SOIL GREENHOUSE GAS EMISSIONS UNDER DIFFERENT LAND-USE TYPES IN SAVANNA ECOSYSTEMS OF KENYA

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Abstract

~~For effective climate change mitigation strategies, adequate data~~Field measurement data on greenhouse gas (GHG) emissions~~ from a wide range of land-use and land cover types area prerequisite. However, GHG field measurement data~~ are still scarce for many land-use types in Africa, causing a high uncertainty in GHG budgets. To address this ~~knowledge~~ gap, we present *in situ* measurements of carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) emissions in the ~~lowland part~~lowlands of southern Kenya. We conducted eight chamber ~~measurements~~ measurement campaigns on gas exchange from four dominant land-use types (LUTs) ~~and included~~including (1) cropland, (2) ~~grazed savanna, (3)~~ bushland, (3) grazing land, and (4) conservation land~~. Between~~ between 29 November 2017 to 3 November 2018, ~~eight measurement campaigns were conducted~~ accounting for regional seasonality (including wet and dry seasons and transitions periods~~) in each LUT.~~). Mean CO_2 emissions for the whole observation period were significantly higher (p-value<0.05) in the conservation land (75±6 mg CO_2-C m^{-2} h^{-1}) compared to the three other sites, which ranged from 45±4 mg CO_2-C m^{-2} h^{-1} (bushland) to 50±5 mg CO_2-~~-~~C m^{-2} h^{-1} (grazing land). Furthermore, CO_2 emissions varied between seasons, with significantly higher emissions during the wet season than the dry season. ~~In contrast, mean~~Mean N_2O emissions were ~~not different between the four sites, ranging from~~ highest in cropland (2.7±0.6 μg N_2O-N m^{-2} h^{-1}) and lowest in bushland (1.2±0.4 μg N_2O-N m^{-2} h^{-1}~~ (in bushland) to 2.7±0.6 μg N_2O-N m^{-2} h^{-1} (in cropland). However~~) but did not vary with season. In fact, N_2O

Commented [WS1]: RC1: Ln 25 – the N2O flux was more than double the cropland than bushland, why do you say is was not different between the four sites?

Commented [WS2R1]: We have corrected emissions were very low both in the wet and dry seasons, with slightly elevated values during the early days of the wet season. seasons in all LUTs. On the other hand, CH_4 emissions did not show any significant differences between LUTs and seasons, and most values . Most CH_4 fluxes were below the limit of detection (LOD, ±0.03- mg- CH_4--C- m^{-2}- h^{-1}). We attributed the difference in soil CO_2 emissions between the four sites to soil C content, which differed between the sites and was highest in the conservation land. In addition, CO_2 and N_2O emissions positively correlated towith soil moisture, thus an increase in soil moisture led to an increase in emissions. Furthermore, vegetation cover explained the seasonal variation of soil CO_2 emissions as depicted by a strong positive correlation between NDVI and CO_2 emissions, most likely because with more green (active) vegetation cover higher CO_2 emissions occur due to enhanced root respiration compared to drier periods in the year. Soil temperature did not show a clear correlation with either, most CO_2 or N_2O emissions, which is likely due to the low annual variation variability in soil temperature. We found a strong positive correlation between soil CO_2 and the normalized difference vegetation index (NDVI), but we observed no correlation with between seasons and sites. Based on our results, soil N_2O emissions. We conclude thatC, active vegetation cover and soil moisture is aare key factor indrivers of soil GHG emissions in these tropical savannaall the tested LUTs. In addition, including vegetation indices in the model greatly improved the results, thus showing the importance of vegetation cover in predicting soil emissions. South Kenya. Our results are within the range of previous GHG flux measurements from soils from various land-use typesLUTs in other parts of Kenya and contribute to more accurate baseline GHG emission estimates from Africa, which are key to reduce uncertainties in global GHG budgets as well as for informing policymakers when discussing low-emission development strategies.

Commented [WS3]: Rephrased based on reviewer one on What is the take home point?

KEYWORDS: Carbon Dioxide, Nitrous Oxide, Methane, Bushland, Conservation, Grazing land, Cropland.

