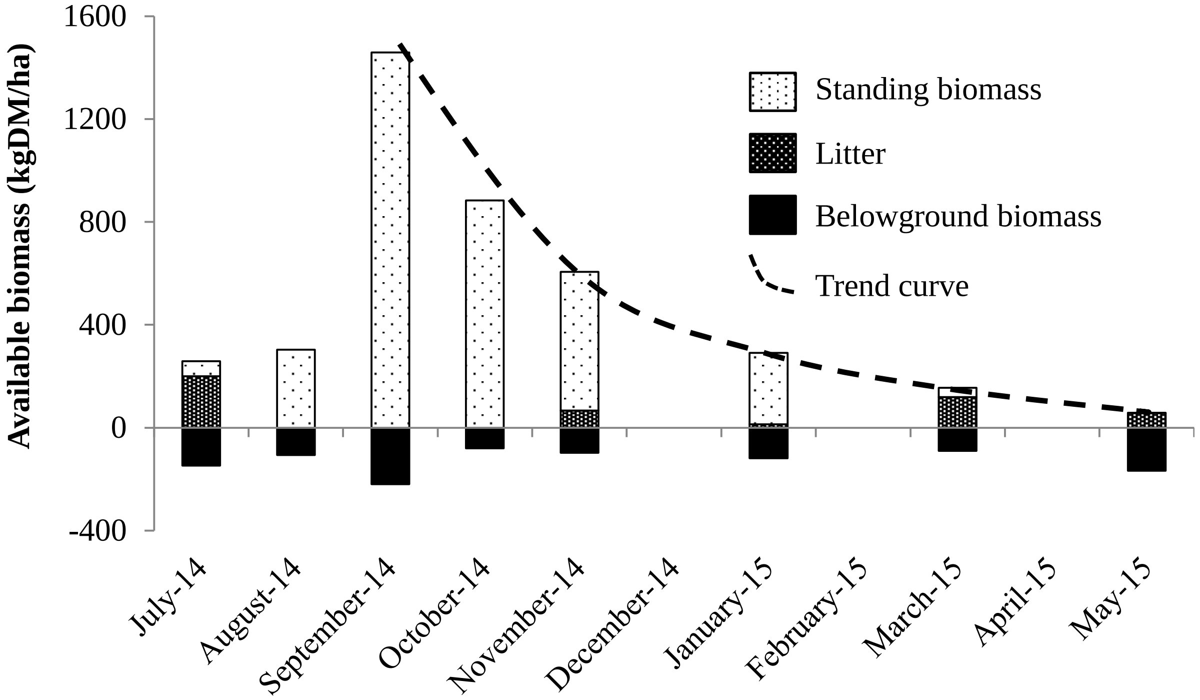

Figure 5. 7. Temporal variability in available herbaceous biomass (from July 2014 to May 2015)

Figure 5.8 shows the temporal variability in the monthly quantity ingested by animals versus available herbaceous biomass. Animals grazed daily between 2.6 kgDM/TLU/day and 7.1 kgDM/TLU/day according to the seasons, abundance and nutritional quality of the available herbaceous biomass. During night paddocking (only concerned cattle herds that were not milked anymore), between 26.4% and 37.2% of this biomass was consumed. Finally, animals that were in the borehole area ingested around 27% of the total production of herbaceous biomass annually.

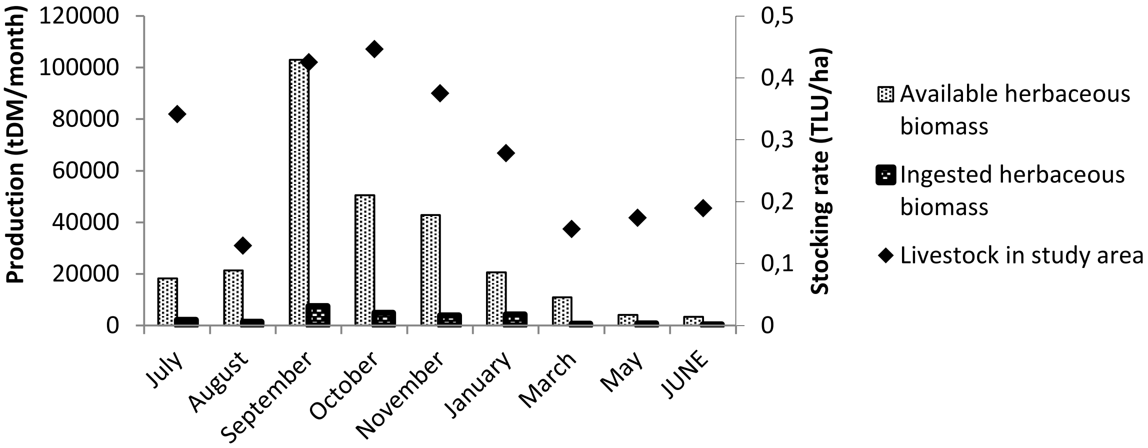

Figure 5. 8. Seasonal variation in aboveground herbaceous biomass (standing biomass and litter) and the herbaceous biomass ingested by livestock

The diet composition of cattle grazing herds varied from one season to another. The variation in diet composition over time is shown in figure 5.9 for grasses (65% on average over the year), herbaceous legumes (23%) and leaves and pods of woody plants (12%). Herbaceous legumes were mostly ingested during the rainy season, gradually with new shoots found in small amounts. They were particularly appetizing and had a better nutritional quality with high digestible protein content. Their biomass decreased before rainfall stopped as leaves fell. Only stems remained, and animals appreciated them so they were rapidly consumed after rainfall stopped. The leaves and pods of woody plants were mostly consumed during the hot dry season, when fresh herbaceous biomass was very limited.

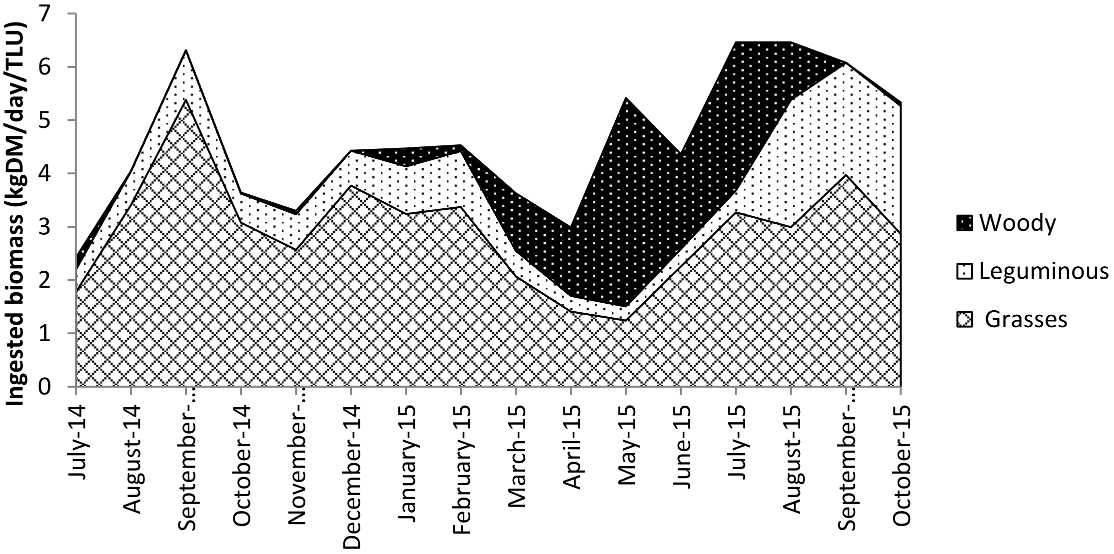

Figure 5. 9. Temporal variation in the composition of the cattle feed ration

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

Figure 5.10 gives the relative contribution of the different GHG sources to total GHG emissions at whole landscape level for a whole year (from July 2014 to June 2015). Nitroux oxide N_2O was the most emitted GHG (59% of total emissions), then methane CH_4 was the second most emitted GHG (41%) and third came carbon dioxide CO_2 (<1%). The three main pools were animal dejections 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.

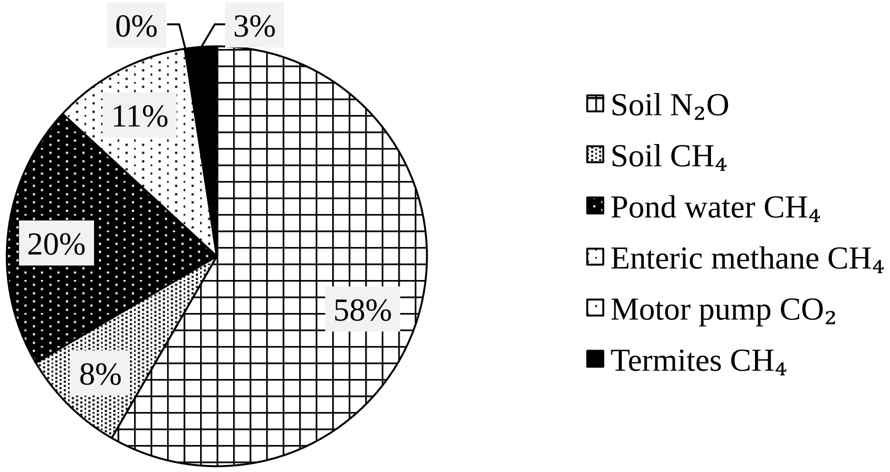

Figure 5. 10. Total emission at whole studied landscape level by category of emission (in CO_2-eq).

Figure 5.11 shows the seasonal variability in GHG emissions (from undifferentiated pools). 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 hot dry season. The relative contribution of each pool was somewhat homogeneous over the year, with a major contribution of i) N_2O emissions from soil related to animal dejections onto the ground (17.4, 5.6 and 3.7 $GgCO_2$-eq/Month in the rainy season, cold dry season and hot dry season, respectively) and ii) enteric CH_4 emissions from ruminants (2.1, 1.6 and 1.2 $GgCO_2$-eq/Month in the rainy season, cold dry season and hot dry season, respectively). The only pool that varied between seasons (90.5, 2.3 and 7.2% $GgCO_2$-eq/Month, in the rainy season, cold dry season and hot dry season, respectively) was CH_4 emissions from hydromorphic areas (surface water and soil). This contribution was much greater in the rainy season because of the existence of water ponds.

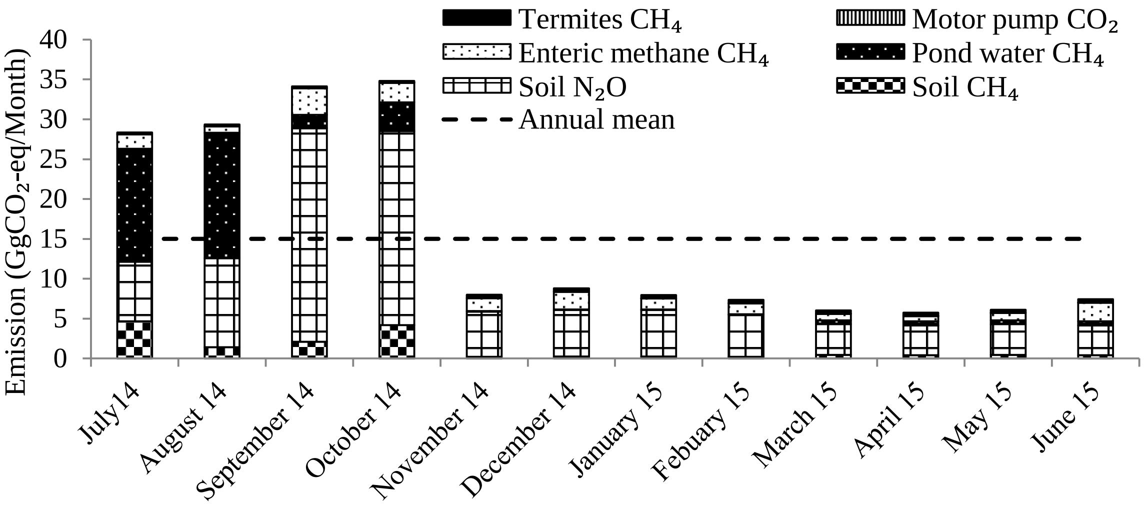

Figure 5. 11. Temporal variability in total GHG emissions at landscape level (all sources included)

3.3. Carbon sequestration in trees, soil and animals

Figure 5.12 gives the relative contribution of the different C stocks to total C accumulation at whole landscape level over the year (from July 2014 to June 2015). 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 sequestrated around 1% of the annual gain in total C stock in the form of animal biomass in the herds. Overall, the ecosystem sequestrated 0.7tc/ha/year according to this distribution: trees 0.45tC/ha/year, soil 0.26tC/ha/year and animals 0.006tC/ha/year.