1. Introduction

Soil is a major source, and in many cases also a sink, of the atmospheric greenhouse gases (GHG) carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) (Oertel et al., 2016). The concentrations of these gases have increased since the onset of industrialization in 1970, leading to global warming (IPCC, 2013). GHGs trap the long-wave radiation emitted by the Earth's surface, thus increasing surface temperatures (Arrhenius, 1896). Soil CO_2 emissions originate from root respiration and heterotrophic decomposition of soil organic matter (Oertel et al. 2016). N_2O can be produced from many pathways in the soil nitrogen (N) cycle, but is considered to result primarily from nitrification and denitrification (Butterbach-Bahl et al. 2013). CH_4 is produced by methanogenesis under anaerobic conditions and consumed by methanotrophic microorganisms under aerobic conditions, with the latter being more important in well-aerated upland soils, which consequently show net CH_4 uptake (i.e. negative flux) (Serrano-silva et al. 2014; Hanson and Hanson 1996). The production and consumption of soil GHGs largely depends on soil physical and chemical properties (Davidson et al., 2006) (e.g. texture, soil organic matter and pH) and are further driven by environmental factors such as soil moisture and soil temperature (Davidson et al., 2006). Thus, soil GHG emissions and uptake along with their controlling factors differ between biomes based on the land use and land-use management.

Land-use changes are reportedly the largest source of anthropogenic GHG emissions in Africa (Valentini et al., 2014). However, *in situ* studies on GHG emissions from various ecosystems in remain scarce, particularly from savanna ecosystems (Castaldi et al., 2006). Savanna is an important land cover type in Africa, covering more than 40 % of its total area (Scholes et al., 1997). In Kenya, savanna and grassland ecosystems cover about 80 % of the total area, comprising various land-use types (LUTs) (GoK, 2013). These ecosystems are subject to accelerating land-use change (Grace et al., 2006) due to population growth (Meyer and Turner, 1992) and land-use management activities (Valentini et al., 2014). Conversion of savanna for small- and large-scale livestock production, crop cultivation, and human settlement is common in Africa (Bombelli et al., 2009). As a consequence, vegetation cover, net primary productivity, allocation of carbon and nutrients in plants and soil (Burke et al., 1998) as well as soil GHG emissions are affected (Abdalla et al., 2018; Carbone et al., 2008).

Overgrazing due to overstocking is a major cause of soil and vegetation degradation in large parts of African savannas (Patton et al., 2007; Abdalla et al., 2018). Factors associated with grazing include animal feeding preferences of certain plant species, thus creating higher pressure for certain species, which decline in numbers over time, leading to species loss and lower pasture nutritive value (Patton et al. 2007). In addition, soil trampling increases soil bulk density and decreases soil water infiltration (Patton et al., 2007). Furthermore, high rates of dung and urine deposition, especially around homesteads and waterholes, create high N concentrations that are toxic for many savanna grass species, affecting vegetation cover and composition (e.g. increase of encroaching species such as *Solanum incanum* L., which is toxic for livestock (van Vegten 1984)). Given that all these factors affect soil properties, soil GHG emissions are most likely similarly affected (Wilsey et al., 2002).

In addition to overgrazing, rapid human population growth leads to more people migrating into savanna ecosystems, which has led to the expansion of cropland (Pellikka et al., 2018; Patton et al.,

Commented [WS4]: RC 1: The introductory paragraph never says what produces and consumes GHGs from the soil?

Commented [WS5R4]: We have included in the introductory

Commented [WS6]: Rephrased

Commented [WS7]: RC: Ln 65. Not all savannah belongs to the ASALs. The humid savannas are relatively wet, with green vegetation almost throughout the year. It is therefore not right to make such a sweeping statement.
AC: *We revised to drylands instead of ASALs.*

Commented [WS8]: RC 2: Ln 88. Revise the sentence. Overstocking leads to grazing pressure. The way the sentence is written is redundant.

Commented [WS9R8]: Done

Commented [WS10]: Rephrased based on RC2

2007). Brink and Eva (2009) found that the area under cropland increased by 57 % between 1975 and 2000 in Africa. In the Horn of Africa, cropland areas increased by 28 % between 1990 and 2010 (Brink et al., 2014), while wooded vegetation in East Africa decreased by 5 % in forests, 16 % in woodlands, and 19 % in shrublands (Pfeifer et al., 2013). As an additional example, in our study area Taita Taveta County in Southern Kenya, the area under cropland increased from 30 % in 1987 to 43 % in 2011 (Pellikka et al., 2018). However, in the Taita Hills, located in the County, this trend has slowed down in recent years, while the savanna lowlands are still being cleared to make way for new cropland (Pellikka et al., 2013).