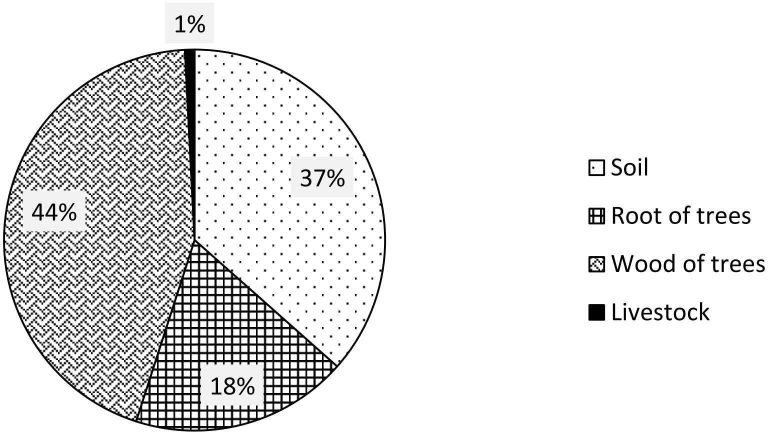

Figure 5. 12. Total C accumulation at whole landscape level by category of C stocks

Figure 5.13 gives the monthly variations in C accumulation in the main ecosystem compartments. 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 (cf. white diamonds in figure 5.13) were somewhat stable in the hot 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 hot 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.

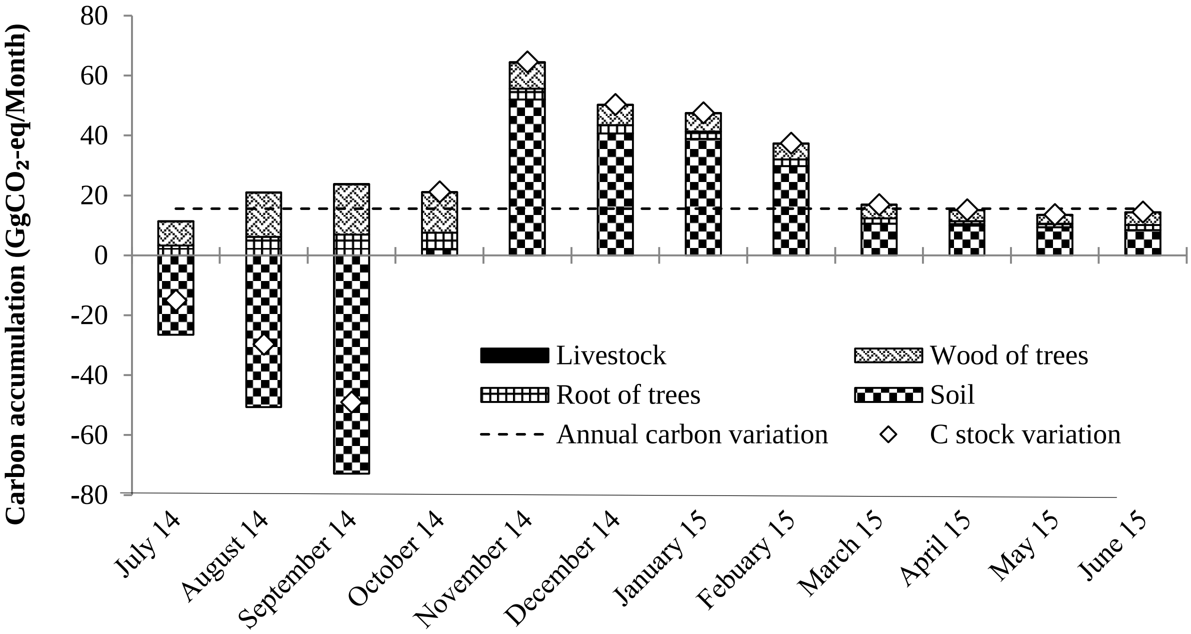

Figure 5. 13. Temporal variability of C stock variations at whole landscape level

3.4. Temporal variability of the GHG balance at whole ecosystem level

Figure 5.14 highlights seasonal variation in the GHG balance on a territory scale. 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-CO_2). It varied from +13.65 to +8.32Ggeq-CO_2/month in October and September, respectively. The GHG balance was negative in the dry season; it was intermediate at -67.47Ggeq-CO_2 in the cold dry season and – 34.64Ggeq-CO_2 in the hot dry season. In the cold dry season, the monthly balance varied between – 56.48 and – 29.96 Ggeq-CO_2/month in November and February, respectively.

In the hot dry season, the monthly budget varied between – 10.85 and – 7 .40 Ggeq-CO_2/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-CO_2/ha/year, on average, and sequestrated -2.64 teq-$C0_2$/ha/year, on average. That is equivalent to an annual GHG balance of -0,72teq-CO_2/ha/year. Thus the sylvo-pastoral ecosystem might sequestrate -0,01teq-C/ha/year.

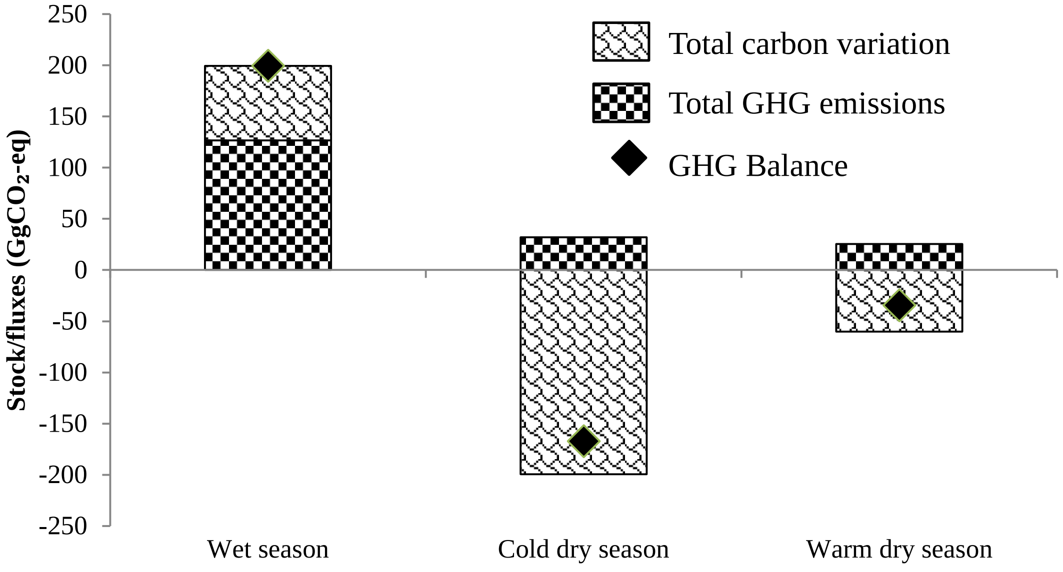

Figure 5. 14. Seasonal variability in the GHG balance at whole ecosystem level

4. Discussion

It seems important to take into consideration the main GHG transfers from ecosystem to 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 CO_2, N_2O and CH_4 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.

4.1. Biotic and abiotic factors explaining temporal variability in the GHG balance

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.*, 2015b). 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 re-growth. This high presence rate resulted in a large quantity of dejections 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 CH_4 and N_2O (Franzluebbers *et al.*, 2000; Kim *et al.*, 2012). Moreover, in this season, large emissions of CH_4 occurred from the surface water of ponds, because of direct excretions into the water while the herd was drinking (Assouma *et al*, 2016 in press). 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 dejections, woody plant leaf senescence and burying of herbaceous litter. The high animal presence rate (Figure 5.5) and the large quantity of available litter (Figure 5.6) 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 (Merbold *et al.*, 2013; Wilson *et al.*, 2015).

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 dejections. This recycling facilitates the return of faeces to the soil, thus contributing to carbon sequestration (Soussana *et al.*, 2010b) 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).

4.2. Uncertainties and research agenda

This study provided an original insight into intra-annual changes in an ecosystem GHG balance. The main GHG fluxes and C stock variations were estimated from *in situ* measurements within the same territory. However, three types of limitations appeared because of knowledge gaps that still remain for this specific ecosystem: i) **extrapolation** based on one-off measurements over time, ii) a disregard of certain fluxes (e.g. leaching) and/or stocks (shrubs, wild fauna) that are considered to be low, iii) under-consideration of interspecific variability in the estimation of certain stocks.

As regards **extrapolation**, most of the fluxes/stocks described in this study were estimated from measurements that were limited over time (one-off), extrapolated to the considered period duration, assuming that fluxes were homogeneous over the same period (months, seasons or years). However, these observations might be judged to be too far apart (e.g. GHG fluxes from the soil), or too close together within the time frame (e.g. C variation in trees). Indeed, GHG fluxes from the soil are highly sensitive to soil humidity (Savage *et al.*, 2014). But humidity can vary very quickly during the rainy season depending on the rainfall rate (Delon *et al.*, 2015) and it is consequently uncertain to extrapolate a one-off measurement to a whole month. It is the opposite for woody plants: an annual increment in tree diameter was obtained from measurements in the space of six years. This period can be considered to be short, if the inter-annual variability of woody plant growth relying on inter-annual variability in climate conditions is taken into account (Takimoto *et al.*, 2008).

The disregard of certain fluxes and stocks in the balance only concerned, in theory, some **negligible fluxes and stocks** (to the best of our available knowledge). For instance, unlike the other two compartments (woody vegetation and animals), soil C stock variation was obtained while expressing the differential between C inflows and outflows. Only gaseous emissions from the soil to the atmosphere were accounted for in terms of outflows. C losses via leaching, organic matter run-off, were probably negligible because of moderate rainfall (Lal, 2004; Kindler *et al.*, 2011), thus they were disregarded in this study. It might be worth measuring these parameters in a future study. The disregard of shrubs (bushes) and wild fauna in the evaluation of the growth in C stock from the woody strata and animals was also one of the limitations of this study, thus probably resulting in a slight under-estimation of C accumulation. Its estimation may be coupled with a description of biodiversity, another important ecosystem service offered by sylvo-pastoral ecosystems (Noble *et al.*, 2002).

Interspecific variability which was not taken into account either primarily involves trees and livestock farming animals. The annual increment in tree diameter was obtained from measurements on several individuals (n=24) of different species locally present in the ecosystem. They were certainly the most representative species in the area, but a more exhaustive consideration of specific diversity and diversity in age groups should be envisaged for a future study. Indeed, annual growth in the diameter of woody plants is linked rather to the trunk size and the species (Lewis *et al.*, 2009). Moreover, parameters related to the population dynamics of woody plants (mortality, regeneration, inter-individual interactions) greatly influence growth in tree diameter. These aspects were not considered for the choice of trees monitored over six years. The low level of knowledge about woody plant root biomass and about its turnover also generates uncertainty in the estimations made in this study, since a unique conversion factor of aboveground biomass/belowground biomass was used for all the woody species. Estimations of weight and enteric emission growth were likewise based on measurements only collected from ruminants and cattle, respectively. These measurements were extrapolated to the other animal species (for weight variations) and ruminants (for methane emissions) on the basis of TLU-equivalents. For a future study it might be interesting to procure more information on these parameters, particularly while distinguishing between animals staying around the borehole (goat and donkeys), and animals leaving for transhumance (cattle and sheep).

These three limitations do not undermine the originality of this work which offers a global (i.e. integrating the different pools of GHG emissions and C sequestration) and dynamic vision of a GHG balance in the same territory. These limitations enabled us to pinpoint the main fluxes and stocks and the missing data - uncertainty sources - that need to be detailed for a future study.

4.3. Inter-annual variability in the GHG balance

In sub-Saharan Africa and in the Sahel in particular, rainfall is characterized by strong inter-annual (Nicholson, 2013) and ten-yearly variability (Le Lay and Galle, 2005). In the region of the Sahel and in the sylvo-pastoral region of Ferlo in northern Senegal, rain is the main climate variable determining changes in the environment of pastoral populations (Ansoumana, 2014) and their practices (Sy, 2010). Rainfall distribution is the main explanatory factor of pastoral rangeland productivity. To a certain degree it also explains water availabilities, even though borehole sinking in the 1950s in Ferlo tremendously reduced this constraint. Rainfall is really important for pastoral populations and ecosystems, since it plays a determining role in sylvo-pastoral ecosystem functioning and, indirectly in their GHG balance. The GHG balance of this study was established in a year of low rainfall. Indeed, the annual rainfall considered in this season (204 mm) was somewhat less than the annual average recorded over the 1974-2015 period (285.8 ± 84,2 mm). Beyond this intra-annual variability (demonstrated in this study), it might be possible that the GHG balance of sylvo-pastoral ecosystems is also characterized by strong inter-annual variability. Indeed, a wetter year would stimulate herbaceous biomass production. On the one hand, this greater production would lead to an increase in vegetation fires, and, on the other hand, it would lead to a delay in the animals' departure for transhumance. The fire risk in low-productivity ecosystems (as in the case study) is greater in the case of burning materials available in the form of standing straw and litter (Pausas and Ribeiro, 2013). Biomass combustion is known as a source of GHG emissions such as carbon dioxide, methane and nitrous oxide (Koppmann *et al.*, 2005), particularly in tropical and subtropical areas (Devineau *et al.*, 2010). The delay in the animals' departure for transhumance is likely to have generated a larger herd daily presence time and animal stocking rate in the study area, thus enhancing the contribution of enteric fermentation to the total GHG emissions in the territory. Stocking rate modifications are also likely to affect the quantity of dejections on the ground, and consequently generate greater C accumulation in the main stocks, primarily at soil level. Indeed, through the longer daily presence of herds in the territory, the animals would have facilitated a greater return of carbon to the soil via dejections onto the ground, and they would also have limited vegetation fire risks. This probable inter-annual variability in the different GHG balance components needs to be demonstrated. It highlights the need to implement observatories monitoring pastoral systems in order to be able to undertake follow-ups over long periods of a few consecutive years. In that way, the complexity of sylvo-pastoral ecosystem functioning in the Sahel under semi-arid climate conditions will be better integrated. These ecosystems might be resoundingly affected by global warming (Abdou, 2010).

5. Conclusions

This paper looks at the greenhouse gas balance of a sylvo-pastoral ecosystem over a complete annual cycle, integrating the different GHG emission sources (animals, soil and water) and carbon sequestration (trees, soil and animals). Describing intra-annual variability in the GHG balance from monthly GHG balances reconstituted from one-off measurements taken for the most part in the same territory makes this work original. 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 (N_2O), water and animals (CH_4). 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 dejections, 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 rate to the available forage).

The strong seasonal variations in emissions and C accumulation globally resulted in a balance between emissions and sequestration of carbon on an annual scale. Sequestrated carbon over the annual cycle appeared to outstrip GHG emissions. Thus, around the Widou borehole area, 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.

This first GHG balance revealed a certain number of uncertainties due to remaining gaps in knowledge and observations limited to the time frame. This study proposed an original approach, cross-analyzing several targeted GHG emission measurements and an inventory of biomass stocks and fluxes, thus highlighting missing data which need to be clarified in a future study. **Observatories** on the setting-up and monitoring of the main biomass stocks and fluxes linked to the different socio-ecosystem components (animal, soil, plants, humans) will eventually lead to a better awareness and understanding of ecosystem services offered by sylvo-pastoral ecosystems.

Conclusions intermédiaires et transition

Ce dernier chapitre (Chapitre 5) montre le caractère fortement saisonné des émissions de GES et des accumulations de C en écosystème sylvo-pastoral. Le bilan GES est négatif sur les deux saisons sèches alors qu'il est très positif en saison des pluies. En effet les plus forts niveaux d'émissions ayant lieu essentiellement en saison des pluies, sur une période courte de 3 à 4 mois. Ce chapitre montre aussi, qu'au-delà de cette forte variabilité saisonnière, le bilan GES annuel apparait équilibré à l'échelle de l'année. En effet, nos calculs aboutissent à un bilan GES annuel proche de zéro, légèrement négatif, indiquant que l'écosystème pris dans son ensemble séquestre du carbone.

Ce nouveau bilan GES de l'aire de déserte du forage de Widou (présenté en Chapitres 4 et 5) peut être considéré comme plus précis et plus juste que celui présenté au début du manuscrit en Chapitre 1. En effet, il a réalisé sur la base d'observations directes de terrain visant à mettre en évidence et expliquer les variabilités spatiales et temporelles des émissions de GES et de séquestration du C. Nous proposons en discussion (Chapitre suivant) de comparer ces deux bilans GES afin de montrer l'importance d'une compréhension des mécanismes écologiques sous-jacents, expliquant le bilan GES, dans la perspective d'identifier des solutions d'atténuation adaptées aux contraintes pédo-climatiques, agro-écologiques et compatibles avec les pratiques pastorales.

Discussion Générale : quels sont les apports d'une approche écosystémique dans la réalisation du bilan GES ?

Dans cette section il est question de :

- définir le concept « d'approche écosystémique du bilan GES » développé dans cette thèse et utile pour la réalisation de bilans GES à l'échelle de territoires agricoles,
- faire une confrontation des résultats d'un bilan GES classique de type IPCC Tier 1 (basé sur des connaissances *a priori*) à ceux d'un bilan GES avec mesures de flux et de stocks *in situ* basé sur des connaissances produites par une approche écosystémique,
- préciser le rôle de l'élevage dans la variabilité spatio-temporelle du bilan GES,
- et proposer une série d'options d'atténuation pour réduire les émissions de GES d'une part et favoriser l'accumulation de C dans le territoire étudié d'autre part, dans la perspective d'accroitre la contribution des écosystèmes pastoraux tropicaux à la régulation du climat.

6.1. Définition de l'approche écosystémique du bilan GES

Cette étude est originale par l'approche méthodologique qu'elle met en œuvre. A l'issue de ce travail nous en proposons une définition qui se veut générique et élargie à l'étude de tout système avec activité anthropique. *Une **approche écosystémique du bilan GES*** peut être définie comme *une méthode permettant d'intégrer la* ***complexité*** *du fonctionnement écologique d'un système dans la comptabilisation de l'ensemble des composantes* de son bilan GES. *C'est une approche* ***pluridisciplinaire*** *qui privilégie l'étude et la compréhension des interactions entre les composantes d'un écosystème en vue d'expliquer le bilan GES et d'identifier un certain nombre de solutions d'atténuation*. *L'approche écosystémique du bilan GES doit donc intégrer une vision spatiale et dynamique du fonctionnement et du bilan GES du système étudié.*

Comme dans toute analyse de **systèmes complexes**, réaliser un bilan GES selon une approche écosystémique nécessite de définir le périmètre du système étudié et ses principales composantes (Adams, 2001). Cette étape importante permet de mieux cibler les données à collecter. L'échelle d'analyse doit être définie selon les particularités du fonctionnement du système étudié. Par exemple ici la mobilité des troupeaux suppose une analyse territoriale et réaliser un bilan GES à l'échelle d'un territoire signifie étudier l'ensemble des flux et des stocks qui supportent les activités de ce territoire. La notion de territoire est ici à comprendre au sens utilisé dans la géographie sociale[2] (Caron, 2005; Di Méo and Buléon, 2005). L'aire de desserte d'un forage est particulièrement pertinente pour l'étude des systèmes sylvopastoraux au Ferlo au Nord du Sénégal puisque l'existence de ces forages structure fortement l'espace, l'eau étant une composante limitante forte de l'écosystème étudié (cf. Introduction).

A l'issue de ce travail de thèse, **une entrée par les stocks-flux d'azote et carbone** apparait comme particulièrement adaptée, elle permet de prioriser les flux et stocks à évaluer et les mécanismes écologiques sous-jacents qui les déterminent. L'accent est mis sur les interactions (les flux et les variations de stock) plutôt que sur l'état (les stocks), car ces interactions peuvent modifier la nature ou le comportement des différentes composantes de l'écosystème et de son bilan GES.

L'approche classique du Bilan GES la plus pratiquée est de type « bilan entrée-sortie ». C'est par exemple celle qui est recommandée par l'IPCC (IPCC, 2006). A des fins d'opérationnalité elle se limite à un bilan annuel statique. Au contraire l'approche écosystémique ici proposée met l'accent sur la **dynamique** intra-annuelle et interannuelle du fonctionnement de l'écosystème et des composantes de son bilan GES. Elle se base donc sur un suivi complet sur

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[2] La géographie sociale analyse la dimension identitaire du territoire, les rapports d'appartenance et d'ancrage

une année entière de toutes les composantes du bilan GES et des éléments déterminant le fonctionnement de l'écosystème. Dans notre étude de cas, cette approche a permis de réaliser un bilan GES global comptabilisant l'ensemble de toutes les émissions de GES et l'ensemble de toutes les accumulations de carbone en tenant compte des variabilités spatio-temporelles qui caractérisent les systèmes pastoraux. L'approche écosystémique du bilan GES doit également intégrer à l'analyse une vision **diachronique**, des différentes composantes de l'écosystème. C'est-à-dire qu'elle doit également s'intéresser la variabilité interannuelle des stocks et flux. Cela n'a pas pu être le cas dans cette étude, qui s'est limité à l'étude de la variabilité interannuelle des stocks.

La quantification des différentes composantes du bilan GES s'inscrit globalement dans la perspective d'une mise en cohérence des objectifs de réduction de la contribution du système étudié au changement climatique. Notre étude de cas montre la nécessité de faire progresser les méthodes de comptabilisation, de collecte de données, trop souvent statiques vers des approches plus dynamiques et **compréhensives**. L'approche méthodologique développée dans le cadre de ces travaux se veut être un outil important d'**aide à la décision** par une compréhension du fonctionnement des écosystèmes reconnus comme complexes, très contrastés et difficiles à étudier.

6.2. Un bilan GES plus juste d'un territoire

La formule fondamentale permettant d'estimer la quantité d'émissions de GES peut toujours s'exprimer comme la multiplication de la donnée d'activité AD (Activity Data, en anglais) par le facteur d'émission EF (Emission Factor, en anglais). Les facteurs d'émission sont des coefficients qui quantifient les émissions ou absorptions d'un gaz par unité de donnée d'activité. Les facteurs d'émission sont des valeurs moyennes représentatives d'émission pour un niveau d'activité donné selon un ensemble donné de conditions d'exploitation. Les données d'activité décrivent l'ampleur d'une activité humaine entraînant des émissions ou des absorptions de gaz à effet de serre, qui a lieu sur une période donnée et sur une zone spécifiée. A titre d'exemple, les effectifs d'animaux, les superficies pâturées et les quantités d'énergie fossile utilisées sont des AD pertinentes pour le calcul du bilan GES d'un écosystème pastoral. Les incertitudes dans l'estimation des composantes du bilan GES sont dues aux incertitudes sur les facteurs d'émissions et sur les données d'activité. Elles peuvent être liées, entre autres, aux lacunes de connaissances et aux variabilités naturelles entre situations d'observation (entre individus, lieux, et moments d'observation). Les dimensions spatiales et temporelles de cette incertitude sont a priori importantes dans notre étude étant donné les forts contrastes saisonniers qui caractérisent le fonctionnement de l'écosystème étudié et la volonté d'une couverture spatiale à propos d'un territoire hétérogène.

Les Lignes directrices de 2006 du GIEC fournissent une documentation riche sur la façon de procéder dans l'estimation des émissions et absorptions (IPCC, 2006). Elles distinguent trois approches selon les méthodes d'estimation utilisées: le niveau Tier 1 qui est la méthode de base et qui reprend des FE proposés par défaut; le niveau Tier 2 qui est la méthode intermédiaire; et le niveau Tier 3 qui est la méthode la plus exigeante, en termes de complexité et de données mobilisées. Cette dernière suppose en particulier des mesures sur le terrain pour les systèmes étudiés. En règle générale, passer à un niveau supérieur permet d'améliorer l'exactitude de l'inventaire et d'en réduire l'incertitude. De ce fait, les niveaux 2 et 3 sont parfois appelés méthodes de niveau supérieur, et sont généralement considérées comme étant plus précises. Dans le cadre de cette thèse le niveau initial des connaissances sur le territoire étudié ne permettait pas d'aller au-delà du niveau Tier 2. La première évaluation du bilan GES réalisée *a priori* avec les connaissances disponibles initialement était essentiellement de niveau Tier 1, avec quelques composantes évaluées selon le niveau Tier 2 (chapitre 1). La réévaluation de ce bilan GES produite *a posteriori* à l'issue de ce travail de thèse (chapitres 4 & 5) se rapproche quant à elle d'une évaluation de niveau Tier 3, avec seulement quelques composantes évaluées selon le niveau Tier 2. On peut donc estimer que la seconde évaluation proposée à l'issue de ce travail de thèse est plus précise, plus juste et moins incertaine que la première. Les résultats de la réévaluation serviront donc de référence pour la comparaison des deux méthodes dans la suite du document.

Une comparaison de ces deux approches, la première assez classique et la seconde un peu plus originale (approche écosystémique), permettra dans cette section de mieux comprendre les différences.