Commented [WS11]: RC2: Ln 96-7. ---Croplands are still being cleared from natural vegetation----re-write the sentence, it's not making the intended meaning.
AC: *Done. Revised --Natural vegetation is being cleared to make way for the expansion of cropland*

Croplands in the Kenyan savannas are mostly managed by smallholder farmers with small land sizes (Waswa and Mburu, 2006). Due to high poverty levels in this region, inputs to improve crop yields, such as the use of fertilizer and herbicide, and mechanized farming are minor (Waswa and Mburu, 2006; CIDP, 2014). Consequently, increase in productivity are mostly generated via cropland expansion. These smallholder farms are likely to have substantial effects on national GHG emission budgets (Pelster et al., 2017). Until now, only a few studies have investigated soil GHG emissions from such agricultural landscapes (Rosenstock et al., 2016), and these studies were mostly carried out in high-potential farming areas such as the Kenyan highlands, which receive >1000 mm rainfall (FAO, 1996). For example, Rosenstock et al. (2016) showed a large variation of CO_2 and N_2O emissions both within and between four crop types as affected by environmental conditions and land management. However, studies measuring GHG emissions from low-productivity croplands in southern Kenya are to the best of our knowledge still missing. Thus, this study focused on soil GHG emissions from different LUTs relevant for the semi-arid region of Southern Kenya.

Given the vast area covered by savanna, land use and land-cover changes are likely to affect global, regional, and national C and N cycles, and hence the quantification of their role is vital (Lal, 2004; Williams et al., 2007). Studies in Kenya have shown large variations of soil GHG emissions in various savanna ecosystems (Otieno et al., 2010; Oduor et al., 2018), due to land-use (Ondier et al., 2019) and management activities (K'Otuto et al. 2013). Due to the high diversity of these savanna ecosystems, such studies may not be entirely representative for every region (Ardö et al., 2008).

The lack of reliable soil GHG flux data from natural savanna and cropland limits our understanding of GHG emissions from African soils (Hickman et al., 2014; Valentini et al., 2014). At the same time, accurate quantification of GHG emissions from multiple LUTs are essential to allow for reliable estimation of Kenya's national GHG inventory (IPCC, 2019). This is particularly important as Kenya currently relies on a Tier-1 approach by using default emission factors (EFs) provided in the

Guidelines for Greenhouse Gas Inventories of the UN Intergovernmental Panel on Climate Change (IPCC) to estimate national GHG emission budgets. Following the Paris Climate Agreement (https://unfccc.int/process-and-meetings/the-paris-agreement/d2hhdC1pcy), most countries across the globe, including Kenya, have not only agreed to accurately report their GHG emissions at national scales following a Tier-2 approach (i.e. using localized data) but also to mitigate anthropogenic GHG emissions in the upcoming decades, as is communicated via their Nationally Determined Contributions (NDCs). Both can only be achieved with locally derived data.

To address the lack of localized GHG emission data from different LUTs in Kenya, our study aims at: (1) providing crucial baseline data on soil GHG emissions from four dominant land uses, namely conservation land, grazing land, bushland, and cropland, and (2) investigating abiotic and biotic drivers of GHG emissions during different seasons. We hypothesized that GHG emissions in cropland ~~will~~would be higher compared to grazing land, bushland, and conservation land because of larger nutrient inputs (i.e. fertilization) in managed land. Further, we hypothesized that GHG emissions ~~will~~would differ between seasons; more precisely, we expected higher GHG emissions in the wet season than in the dry season ~~because of~~caused by higher soil moisture.

2. Materials and Methods

2.1. Study ~~area~~Area

This study was conducted in the lowlands (800–1000 m a.s.l.) of Taita Taveta County~~, southern Kenya (Fig. 1), between~~ (latitude 3° 25´ S and longitude 38° 20´ E~~.~~) located in southern Kenya (Fig. 1). Taita Taveta County is one of Kenya's ~~ASAL regions~~dryland areas, with 89 % of the ~~county~~ area characterized ~~by~~as arid and semi-arid ~~and arid conditions~~area. The county is divided into three major geographical regions, namely the mountainous zone of the Taita Hills (Dawida, Kasigau, Sagalla), Taita lowlands, and the foot slopes of Mt. Kilimanjaro around Taveta.