La figure 6.1, présente l'ensemble des émissions de GES évaluées suivant les deux approches. L'approche « IPCC Tier 1 » conduit à une part importante de la fermentation entérique (60% des émissions totale) dans les émissions totales. On retrouve la tendance décrite dans les évaluations faites à l'échelle du secteur de l'élevage en Afrique Subsaharienne (Gerber *et al.*, 2013) puisque elles sont essentiellement basées sur les facteurs d'émission proposées par défaut dans les guidelines de l'IPCC. Contrairement à cette tendance, l'approche écosystémique donne une participation significativement moins importante de la fermentation entérique (11%). Cet écart est essentiellement lié à deux principales raisons : d'une part des facteurs d'émission (FE) par défaut sur-évalués et d'autre part la non prise en compte de la variation intra-annuelle des effectifs animaux présents dans le territoire étudié, une donnée d'activité nouvelle produite dans la thèse. En effet, le FE d'émission utilisée dans l'approche classique et proposé par l'IPCC pour les bovins en ASS (46kgCH_4/UBT/an) est presque le double du facteur démission moyen obtenu à l'issue des mesures directes effectuées sur le terrain (23.7kgCH_4/UBT/an) (Tableau 6.1). Cette faible valeur s'explique essentiellement par la forte variabilité intra-saisonnière de la qualité (Chagunda *et al.*, 2010) et de la quantité (Bouchard *et al.*, 2015) de fourrage ingéré quotidiennement par les animaux. La probable surévaluation des facteurs d'émission concernant le méthane entérique avait été annoncée à propos d'autres terrains ouest africains par Lecomte *et al.* (2016). La forte variation des effectifs du cheptel présent dans l'aire de desserte du forage de Widou pris en compte dans l'approche écosystémique entraîne une délocalisation de près de 30% des émissions totales de méthane entérique hors du territoire étudié. Ce fort transfert des émissions de méthane entérique est lié au départ en transhumance d'une grande partie du bétail. Cette « grande transhumance » concerne surtout les ruminants, les bovins à 90% et les ovins à 70% (Chapitre 2).

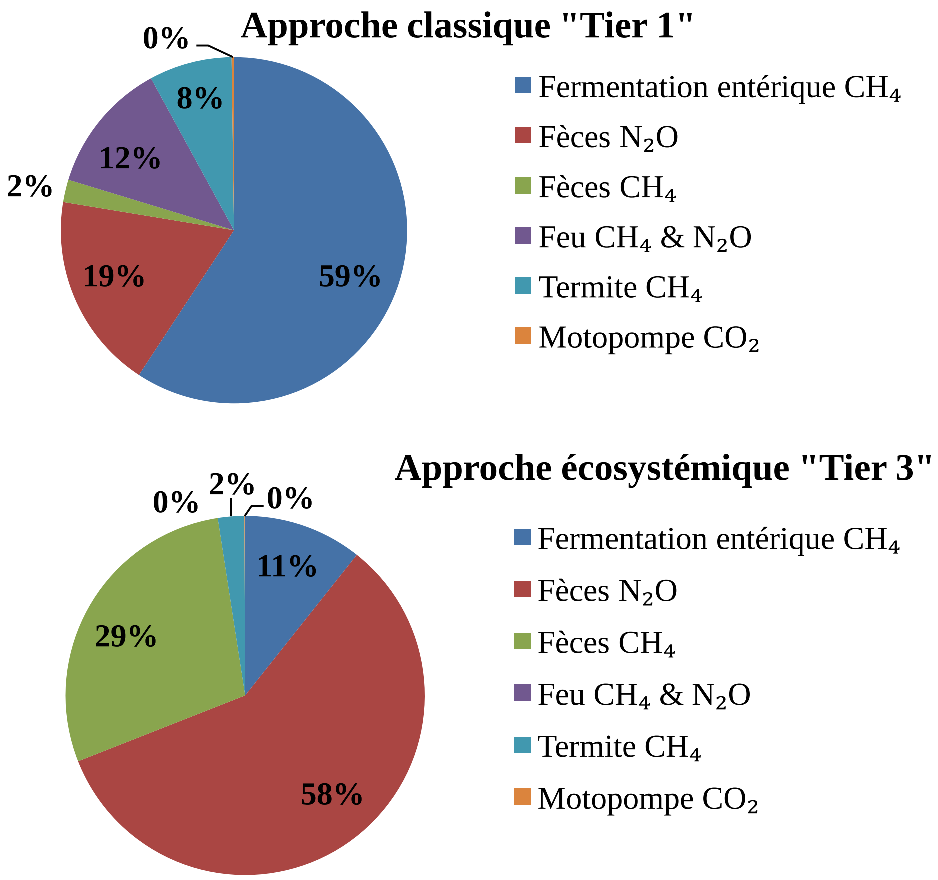

Figure 6. 1 : Emissions totales de GES à l'échelle d'un écosystème sylvopastoral suivant une approche classique « IPCC Tier 1 » (en haut) et une approche « écosystémique » (en bas).

Inversement l'approche IPCC Tier 1 sous-évalue la contribution des fèces aux émissions totales de GES de l'écosystème. Elle avoisinait 21% des émissions totales dans l'approche IPCC Tier 1 et elles représenteraient directement et indirectement près de 86% des émissions totales de GES selon l'approche écosystémique, à l'issue de mesures de terrain (Chapitre 3). Cette sous-évaluation des émissions liées aux apports de fèces s'explique par deux situations révélées par l'approche écosystémique : une concentration des apports de fèces dans des unités paysagères privilégiées (mares et forage) et l'existence d'eaux stagnantes dans le territoire (Chapitres 3 et 5). L'existence de zones d'accumulation forte de déjections animales accompagnées de phénomènes de flush de minéralisation de l'azote au moment des pluies (Herrmann and Witter, 2002) explique des forts niveaux d'émissions de N_2O. De plus l'hydromorphie partielle et passagère de sols recevant par ailleurs de grandes quantités de déjections entraine également des émissions de CH_4 localisées dans le temps (Harrison-Kirk *et al.*, 2013). L'existence de zones avec eaux stagnantes avait largement été sous-évaluée dans l'approche IPCC Tier 1. La présence d'eaux stagnantes de surface à proximité du forage en saison sèche ou dans les mares naturelles en saison des pluies sont des éléments importants révélés dans l'approche écosystémique. Les hauts niveaux d'apport de déjections pendant l'abreuvement dans ces zones inondées expliquent des émissions fortes de CH_4 (Chapitre 3). Ces dernières totaliseraient 20% des émissions totales de GES. Ces fortes valeurs d'émission se traduisent par des facteurs d'émissions liée au dépôt des déjections largement supérieurs aux normes proposées par défaut dans les lignes directrices de l'IPCC (2006) tel que résumés dans le tableau 6.1. Les valeurs obtenues dans cette étude sont de 3 à 8 fois supérieures aux normes utilisées par défaut pour les émissions de CH_4 et N_2O liées aux dépôts des déjections dans le sol et dans l'eau des mares.

Tableau 6. 1 : Comparaison des facteurs d'émission obtenus aux valeurs par défaut proposées par l'IPCC, 2006 dans les lignes directrices pour les inventaires nationaux des GES.

			Facteurs d'émissions	
			Valeurs proposées par cette étude	Valeurs par défaut (IPCC, 2006)
Fèces	Bovins	*kg CH_4/tête/an*	6,82	1
	Ovins	*kg CH_4/tête/an*	1,74	0,21
	Caprins	*kg CH_4/tête/an*	1,87	0,22
	Bovins	*kg N_2O/tête/an*	4,23	0,8
	Ovins	*kg N_2O/tête/an*	1,17	0,24
	Caprins	*kg N_2O/tête/an*	1,07	0,24
	Parcours	*kg N_2O-N/kg N excrété*	0,08	0,02
Méthane entérique	Bovins	*kg CH_4/tête/an*	27,07	46
	Ovins	*kg CH_4/tête/an*	7,37	5
	Caprins	*kg CH_4/tête/an*	7,34	5

1 tête= un bovin de 250kg de poids vif, un ovin de 45 kg de poids vif et un caprin de 40kg de poids vif.

Des différences importantes sont également à noter concernant les émissions liées aux feux de végétation. Dans le chapitre 1, les surfaces brûlées avaient été estimées selon une moyenne définie à partir d'observations satellitaires réalisées au Sénégal (Kane and Prevost, 1994; Nielsen *et al.*, 2003). Ces surfaces se sont révélées être nulles l'année de mise en œuvre de l'approche écosystémique. Aucun feu de végétation n'a été observé dans le territoire étudié pendant la période de suivi. Ceci s'explique par une année à pluviosité faible caractérisée par une production de biomasse herbacée limitée et une consommation rapide de cette biomasse par les animaux. Une disparition de plus de 80% de la biomasse herbacée érigée par ingestion et piétinement a été observée de Septembre à Janvier (Chapitre 5). Ces deux éléments ont fortement limité les risques d'installation des feux de végétation sur la période étudiée. Au-delà de la singularité de l'année étudiée, les feux de végétation sont des éléments importants du fonctionnement des écosystèmes de savane (Thonicke *et al.*, 2001). Les feux de brousse ont des effets variables sur émissions de GES. Leurs effets dépendent aussi bien de leurs intensités que de leur origine (Moussa *et al.*, 2011). La combustion des biomasses végétales est reconnue comme une source d'émission de gaz à effet de serre tels le dioxyde de carbone, le méthane et l'oxyde nitreux (Koppmann et al., 2005) et ceci en particulier dans les régions tropicales et subtropicales (Devineau et al., 2010).

La figure 6.2 la répartition du potentiel d'accumulation de carbone entre les principaux puits de C suivant une approche classique et une approche écosystémique. Les facteurs de séquestration du C dans le sol retenus dans les deux approches sont très proches : 0,28 tC/ha/an pour l'approche classique et entre 0,26 et 0,32 tC/ha/an pour l'approche écosystémique. Idem pour les variations de poids des animaux : 30,6 kgPV/tête/an pour l'approche classique et entre 0,26 et 32,04 kgPV/tête/an pour l'approche écosystémique pour les bovins. Par conséquent la différence entre les deux approches intervient essentiellement au niveau des ligneux. L'approche écosystémique a permis de mieux intégrer la variabilité spatiale des densités d'arbres selon les unités d'aménagement et de préciser l'incrément annuel du diamètre des arbres. La densité des arbres dans les plantations forestières, autour des mares est respectivement 3 à 4 fois plus élevée que celle des parcours. La densité observée et l'incrément annuel obtenu dans le cadre du suivi sont respectivement 22% et 30% plus élevé que la moyenne disponible dans la littérature et utilisée dans l'approche classique IPCC Tier 1 (Woomer *et al.*, 2004; Diouf *et al.*, 2005). En effet les études s'intéressent en priorité aux unités paysagères dominantes, à savoir les parcours.

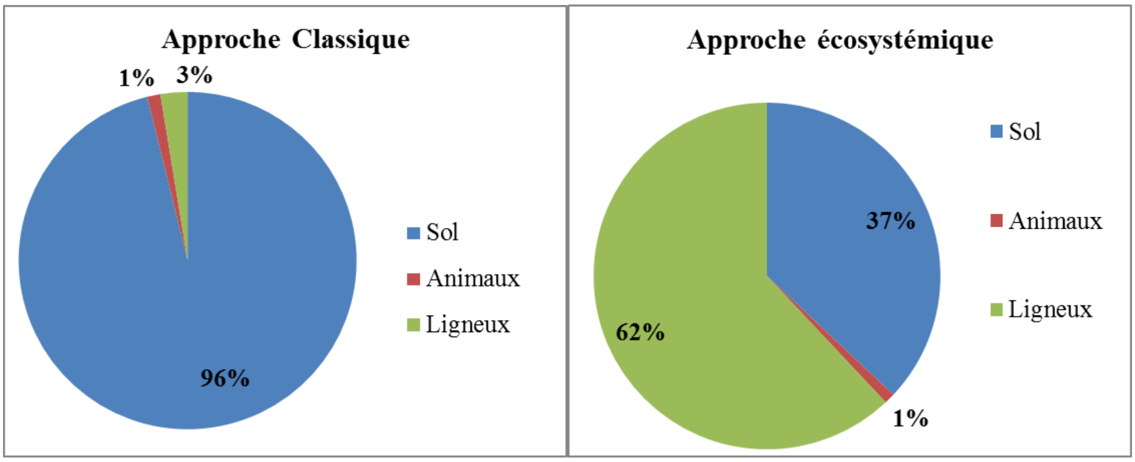

Figure 6. 2 : Accumulation totale annuelle de C dans les principaux réservoirs d'un écosystème sylvopastoral suivant une approche classique « IPCC Tier 1 » (à gauche) et une approche « écosystémique » (à droite).

Les deux approches ont donné un bilan GES légèrement négatif indiquant ainsi un écosystème proche de l'**équilibre** entre émissions et séquestration à l'échelle globale du territoire. L'approche classique a permis d'obtenir un bilan global de -0,1tC/ha/an alors que l'approche écosystémique a permis d'obtenir un bilan variant entre -0,01 et -0,09 tC/ha/an. Ces résultats confirmeraient la tendance observée pour les systèmes prairiaux tempérés décrits par (Soussana *et al.*, 2007) qui ont obtenu des bilans variant entre -0,3 et -1,7 tC/ha/an. Ce potentiel de séquestration plus élevé en contexte tempéré se justifie par le faible potentiel de séquestration de carbone en contexte tropical aride lié à la nature des sols (sol sableux), aux fortes températures et au faible niveau de pluies (Kotir, 2011).

6.3. Une meilleure compréhension de l'impact de l'élevage transhumant sur le bilan GES du territoire

Au-delà d'un gain de précision, le deuxième grand avantage de l'approche écosystémique développée dans cette thèse est qu'elle entre dans le cœur du fonctionnement de l'écosystème étudié. En effet elle permet de mieux évaluer et expliquer i) d'une part l'hétérogénéité spatiale au sein du territoire étudié (chapitre 4) et ii) d'autre part la variabilité temporelle du bilan GES (chapitre 5). Ces visions dynamique et spatiale sont des éléments importants de compréhension des facteurs d'élaboration du bilan GES à l'échelle globale du territoire. L'approche écosystémique permet en particulier de mieux appréhender le rôle de l'élevage dans l'élaboration de ce bilan GES.

L'élevage joue un rôle primordial à la fois dans la dégradation de l'environnement et dans le maintien de la fertilité des sols dans la zone semi-aride du Sahel. Tout comme en systèmes agro-pastoraux (Dugué, 1998; Manlay *et al.*, 2004b; Schlecht *et al.*, 2004), les animaux en systèmes sylvopastoraux orchestrent des transferts de nutriments et de C via l'ingestion de fourrages et l'excrétion de fèces et d'urine. Cette étude montre qu'en systèmes sylvopastoraux ces transferts se font essentiellement depuis les parcours vers les campements et les points d'eau (mares et forage) (chapitres 2). En effet, les herbivores et en particulier les ruminants constituant l'essentiel du cheptel en milieu sahélien, peuvent participer activement aux transferts de fertilité à l'échelle des terroirs pastoraux. Ceci à travers les fonctions spécifiques d'ingestion, digestion, excrétion et mobilité qui leur permettent de prélever de la phytomasse en certains points du territoire, s'en nourrir, la transformer et déposer leurs déjections en d'autres points (Bloor *et al.*, 2012). La proportion du paysage affecté par ce phénomène dépend des espèces animales présentes, du chargement animal et des temps de présence des animaux dans chacune des unités paysagères (Chapitre 2 et 5). Ainsi les vastes zones de parcours (89% de la surface du territoire) et les plantations constituent des zones où les chargements animaux instantanés sont relativement limités et où les prélèvements de biomasse végétales dominent les restitutions. A l'inverse les zones autour du forage, des campements et des mares sont des aires de dépôt de déjections animales. Le forage et les mares sont fortement fréquentés par l'ensemble des animaux du territoire pour l'abreuvement et les alentours des campements abritent les enclos de petits ruminants et de gros ruminants. La forte présence des animaux se manifeste de façon visuelle par la présence d'amas de bouses dans ces unités paysagères avec des concentrations de déjections par unité de surface parfois très élevées (Chapitre 3 ; Annexe 9). La déposition de déjections animales (urine et fèces), en raison de leurs propriétés physico-chimiques, affectent les cycles de nutriments au sein de la prairie (Vendramini *et al.*, 2014) mais également le bilan GES de ces écosystèmes (da Silva Cardoso *et al.*, 2016). Ces dépôts crée une distribution non homogène des déjections se traduisant par des transferts de nutriments inégaux, une accumulation de nutriments à certains endroits du paysage et un risque plus élevé de pertes de nutriment par lessivage (Wachendorf *et al.*, 2008) et de perte gazeuse à l'interface air-sol (Chapitre 3). Cette hétérogénéité dans l'espace pastoral comme c'est le cas dans l'aire de desserte du forage de Widou est en partie responsable de la **forte hétérogénéité spatiale du bilan GES** montrée dans cette étude (Chapitre 4). En effet les zones fortement fréquentées et ayant de fortes concentrations de déjection (forage, campements et mares) présentent des bilans GES largement positifs indiquant que les émissions totales surpassent largement le potentiel de séquestration de carbone de ces unités paysagère. Contrairement à cette tendance, les autres unités paysagères plus vastes (parcours, plantations forestières) avec de faibles concentrations de déjections par unité de surface se comportent comme des puits de carbone avec des bilans négatifs. En effet, les déjections animales sont riches en matière organique en partie digérée et en nutriments, notamment l'azote et le phosphore. Les déjections solides animales subissent soit une dégradation physique (principalement par le piétinement des animaux et l'action mécanique de la pluie) ou une dégradation biologique liée aux activités de la faune et des microorganismes coprophages principalement des bousiers à action rapide en saison des pluies. Lors de ce processus de dégradation, les nutriments présents dans la matière fécale peuvent être incorporés dans le sol, ou «perdus» pour le système prairial s'ils sont émis sous forme gazeuse (CO_2, N_2O et CH_4) (Pinares-Patiño *et al.*, 2007) ou si les nutriments solubles sont lessivés. La dégradation des déjections s'accompagne donc d'une accumulation temporaire de C&N du sol (Aarons *et al.*, 2004) et d'une augmentation des flux de GES dans les unités paysagères d'accumulation des déjections. La majeure partie du carbone (C) des déjections est transformée en dioxyde de carbone (CO_2) lors de la dégradation, environ 80% selon les travaux de (Bol *et al.*, 2000). Ces émissions de CO_2 sont particulièrement importantes durant les premières semaines après la production de la déjection (Priano *et al.*, 2014). (Bol *et al.*, 2000) ont également montré que 12,6% du C fécal persiste dans la couche superficielle du sol (0-5cm) tandis que 4% du C fécal se retrouve dans le lixiviat du sol (>30 cm de profondeur) suite à la disparition des déjections. Le bétail intervient de cette façon sur le cycle du C au niveau du sol. C'est ainsi que les emplacements des anciens parcs de nuit autour des campements, de l'aire de repos autour du forage et des mares présentent des sols plus riches en matière organique et avec des teneurs en C et en nutriments (notamment P) plus élevées (Chapitre 3). Les animaux créent ainsi dans l'espace une forte variabilité des émissions de GES d'une part et du potentiel de séquestration de C d'autre part induisant le fort contraste observé dans les différentes unités d'aménagement pour le bilan GES.

Cette étude a aussi permis de montrer la forte **variabilité saisonnière du bilan GES** avec un bilan positif en saison des pluies et négatif tout au long de la saison sèche (Chapitre 5). Cette vision variable sur une année reste un résultat assez marquant de cette thèse et à notre connaissance de la littérature reste jusqu'à ce jour non documentée. Ces résultats sont en accord avec le caractère fortement saisonnés des écosystèmes pastoraux dans le Sahel. Ces milieux sont caractérisés par de fortes variations spatiales mais aussi temporelles des précipitations même à une échelle locale (Nicholson, 2013). Dans cette région, l'essentiel de la production fourragère a lieu pendant la saison des pluies qui dure quatre mois (de Juillet à Octobre). L'utilisation de ce stock fourrager qui constitue la principale ressource disponible pour les animaux au cours de la longue saison sèche (huit mois) suppose une bonne connaissance de sa dynamique saisonnière sous l'effet conjugué du climat et de la pression pastorale. Dans ces territoires pastoraux, les herbivores domestiques ont acquis un potentiel génétique particulièrement adapté aux pratiques pastorales et aux milieux difficiles du point de vue climatique qu'ils exploitent (Mandonnet *et al.*, 2011). Ce qui participe à la résilience et à la pérennité des systèmes pastoraux. Les troupeaux se déplacent et ont une grande capacité à s'adapter à des régimes alimentaires variables en fonction de la disponibilité des ressources (eau, fourrages). Tout l'art de l'éleveur consiste alors à mener son troupeau vers les meilleures ressources du moment dans la limite d'un niveau d'effort acceptable pour les animaux ; ce qui l'oblige à se déplacer chaque jour et selon les saisons. Le principal moyen dont dispose l'éleveur, le bouvier ou le berger pour orienter le régime alimentaire de ses animaux, repose sur les pratiques de conduite extensive des troupeaux au pâturage. La mobilité des troupeaux comme moyen d'adaptation au fonctionnement saisonnier des écosystèmes pastoraux induit de fortes variations saisonnières de la charge animale supportée par l'espace pastoral. Cette forte variation saisonnière du chargement animal influence le bilan GES de ces écosystèmes et le rend variable dans le temps. En effet, en période d'abondance de biomasse en saison de pluies et une partie de la saison sèche, il est observé un chargement animal plus élevé dans l'écosystème pastoral avec une forte valorisation de la biomasse herbacée impliquant un fort retour de déjections au sol. Ce chargement plus élevé dans cette période de l'année influence le fonctionnement de l'écosystème et dans le même temps les cycles de l'N et du C et donc les composantes du bilan GES. Les périodes à fort chargement animal se traduisent par une augmentation concomitante des émissions de GES globales et du processus d'accumulation de carbone dans les sols (et indirectement dans les ligneux via les apports de nutriments). Ainsi la présence accrue des animaux coïncidant avec une humidité importante des sols font que l'écosystème se comporte sur cette période de l'année comme une source de GES, avec des émissions de GES qui surpassent la séquestration du C. En effet les forts dépôts de déjections au sol (da Silva Cardoso *et al.*, 2016) et la forte humidité des sols accompagnée par endroit de zones d'hydromorphie (à proximité des mares et du forage) induisent une augmentation très importante des émissions de GES (Delon *et al.*, 2015). Pendant cette période d'abondance de fourrage d'assez bonne qualité le cheptel reconstitue sa masse corporelle (et séquestre du C). Dès que la disponibilité quantitative et qualitative des ressources fourragères diminue, on assiste à un départ en transhumance progressif d'une partie du cheptel de l'espace pastoral s'accompagnant d'une dégradation de l'état corporel du cheptel du fait de niveaux d'alimentation plus faibles et de dépenses énergétiques du fait de déplacements plus importants (Chapitre 2). Le départ en transhumance s'accompagne d'une baisse saisonnière du chargement animal dans l'espace pastoral et de ce fait induit une baisse de la contribution des animaux au bilan GES via les émissions entériques et l'apport de déjections. De plus la saison sèche est également caractérisée par une diminution rapide (en surface) et progressive (en profondeur) de l'humidité des sols. L'activité biologique et les processus chimiques dans la partie supérieure des sols (0-30 cm) favorisant les fortes émissions de GES sont donc considérablement ralentis en saison sèche. La saison sèche est également marquée par un niveau important de séquestration au niveau du sol car c'est une période de forte sénescence, de retour de biomasse herbacée sous forme de litière (dont action de piétinement des animaux) et de retour au sol de quantités importantes de biomasses fécales (surtout dans la première partie de la saison sèche avant le départ des animaux en transhumance). La baisse du niveau des émissions, couplée à un niveau important de séquestration au niveau du sol, explique un bilan négatif sur toute la saison sèche.

Par ailleurs, les résultats de l'approche écosystémique laissent entrevoir une forte **variabilité interannuelle** du fonctionnement de l'écosystème étudié, des cycles du C et de l'N et donc de son bilan GES. Les territoires pastoraux de la zone sylvopastorale du Sénégal sont soumis à une forte variabilité interannuelle et décennale des précipitations (cf. figure i2). En effet les observations n'ont couvert qu'une seule année. L'année étudiée se trouve être une année sèche avec un cumul des précipitations de 204 mm, inférieur de près de 28% à la moyenne annuelle (284 mm) et une distribution des évènements pluvieux réduite dans le temps (15 jours contre une moyenne de 20 jours). L'approche écosystémique permet d'identifier un certain nombre d'arguments laissant prévoir une forte variabilité inter-annuelle du bilan GES du territoire étudié en lien avec l'importance des activités d'élevage. En effet, la variation intra-annuelle de la charge animale est une variable clef de l'adaptation de la conduite des troupeaux en système pastoral, elle est fonction de la quantité de biomasse végétale disponible, elle-même fortement expliquée par la pluviosité annuelle. Or cette charge animale détermine les émissions entériques locales (CH_4) et les émissions depuis le sol (N_2O et CH_4). Les risques de feux semblent aussi fortement déterminés par la biomasse végétale disponible, ils sont plus importants les années à pluviosité élevée (Nielsen *et al.*, 2003). Ces deux composantes augmentent le bilan GES. Mais il est à ce stade difficile de conclure si une année plus humide conduirait à un bilan plus élevé (ou inversement) tant les interactions sont complexes entre les différentes composantes de l'écosystème. Certes une année plus pluvieuse conduit à une présence d'animaux dans le territoire plus prolongée dans le temps et des risques de feu plus importants (et donc plus d'émissions de GES). Mais à l'inverse une pluviosité plus élevée conduit à une production de biomasse herbacée plus élevée, à une croissance de la végétation ligneuse plus importante et potentiellement à une activation de la séquestration du C dans les arbres et le sol du fait d'apports de déjections plus importants.