In the lowlands, ~~which is our study site,~~ vegetation types include woodlands, bushlands, grasslands, and riverine forests/swamps. Tsavo East and Tsavo West National Parks ~~cover~~covers ca. 62 % of the county area ~~for wildlife conservation~~ (CIDP, 2014). The parks are open savanna and ~~bush woodland~~bushland that support ~~elephants, buffaloes, lions, antelopes, gazelles, giraffes, zebras, rhinoceroses,~~large herbivores, predators and a wealth of birdlife. There are 28 ranches designated for livestock production and two wildlife sanctuaries (Taita Hills Wildlife Sanctuary and LUMO Community Wildlife Sanctuary). ~~Livestock in the region is mainly managed in the form of nomadic~~

Commented [WS12]: *We harmonize this in the revised manuscript to bushlands as found in Tsavo East and West national park*

Commented [WS13]: Rephrased

pastoralism and only limited ranching occurs (CIDP, 2014). Other important land use includes croplands with dryland agriculture in small-scale farming operations with low farm inputs (CIDP, 2014), dry thickets and shrublands, and sisal farming (Pellikka et al., 2018). The main soilOther important land uses include cropland under small-scale farming (CIDP, 2014), shrublands, and sisal farming (Pellikka et al., 2018). Soil type is characterized by dark red, very deep, acid sandy clay soil (Ferralsols). Our study sites were located in four of these key land uses in the region, namely including cropland, bushland, wildlife conservation land, and grazing land.

The lowland area has a bimodal rainfall pattern with two rainy seasons – a long rainy period between March and May and a short rainy period between October and December (CIDP, 2014). The hottest and driest months are January and February, while the dry season from June to October is cooler (Pellikka et al., 2018). Mean annual rainfall is 500 mm and the average annual air temperature is 23 °C, with an average daily minimum temperature of 16.7 °C and a maximum temperature of 28.8 °C (CIDP, 2014).

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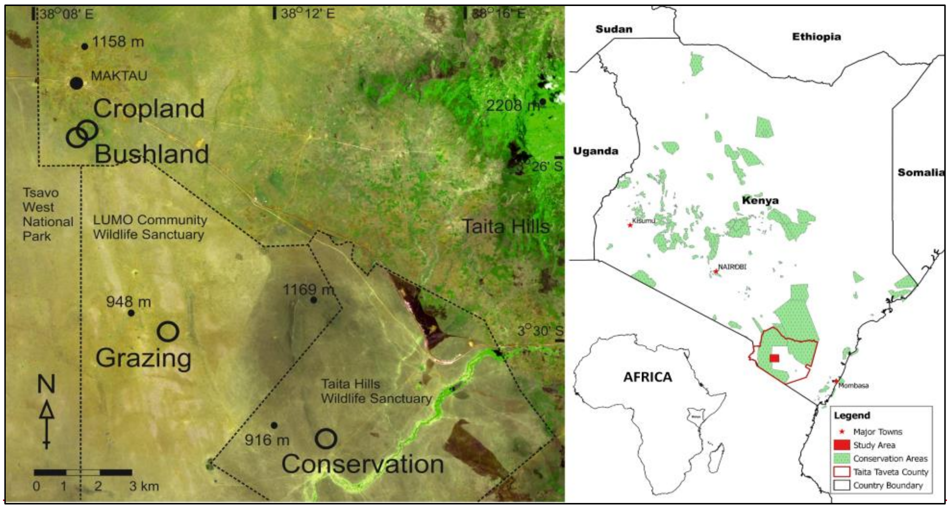
The first site isinvestigated is a cropland located in Maktau (1070 m a.s.l.,., Fig. 1). The farm measured approximately1, Fig. 2a) with a size of about one and a half hectares, cultivated with maize (Zea mays L.) intercropped with beans as the main crops.. The farm can be considered as a typical rain-fed smallholder agriculture. Cropfarm and crop growing closely follows the rainy seasons, with maize and beans sowedsowing in March, and bean and maize harvesting occurring in June for beans and August, respectively. Other crops on the farm included cowpeas, pigeon peas, cassava, and sweet potatoes. Land preparation was performed by for maize. Animal ploughing using animal tractionis done to prepare land before seeding, while and weeding was performed is by hand hoehoeing. Small quantities of fresh and dry manure (roughly 20 kg, accounting for less than 1 kg of N) were used every month to improve soil fertility by applying approximately 20 kg of mixed dry and fresh animal manure (less than 1 kg of N) every month during the campaign period (Fig. 2a). .