De la même manière **la contribution des animaux au bilan GES reste encore à préciser**. Certes cette étude confirme que les animaux sont responsables de quantités importantes de GES directement via le méthane entérique (Chapitre 2), et indirectement via la déposition de leurs déjections sur le sol et dans les points d'eau (Chapitre 3). Mais cette étude laisse également entrevoir des effets d'atténuation du bilan GES par la présence des troupeaux dans l'écosystème via trois mécanismes :

- la valorisation de la biomasse herbacée produite par ingestion et son piétinement sont deux facteurs importants de régulation des risques de feux et de la présence des termites ; en effet à l'échelle du Sénégal il a été montré que le risque de feu est très fortement corrélé à la biomasse érigée disponible (Sannier *et al.*, 2002; Nielsen *et al.*, 2003), de même il s'emblerait que l'abondance de termites soit proportionnelle à la biomasse disponible (Lepage, 1974),
- le recyclage accéléré de la biomasse végétale par digestion des fourrages cellulosiques et une incorporation probablement accéléré/facilitée du C dans le sol via les interactions entre animaux d'élevage et coprophages ; les bousiers et autres coprophages ont en effet un rôle important dans l'enfouissement de la matière organique dans les sols (Hughes, 1975; Yamada *et al.*, 2007) et leur diversité est très fortement liée à la diversité des espèces d'animaux d'élevage présente (Dormont *et al.*, 2004) ; l'enfouissement de la matière organique par les coprophage pourrait jouer un rôle non négligeable dans

l'atténuation des émissions liées au dépôt des déjections et la stabilisation du C du sol (Slade *et al.*, 2016) ;

- une amélioration de la croissante des arbres à travers le dépôt des déjections (urine et fèces) au sol augmentant l'apport de matière organique et de nutriments, avec un apport préférentiel sous les arbres au moment des phases de repos des animaux aux heures chaudes; l'azote est en effet un élément limitant de la croissance des plantes au Sahel (Vayssières and Rufino, 2012) ; Le rôle des animaux dans la séquestration du C par les ligneux doivent également tenir compte de l'effet long terme des animaux d'élevage sur la nature et l'évolution du couvert végétal, sur l'importance des ligneux dans le paysage en particulier (Miehe *et al.*, 2010).

Un approfondissement de ces trois composantes du fonctionnement de l'écosystème reste à conduire par des suivis sur le long terme d'écosystèmes sylvo-pastoraux permettant une quantification des variations interannuelles de leur fonctionnement et de leur bilan GES. Une analyse des cycles de l'N et du C en distinguant les différences entre unités paysagères, semble également une piste intéressante pour mieux comprendre le rôle de l'élevage. En effet les différentes unités paysagères présentent des chargements animaux variables, avec des unités où l'élevage prélève ou restitue préférentiellement (Chapitre 4). L'existence de mises en défend dans l'aire de déserte du forage de Widou, avec une pression animale proche de zéro est une opportunité pour approfondir ces trois mécanismes, ces dernières pourraient en effet servir de base de référence (i.e. de témoin).

6.4. Une mise en évidence d'options d'atténuation facilitée

Les recommandations du GIEC argumentent pour la mise en œuvre rapide de mesures fortes d'atténuation du changement climatique (IPCC, 2014). Dans l'optique d'une atténuation des émissions de gaz à effet de serre des systèmes d'élevage, cette étude confirme que les écosystèmes pâturés tropicaux peuvent jouer un rôle important vu leur potentiel de séquestration de carbone (C) dans les sols et la végétation (cf. chapitres 4 et 5) et compte tenu de leur superficie qui représente près de 40% des terre émergées en Afrique (White *et al.*, 2000). L'atténuation est une intervention humaine visant à réduire les sources ou à renforcer les puits de gaz à effet de serre (IPCC, 2014).

L'approche écosystémique utilisée dans cette étude a permis de mieux identifier dans le temps et dans l'espace les options d'atténuation pouvant permettre d'accroitre le potentiel d'accumulation de carbone dans les principaux réservoirs et de réduire les émissions totales de GES à l'échelle d'un territoire sylvo-pastoral. Au-delà de l'approche classique de replantation (cf. projet de la Grande Muraille Verte), trois grandes options d'atténuation émergent de cette étude ; il s'agit de l'aménagement des environs des points d'eau, de la collecte et valorisation des fèces à proximité des campements en vue de leur méthanisation, et de la constitution de stocks de fourrages récoltés et conditionnés sur l'ensemble du territoire.

Les émissions de N_2O et CH_4 depuis le sol et les eaux de surface constituent l'essentiel (86%) des émissions du territoire sylvo-pastoral étudié dans cette thèse (Chapitre 5). Un **aménagement des environs des points d'eau** (forage et mares) pourrait permettre de réduire ces émissions. En effet le fait d'aménager et entretenir des abreuvoirs autour des points d'eau avec mise en défend des zones d'accumulation d'eau en surface devrait limiter le dépôt direct de déjections dans l'eau ou sur les zones d'hydromorphie à proximité des points d'eau et donc limiter les émissions de méthane du territoire.

Des quantités très importantes de fèces (0,19 tMS/ha/an sont accumulées une grande partie de l'année également à proximité des campements au niveau des aires de repos des troupeaux en particulier. La forte concentration des bouses à proximité des habitations pourrait faciliter leur **collecte et leur valorisation dans des bio digesteurs**. La mise en place de « mini-centrales de méthanisation à la ferme » connait un grand succès en Inde et se développe en zone agro-pastorale d'Afrique de l'Ouest (Raineau, 2011). Outre la réduction des émissions de GES liées au dépôt de déjections animales, ces mini-centrales produisent de l'énergie renouvelable pour les populations rurales isolées avec des effets positifs sur la réduction des coupes de bois, sur la qualité de vie et l'éducation (Demirbas and Demirbas, 2007). Le digestat produit à l'issu de la fermentation conserve les propriétés fertilisantes des bouses collectées et pourrait être avantageusement utilisé pour la fertilisation des jeunes plantations d'arbre.

Dans le cas de l'aire de déserte de Widou, les observations et mesures de terrain ont permis de constater que sur une année entière seulement 30% de la biomasse herbacée produite est ingérée par les animaux présents (Chapitre 2 ou 5), le reste étant majoritairement restitué au sol sous forme de litière par piétinement des animaux (Hiernaux *et al.*, 1999). Nos calculs montrent qu'une valorisation de 70% de cette biomasse résiduelle permettrait de combler les besoins de l'ensemble du cheptel présent dans l'aire de déserte (l'équivalent de UBT), sous hypothèse d'un non départ en transhumance de la totalité des troupeaux et d'une couverture des besoins des animaux au plus haut niveau d'ingestion observé au cours de l'année de suivi des troupeaux (à savoir 6,30 kgMS/UBT/j). L'année de nos observations est une année sèche avec une pluviosité en dessous de la moyenne (Chapitre 4). Le surplus de biomasse non ingéré et potentiellement valorisable par le bétail devrait être encore plus élevé dans les cas d'une année plus pluvieuse. Le mode de valorisation le plus adapté semble être la **constitution d'une banque fourragère**

sous forme de foin ou d'ensilage d'herbe. Idéalement la coupe et le conditionnement des graminées se fera pendant la saison des pluies (entre Août et Septembre) afin de récolter et de stocker les jeunes repousses reconnues comme étant des fourrages de qualité supérieure. Cette mesure devrait avoir un triple effet positif sur la réduction du bilan GES par à la fois une réduction des émissions de méthane entérique (fourrage de meilleur qualité), une amélioration des performances animales et un meilleur stockage de C dans les animaux (limitation des dépenses des animaux) et une réduction des risques de feu (limitation de l'importance du pic de biomasse sur pied en saison sèche froide). Des travaux en contextes tempérés avaient également montré l'intérêt d'un aménagement et la gestion d'un territoire prairial en vue d'améliorer la disponibilité et la qualité du fourrage pour réduire la production de méthane entérique par unité de produit (McCaughey *et al.*, 1999). Il est aujourd'hui largement connu que la qualité des fourrages ingérés influence les émissions de méthane par unité de produit (viande et lait) et par tête (Molano and Clark, 2008; Chagunda *et al.*, 2010). Des travaux plus récents intégrant une approche globale des cycles de l'N et du C à l'échelle de la ferme montrent qu'une amélioration de la ration permet de réduire le bilan GES des écosystèmes agro-pastoraux en contexte tropical (Vayssières *et al.*, 2016).

Ces résultats soulignent l'intérêt de l'approche écosystémique du bilan GES proposée dans cette thèse pour également proposer des solutions de mitigation efficaces. En effet ces propositions d'options d'atténuation sont issues d'une analyse conjointe du fonctionnement et du bilan GES de l'écosystème étudié et de leur variabilité dans le temps et dans l'espace. Il reste cependant à évaluer la faisabilité économique et sociale de ces différentes options du point de vue des populations de pasteurs vivant dans les territoires sylvo-pastoraux. La mise en œuvre de ces différentes options pourrait-être intégrée à des réflexions plus globales d'aménagement des territoires sylvopastoraux et de mise en place de mécanismes incitatifs du type « paiements pour services environnementaux » (Dutilly-Diane *et al.*, 2007). En effet au-delà du rôle que peuvent jouer ces écosystèmes dans l'atténuation du changement climatiques ces écosystèmes abritent une biodiversité riche et méconnue (Cresswell *et al.*, 2007).

Conclusions et perspectives

Cette thèse, basée sur une **approche écosystémique**, a permis d'apporter des éléments de compréhension du fonctionnement des écosystèmes sylvopastoraux tropicaux peu décrits en contexte tropical et de proposer un bilan gaz à effet serre (GES) jusque-là peu renseigné. Cette étude s'est basée sur un dispositif expérimental unique s'intéressant à un territoire sylvo-pastoral de 706 km^2 centré autour du forage de Widou. Ce territoire peut être considéré comme un exemple illustratif de la complexité des territoires pastoraux en région sahélienne.

A l'issu de cette thèse, les écosystèmes pastoraux semblent être caractérisés par une forte **variabilité saisonnière** et une forte **hétérogénéité spatiale du bilan GES**. Ainsi le bilan GES du territoire étudié est largement positif en saison des pluies et négatif au cours des saisons sèches froide et chaude. Le bilan GES est par ailleurs largement positif dans les unités paysagères accueillant les animaux pour le repos et l'abreuvement (les abords des campements, les berges des mares et les alentours du forage) et négatif dans les autres unités paysagères sources de biomasses fourragères (les parcours et les plantations forestières). Ce bilan semble en grande partie déterminé par l'activité dominante de ce type d'écosystème, à savoir l'élevage. Une compréhension des principales contraintes affectant l'élevage et donc le fonctionnement de ce type d'écosystème permet de mieux comprendre comment l'élevage contribue à la construction de cette forte variabilité temporelle et de cette forte hétérogénéité spatiale :

- L'eau est la contrainte majeure dans ces milieux secs. Dans un territoire pastoral l'abreuvement des animaux se fait au niveau des points d'eau aménagés par l'homme (forage ou puits pastoraux) et dans les mares alimentées en saison des pluies. L'eau stagnante au niveau des points d'abreuvement constitue la principale source de méthane du territoire étudié du fait des dépôts importants de déjections dans les eaux. La forte saisonnalité de l'humidité des sols explique également les plus fortes émissions du sol en saison des pluies.
- La biomasse fourragère constitue la seconde contrainte la plus importante pour la conduite des troupeaux. Dans un territoire pastoral, la question du chargement est déterminante pour comprendre le fonctionnement de l'écosystème. L'effectif des animaux présents dans un territoire varie en fonction de la quantité et de la qualité de la biomasse fourragère disponible au cours de l'année. Un peu moins du tiers du maximum de production de cette biomasse herbacée est consommé par les herbivores présents sur

le territoire et entre 40 et 70% des effectifs (en UBT) partent en transhumance pendant 6 mois de l'année. Les animaux dans ces conditions de forte variabilité du disponible fourrager se déplacent et ajustent leur consommation à ce disponible avec des conséquences importantes sur les émissions entériques du territoire.

Au-delà de cette forte variabilité temporelle et de la grande hétérogénéité spatiale du bilan GES, ce dernier reste légèrement négatif indiquant que sur une année entière l'ensemble des émissions de GES semblent être compensées par la séquestration de C dans les arbres, les sols et les animaux. Les parcours pastoraux tropicaux en milieu sahélien auraient donc un potentiel de séquestration de C, tout comme les écosystèmes prairiaux tempérés. Ce potentiel pourrait être valorisé sur le marché du Carbone à l'international. Le bilan GES pourrait à l'avenir constituer un indicateur supplémentaire pour évaluer la santé d'un écosystème. Il est ici proche de zéro, indiquant **un écosystème proche de l'équilibre**.

En terme de perspectives, pour vérifier cet état d'équilibre nous suggérons en priorité de i) mettre en place un dispositif méthodologique plus solide permettant de mieux estimer les variations de stocks de carbone dans les sols en particulier, et ii) de valider le facteur d'émission de méthane entérique avec des mesures directes faites sur les animaux in situ. Afin d'approfondir le rôle de l'élevage dans l'élaboration du bilan GES nous suggérons de mettre en place :

- une étude détaillée sur le long terme ciblant les principaux mécanismes affectés par la charge animale par la valorisation des placettes en défend existantes à Widou et la mise en place de placettes supplémentaires avec pression animales variables et contrôlées,
- une analyse sur le long terme de la variabilité interannuelle du bilan GES ; en effet l'importante variabilité interannuelle du régime des pluies affecte la production de biomasse, les départs en transhumance, la charge animale effective et conditionne donc indirectement le bilan GES.

Cette thèse montre également l'intérêt d'une approche écosystèmique du bilan GES pour **proposer des options d'atténuation** efficaces et adaptées au fonctionnement de l'écosystème. A l'issu de ce travail de thèse, au-delà de l'importance des replantations (déjà largement connu) le report de stocks fourragers et l'aménagement des abords des points d'eau apparaissent comme deux options d'atténuation supplémentaires à privilégier. Aller vers des territoires pastoraux captant du C pourrait à l'avenir être une alternative pour faire face aux énormes défis mondiaux du changement climatique.

Enfin peut-on imaginer d'aller vers une analyse des pratiques de **gestion d'un écosystème sylvo-pastoral** (et non pas seulement une simple analyse du fonctionnement de l'écosystème)? Des formes de gestion des territoires pastoraux plus ou moins collectives existent probablement. Les pasteurs mobilisent individuellement des savoirs locaux particulièrement riches qu'ils mobilisent très fortement pour ajuster leurs pratiques de conduite des troupeaux avec probablement un déterminisme fort sur l'équilibre entre émissions et séquestration observés dans cette étude de cas.

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Annexes

Annexe 1. Facteur de conversion en Unité Bovin Tropical (UBT) par catégorie d'espèce animale

		Masse (kg)	Equivalent en UBT
Bovins	*Jeune*	200	0,80
	Adulte mâle	322	1,29
	Adulte femelle	251	1,00
	Nouveau nés	17	0,07
Ovins	*Jeune*	20	0,08
	Adulte mâle	41	0,16
	Adulte femelle	30	0,12
	Nouveau nés	2,3	0,01
Caprins	*Jeune*	18	0,07
	Adulte mâle	25	0,10
	Adulte femelle	20	0,08
	Nouveau nés	1,6	0,01
Asines	*Jeune*	100	0,40
	Adulte mâle	175	0,70
Equins	*Jeune*	140	0,56
	Adulte mâle	200	0,80

Annexe 2. Moyennes mensuelles des états de feuillaison en pourcentage du maximum annuel par type phénologique tirée de (Brandt et al. 2016)

Foliage phenology[1]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ds	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,3	0,4	0,2	0,0	0,0
Dm	0,0	0,0	0,0	0,0	0,0	0,1	0,2	0,2	0,2	0,2	0,1	0,1
Dl	0,1	0,1	0,1	0,0	0,0	0,0	0,1	0,1	0,1	0,1	0,1	0,1
Di	0,2	0,1	0,1	0,1	0,0	0,0	0,0	0,0	0,1	0,1	0,2	0,2
Ed	0,1	0,1	0,1	0,1	0,1	0,0	0,1	0,1	0,1	0,1	0,1	0,1
Ew	0,1	0,1	0,0	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1

Annexe 3. Moyennes mensuelles de chute des feuilles en pourcentage du maximum annuel par type phénologique tirée de (Hiernaux et al. 1999)

Foliage phenology[1]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ds	0,00	0,00	0,00	0,00	0,00					0,40	0,52	0,08
Dm	0,20	0,11	0,05	0,00					0,05	0,09	0,18	0,32
Dl	0,04	0,12	0,18	0,26	0,25	0,15						0,00
Di	0,03	0,12	0,25	0,22	0,23	0,13	0,02					0,00
Ed	0,08	0,07	0,09	0,11	0,15	0,20	0,12	0,10			0,02	0,06
Ew	0,11	0,15	0,15	0,20	0,09			0,02	0,06	0,06	0,07	0,09

[1] : Short deciduous (Ds), Medium deciduous (Dm), Long deciduous, (Dl), Inversed deciduous (Di), Evergreen bud with rains (Ew), Evergrenn bud with dry (Ed)

Annexe 4. Variation mensuelle des effectifs des différentes espèces présentes autour du forage de Widou et transhumés

		Cattle		Sheep		Goat		Donkey		Horse		All species		Stocking rate/ha
Jully	**Hd**	**17230**	**6314**	**52478**	**17190**	**18332**	**4139**	**5956**	**729**	**958**	**540**	**94955**	**28913**	**1.40**
	TLU	15279	6107	8180	1922	1396	326	3730	510	693	432	29278	9296	0.43
	MW	915718	386928	812514	208480	215793	38655	262401	35064	47143	28712	2253569	697839	33.14
August	**Hd**	**11785**	**15947**	**16708**	**35462**	**16161**	**1741**	**2664**	**3520**	**609**	**762**	**47926**	**57431**	**0.70**
	TLU	8334	15463	3739	4086	1266	139	1528	2464	407	609	15275	22762	0.22
	MW	463781	979105	343046	440376	171198	16438	109682	169357	28209	40503	1115915	1645780	16.41
September	**Hd**	**22014**	**2594**	**42415**	**3640**	**19455**	**0**	**5784**	**126**	**1223**	**46**	**90891**	**6405**	**1.34**
	TLU	18576	2539	6030	400	1429	0	3703	88	934	36	30672	3064	0.45
	MW	######	160401	607054	43601	204800	0	259258	6050	62744	2420	2248200	212472	33.06
October	**Hd**	**21856**	**3670**	**49943**	**10702**	**23719**	**474**	**5288**	**530**	**1352**	**86**	**102157**	**15461**	**1.50**
	TLU	18118	3541	6907	1212	1711	37	3380	371	1020	69	31136	5230	0.46
	MW	######	224495	695271	131096	261749	4433	236767	25482	68682	4568	2348896	390074	34.54
November	**Hd**	**22924**	**4287**	**50122**	**3450**	**23578**	**93**	**5714**	**330**	**1140**	**118**	**103478**	**8278**	**1.52**
	TLU	18032	4230	7170	406	1664	7	3729	231	869	94	31464	4969	0.46
	MW	######	266758	721819	43539	249549	865	260013	15886	58392	6266	2365807	333315	34.79
December	**Hd**	**22415**	**5830**	**58934**	**5904**	**26857**	**83**	**6837**	**246**	**1186**	**88**	**116228**	**12150**	**1.71**
	TLU	17510	5650	8308	674	1926	6	4444	172	907	70	33095	6572	0.49
	MW	######	357782	838679	72787	297399	752	310166	11830	60910	4673	2550402	447824	37.51
January	**Hd**	**12353**	**14332**	**53686**	**12205**	**25547**	**922**	**6315**	**1316**	**1002**	**274**	**98903**	**29048**	**1.45**
	TLU	11456	13932	7680	1357	1919	73	4099	921	763	219	25916	16503	0.38
	MW	651455	881654	772427	147421	298950	8611	286153	63339	51268	14554	2060252	1115580	30.30
February	**Hd**	**12483**	**15233**	**50855**	**14335**	**24373**	**2987**	**6527**	**1096**	**1178**	**182**	**95416**	**33832**	**1.40**
	TLU	10976	14765	7358	1578	1851	236	4229	767	894	145	25309	17492	0.37
	MW	620599	935009	739276	171835	290879	27955	295380	52722	60131	9668	2006264	1197188	29.50

March	**Hd**	**7918**	**21106**	**33771**	**21241**	**15996**	**6531**	**4602**	**1881**	**833**	**437**	**63120**	**51196**	**0.93**
	TLU	7686	20252	5286	2325	1201	511	2843	1316	613	350	17630	24754	0.26
	MW	409879	1285519	522661	253439	201110	60718	200642	90480	41543	23262	1375835	1713418	20.23
April	**Hd**	**7906**	**21146**	**32080**	**25499**	**19957**	**8139**	**5012**	**1609**	**1019**	**587**	**65973**	**56980**	**0.97**
	TLU	6472	20194	5024	2761	1522	634	3122	1126	747	469	16887	25184	0.25
	MW	342983	1283279	495669	301775	249469	75421	219898	77403	50668	31201	1358687	1769079	19.98
May	**Hd**	**9967**	**19554**	**35091**	**22302**	**14500**	**8123**	**4762**	**1713**	**1115**	**506**	**65435**	**52199**	**0.96**
	TLU	7999	18598	5403	2403	1109	633	2936	1199	818	405	18265	23237	0.27
	MW	440442	1182996	536320	262928	198925	75281	207295	82397	55476	26906	1438458	1630508	21.15
June	**Hd**	**24449**	**2004**	**41493**	**11427**	**17915**	**1129**	**5071**	**522**	**977**	**41**	**89904**	**15122**	**1.32**
	TLU	19217	1899	6212	1259	1372	88	3134	366	743	32	30678	3644	0.45
	MW	######	120922	621708	137052	212901	10429	221157	25138	49938	2157	2266493	295697	33.33

Annexe 5. Abstract soumis au congrès 3R (Rencontres Recherches Ruminants) 2014

Bilan Gaz à Effet de Serre d'un écosystème sylvo-pastoral tropical dans la zone semi-aride du Sénégal

M.H. Assouma[a], J. Vayssières[a], M. Bernoux[b], P. Hiernaux[c] et P. Lecomte[d]

[a]CIRAD- Umr Selmet, LEMSAT Centre Bel Air, B.P. 1386, 18 524 Dakar, S´en´egal

[b]IRD IRD UMR Eco&Sol, Bˆatiment 12 2 place Viala, 34000 Montpellier, France

[c]CNRS - Umr Get, 14 avenue Edouard Belin, 31400 Toulouse, France

[d]CIRAD - Umr Selmet, Campus International Baillargue, 34398 Montpellier, France

Abstract

Le rapport de la FAO de 2013 ″Tackling climate change through livestock : A global assessment of emissions and mitigation opportunities″ confirme la contribution importante de l'élevage aux émissions mondiales de Gaz à effet de Serre (GES) d'origine anthropique. Les systèmes pâturant extensifs d'Afrique sub-saharienne seraient responsables des plus hauts niveaux d'émissions par unités de produits (viande et lait). Ce type de système d'élevage valorise les parcours naturels des zones arides et semi-arides. Il est caractérisé par la forte mobilité des animaux en réponse `a une forte variabilité saisonnière des disponibles fourragers, ce qui rend leur évaluation particulièrement complexe. Cette complexité explique probablement le fait que ces systèmes soient très peu documentés en termes de bilan environnementaux. Ce travail propose un premier bilan GES `a l'échelle d'un écosystème sylvo-pastoral dans la zone semi-aride du Sénégal, au Ferlo. Ce territoire est organisé en un maillage de forages espacés de 30 km en moyenne pour faciliter l'abreuvement des animaux en saison sèche. L'aire de desserte d'un forage a donc été retenue comme unité spatiale d'analyse (cercle de 15km de rayon autour du forage, soit 706,5 Km²). Ce bilan net intègre les principales émissions directes (fermentation entérique des animaux, déposition des fèces de l'ensemble des animaux d'élevage, activité des termites, feux de brousse et combustion du fuel de la motopompe) et les accumulations de stocks de carbone (C) dans le sol et les plantes pérennes. Les émissions ont été évaluées suivant l'approche Tiers1 proposée par l'IPCC. Les inventaires d'animaux ont recoupé les déclarations faites au forage avec des données d'enquêtes sur l'ensemble des campements (n= 354). Les facteurs d'émission et de séquestration, ainsi que les coefficients techniques (ex. mortalité et productivité animales), ont été renseignés autant que possible à partir des données de la littérature propres à la région d'étude.

Selon ce premier bilan GES, le sol représente le réservoir de C le plus important (66% du stock de C total). Si l'on tient compte de la séquestration annuelle de C par le sol et les arbres, l'écosystème séquestre globalement du carbone. Son bilan GES net est de - 0,12tC/ha/an, autrement dit les ´émissions liées au troupeau seraient compensées par l'accumulation de C dans le sol et les arbres. Les principales sources d'émission sont la fermentation entérique des ruminants (56%) et la déposition de fèces par les ruminants (16%). Le feu et les termites sont également d'importantes

sources d'émissions. Ils représentent à eux deux environ 20% des ´émissions. Les bilans GES ramenés au kilogramme de produit sont effectivement élevés du à la faible productivité des animaux et à des rations fortement méthanogène. Ils sont du même ordre de grandeur que ceux proposés dans la littérature environ 69kg eq.CO_2/kg de poids carcasse et 9kg eq.CO_2/kg FPCM pour les bovins et environ 28kg eq.CO_2/kg de poids carcasse et 11kg eq.CO_2/kg FPCM pour les ovins. Mais du point de vue des auteurs, ces bilans sont incomplets. Les auteurs recommandent à l'avenir des bilans ramenés au kg de produit animal " conséquentiel ", i.e. prenant en compte l'ensemble des effets des animaux à la fois en termes d'émissions directes (comme dans cette étude) mais aussi en termes de modifications du fonctionnement de l'écosystème (ce qui n'est pas le cas ici). Ces modifications du type réduction du risque de feu de brousse et de la présence des termites correspondent dans certains cas à des émissions évitées (à déduire du bilan actuel).

Nombre de mots du résumé: 551

Mots-clé: Emission GES - Séquestration carbone - Ecosystème sylvo-pastoral - Ruminants

Thème: Systèmes d'élevage

Session spéciale: Pas de session spéciale particulière

Présentation: Communication courte

Equipement particulier: Pas d'´équipement particulier

Annexe 6. . Abstract soumis au congrès Animal change 2015

Greenhouse Gas Balance of a Tropical Sylvo-Pastoral Ecosystem in Senegal's Semi-Arid Region

M.H. Assouma[a], J. Vayssières[a], M. Bernoux[b], P. Hiernaux[c] and P. Lecomte[d]

[a]CIRAD, 37 av. Jean XXIII, Dakar Etoile, BP 6189 Dakar, Senegal

[b] IRD - Umr Eco&Sols, SupAgro, 2 place Viala, 34060 Montpellier, France

[c] CNRS - Umr Get, 14 avenue Edouard Belin, 31400 Toulouse, France

[d] CIRAD - Umr Selmet, Campus International Baillarguet, 34398 Montpellier, France

jonathan.vayssieres@cirad.fr

Abstract

Extensive pastoral systems of sub-Saharan Africa are said to be responsible for the highest rates of greenhouse gas (GHG) emissions per unit of animal products. Tropical sylvo-pastoral systems, which make use of rangelands in arid and semi- arid areas, are characterized by a high mobility of cattle as a response to a high seasonal variability of the availability of forages, which makes their evaluation in terms of environmental sustainability particularly complex.

This study o_ers a first GHG balance at the sylvo-pastoral ecosystem scale in the Ferlo, a semi-arid region of Senegal. The Ferlo is organized in a network of well drillings. The drilling access territory (706.5 Km2) was used as the unit of area for this analysis. The net balance includes the main direct emissions and the accumulation of carbon (C) stocks in soil and in trees. The Tier 1 IPCC method was used to evaluate emissions. An inventory of animal stocks was made by cross-checking data collected from statements at the drilling with data from surveys conducted at the camps (n=354).

Emission and sequestration factors as well as technical coe_cients (e.g. productivity and mortality of animals) were extracted from literature.

According to this first assessment, soil represents the most important reservoir of C (66% of the total C stock). Taking into account annual carbon sequestration by the soil and trees, the net GHG balance is - 0.12t C.ha^{-1}.year^{-1}, i.e. emissions from herds are compensated by the accumulation of C in soil and trees. The main sources of emissions are enteric fermentation (56%) and deposition of faeces by ruminants (16%). Fire and termites, two other important sources of emissions, together represent about 20% of emissions. The GHG balances per kg of animal products are high due to the low productivity of animals and the high methanogen potential of feed rations. They are similar to those found in the literature: 69 kg eq. CO_2.kg^{-1} of carcass weight and 9 kg eq. CO_2.kg^{-1} FPCM (Fat and Protein Corrected Milk)

for cattle and roughly 28 kg eq. CO^2.kg^{-1} of carcass weight and 11 kg eq. CO_2.kg^{-1} FPCM for sheep.

In the authors' view, these balances per kg of animal product are incomplete. They recommend making the assessments ”consequential”, i.e. also taking into account changes in the functioning of the ecosystem due to livestock. Adjustments such as the reduction in bush fires and termite activity can represent in some situations avoided emissions (which should be subtracted from these first balances).

Number of words in abstract: 408

Keywords: GHG Ballance - Carbone sequestration - Sylvo-Pastoral Ecosystem - Ruminants

Theme: Mitigation options

Presentation: No preference

Annexe 7. . Abstract soumis pour la conférence GGAA 2016

Impact of livestock on the spatial heterogeneity of soil CO_2, N_2O, CH_4 emissions in a sylvo-pastoral ecosystem in Western sub-Sahara Africa

M. H. Assouma[a,b], J. Vayssières[a,b], D. Serça[c], F. Guerin[c], V. Blanfort[a], P. Lecomte[a,b], I. Touré[a,b,d], A. Ickowicz[a,b], R. Manlay[e], M. Bernoux[g]

[a] CIRAD - Umr Selmet, Campus International Baillarguet, 34398 Montpellier, France

[b] Dp PPZS, ISRA-LNERV, BP 2057 Dakar Hann, Sénégal

[c] Laboratoire d'Aérologie-OMP, Université Paul Sabatier, Toulouse, France

[d] CILSS 03 BP 7049 Ouagadougou, Burkina Faso

[e] AgroParisTech - Umr Eco&Sols, 2 place Viala, SupAgro,340 60 Montpellier, France

[g] IRD - Umr Eco&Sols, 2 place Viala, SupAgro, 34060 Montpellier, France

Abstract

Pastoral ecosystems, a quarter of the earth's land surface, are known for their major contribution to global warming. Related to animal excretions, the soil and surface water emissions are important components of the GHG balance of these ecosystems but they are poorly documented in tropical environments. A typical pastoral landscape in the semi-arid zone of Senegal has been investigated. The study area (706.5 km^2 of 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 varying from 0.11 to 0.39 Tropical Livestock Unit per hectare according to the seasonal mobility of animals. 6 descriptive units were categorized (vicinity of the borehole, natural ponds, natural rangelands, forest plantations, settlements, and enclosed plots). CO_2, N_2O and CH_4 fluxes were measured with static chambers on 13 sites spread to cover the 6 units and to characterize the spatial heterogeneity of emissions. A total of 216 fluxes were measured during a whole year period (May 2014 – April 2015).

Results show a large spatial heterogeneity of the GHG emissions. CO_2 fluxes varied from 486.3±7.8 mg/m^2.day in rangelands to 161,152.9±10,813.6 mg/m^2.day in the vicinity of the borehole. N_2O fluxes varied from 0.6±0.1 mg/m^2.day in rangelands to 35.7±2.1 mg/m^2.day in the vicinity of the borehole. Apparently CH_4 fluxes varied from -3.2±0.3 mg/m^2.day in rangelands to 8,788.5±989.1 mg/m^2.day from surface water in the vicinity of the borehole.

At the whole ecosystem level, soils and surface water emit on average of 2 $MgCO_2$-eq/km^2.year. This study identified GHG emission "hot spots" in the landscape. Soil Emissions rates are significantly higher in the most animal frequented units (borehole and settlements). Emissions rates of CH_4 are significantly higher in the humid areas: the borehole all year round and the ponds during the wet season.

Key words: Greenhouse gases, Soil, Surface water, Livestock, Landscape, Senegal.

Annexe 8. Abstract soumis au congrès IRC 2016

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

M. H. Assouma[a,b,]*, J. Vayssières[a,b], P. Lecomte[a,b], P. Hiernaux[c], M. Bernoux[d], J. C. Ganglo[e], A. Ickowicz[a,b]

[a]CIRAD - Umr Selmet, Mediterranean and Tropical Livestock Systems, Montpellier, France. [b]Dp PPZS - Pastoral Systems & Dry Lands, Dakar, Senegal. [c]CNRS - Geosciences Environnement Toulouse (GET), Toulouse, France. [d]IRD - Umr Eco&Sols, Functional. Ecology&Biochemistry of soils&Agro-ecosystems Montpellier, France. [e]UAC - LFS, Laboratory of Forest Sciences, Faculty of Agricultural Sciences, Calavi, Benin. Habibou.assouma@cirad.fr ; mohabibou06@yahoo.fr

Key words: Ecosystem functioning, Animal-soil-plant interactions, Landscape, Senegal

Introduction

Extensive pastoral ecosystems, a quarter of the earth's land surface, are said to be major contributors to global warming. In sub-Saharan Africa, they 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. Pastoral landscapes are characterized by constraining climatic conditions with little precipitation falling in a limited time frame that creates high seasonal variability in forage availability. The GHG balance for these landscapes is commonly calculated at regional and yearly scales. 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. The study is original in its capacity to integrate the various components of the ecosystem (animals, soil, and plants) and to consider all components of the GHG balance at the landscape level.

Material & Methods

The studied landscape is a circular area of 15 km centred on the Widou borehole (15°59'N, 15°19'W, 706 km^2) representative of the sylvo-pastoral Ferlo Region in Sahelian zone of West Africa (North of Senegal). For this study, an original measurement protocol was implemented from May 2014 to October 2015 to estimate full GHG emissions and carbon accumulation in the studied landscape. Methane emissions from livestock enteric fermentation were evaluated 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). Nitrous oxide (N_2O) and methane (CH_4) emissions in the soil and water due to manure deposition were measured with the static chamber method proposed by Khalil et al. (1998). 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. 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. 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 sequestrated in the livestock. Supplementary data on herbaceous biomass production were also collected to better explain the dynamic functioning of the studied ecosystem. The GHG balance for the whole landscape unit was calculated by subtracting the total of carbon accumulation from the total GHG emissions.

Results & Discussion

Livestock related biomass fluxes and stocks

Total livestock in Widou area is 31560 Tropical Livestock Units (one TLU is equivalent to an animal of 250 kg live weight) with 49% of cattle, 32% of sheep and goats, 19% of donkeys and horses. The study shows that this area supports a stocking rate ranging from 0.34 to 0.21 TLU/ha depended on livestock seasonal movements. Besides water, the herbaceous layer constitutes a basic element in the functioning and survival of the pastoral systems in semi-arid regions such as our studied landscape. The peak of forage availability is observed in September with a total aboveground herbaceous biomass of 1.49 t DM/ha and a total belowground biomass of 0.22 t DM/ha. Livestock ingest daily between 2.6 and 7.1 kg DM/TLU according to seasons and herbaceous biomass availability. Between 26.4% and 37.2% of the biomass is consumed during the night. At the landscape level, only 27% of total produced biomass is ingested by the animals during one year, the rest returns to soil or is burnt during bush fires.

Temporal variability of the GHG balance at the whole ecosystem level

Fig 1 shows the monthly variations of the full GHG balance for the studied landscape. The GHG balance is positive and varies between 9,996.2 t CO_2-eq/month and 80,632.1 t CO_2-eq/month during the wet season (from July to October). However, during the two dry seasons (cold dry season from November to February and warm dry season from March to June) the GHG balance is negative and varies between -55,769.4 t CO_2-eq/month and -6,992.7 t CO_2-eq/month. At the landscape level and over one full year the full GHG balance is –0.02 t C-eq/ha. This negative value for the GHG balance indicates that the GHG emissions are compensated by total carbon accumulation in the soil, trees and animals. Negative values were also found for temperate pastoral ecosystem (Soussana et al., 2007). However this value is lower than the ones observed under temperate conditions because of lower carbon sequestration potentials in soils under semi-arid tropical conditions due to limited rainfalls and high temperatures (Kotir, 2011).

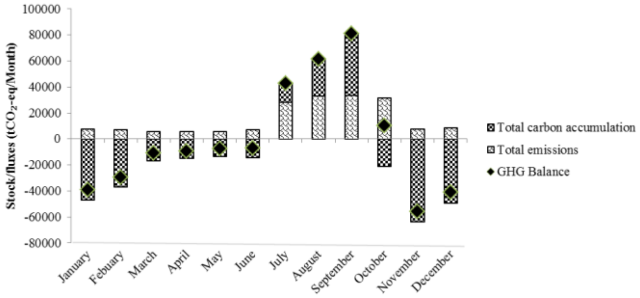

Fig 1. Temporal variability of the full GHG balance at the whole landscape level

Conclusions & Implications

This study shows a strong temporal variability of the full GHG balance in a semi-arid sylvo-pastoral region. At the whole Widou borehole coverage area level, the yearly GHG balance appears slightly negative indicating a more or less equilibrated state between the total GHG emissions and the total carbon accumulation in soils, tree and livestock. Transhumance plays a key role in this equilibrium because herders carefully adapt the livestock stocking rate to the available biomass.

Annexe 9. Photos de Widou

Vue d'en haut de la citerne recueillant et stockant l'eau au forage

Les animaux autour du Forage et sur l'aire de repos à proximité

Les animaux dans une mare juste après les premières pluies

Départ en transhumance des familles d'éleveur

Les animaux au pâturage de jour comme de nuit

Les campements peuhls.

Concentration de bouses autour des campements

Plantation forestière d'*Acacia senegal*