Commented [WS14]: Corrected

Commented [WS15]: SC: l. 171: Height a.s.l. is only given for the cropland site and should be given as well for the other sites.
AC: *This is done in the revised manuscript for all the sites*



~~***Figure 1.** Location of the study sites cropland, bushland, grazing land, and conservation land in the savanna area in the lowlands of Taita Taveta County in southern Kenya.*~~

The second site is located in a private bushland in Maktau next to the cropland (1076 m a.s.l., Fig. 1, Fig.~~ 2c~~ 2b). In ~~Taita Taveta~~this region, bushland is found both within the conservation areas and under private ownership. ~~In this region, bushland~~Bushland forms a cover with over 50 % of thorny shrubs and small trees, characterized by *Acacia spp* and *Commiphora* ~~*ssp*~~*spp*. The bushes may vary in height ranging from two to five metres. Herbs and savanna grasses (mostly annual or short-lived perennials) less than one~~-~~ metre tall form the ground cover. ~~On private~~Private bushland similar to our study site~~, individual~~ is used by the farmers ~~usually maintain woodlots of trees and shrubs as part of their farms, where they~~to generate~~ a~~ small income from forest products such as timber, poles, and firewood, and charcoal to some extent. Additionally, some grazing occurs ~~on the bushland,~~ primarily by livestock owned by the farmer (CIDP, 2014).

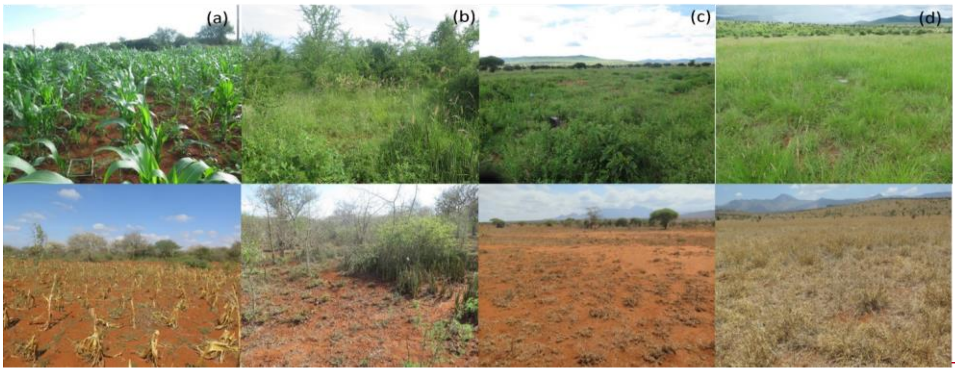
Commented [WS16]: **RC1:** Ln 187 – ssp
AC: *Corrected to spp*

The third site, grazing land (covering approximately 460 km^2) is located in the LUMO Community Wildlife Sanctuary (970 m a.s.l, Fig.~~ ~~ 1, Fig. 2c) next to Tsavo West National Park and Taita Hills Wildlife Sanctuary~~ and covering approximately 460 **km^2**.~~. The sanctuary was formed by merging three ranches, namely ~~the~~ Lualenyi and Mramba communal grazing areas and ~~the~~ Oza group ranch~~, which were given~~ thus the name "LUMO".~~ ~~ This sanctuary is communally owned (GoK, 2013) designated for community livestock grazing~~ by local communities, with~~, where wildlife is also present, as conservation areas are not necessarily fenced. ~~No individual land ownership occurs, as the land is communally owned (GoK, 2013). Overgrazing~~However, overgrazing is a major challenge,

~~especially~~caused by herders who enter the conservancy illegally~~, leaving the soil bare for most of the year but~~ especially ~~during~~in the dry season ~~(CIDP, 2014). During this time, livestock~~(CIDP, 2014).

The forth site is ~~forced from LUMO into the Taita Hills Sanctuary~~ the conservation land ~~because of the open boundary it shares with LUMO (Fig. 2d).~~

~~The conservation land is~~ located within the Taita Hills Wildlife Sanctuary (928 m a.s.l., Fig.~~ 1).~~ ~~**Covering**~~ 1, Fig. 2d) covering an area of ca. 110 km^2 ~~**hectares, it**~~. This is a private game sanctuary for wildlife conservation located between LUMO and communal land. The sanctuary is an open savanna grassland dominated by *Schmidtia bulbosa* and *Cenchrus ciliaris* grass species forming an open to closed ground cover, ~~scrublands~~shrublands, and scattered woodlands with *Acacia spp.* as main tree species. However, most trees have been damaged by elephants, leaving the landscape ~~more~~ open. The sanctuary is well managed with the application of ecological management tools such as controlled fires. Through these and other conservation efforts, the sanctuary has attracted a higher diversity of large mammals, many of which remain within the unfenced sanctuary throughout the year. Wildlife are the predominant grazers and browsers, although livestock encroachment may be a problem especially during the dry season on the western and eastern borders of the sanctuary ~~(GoK, 2013) (Fig. 2c).~~(GoK, 2013).



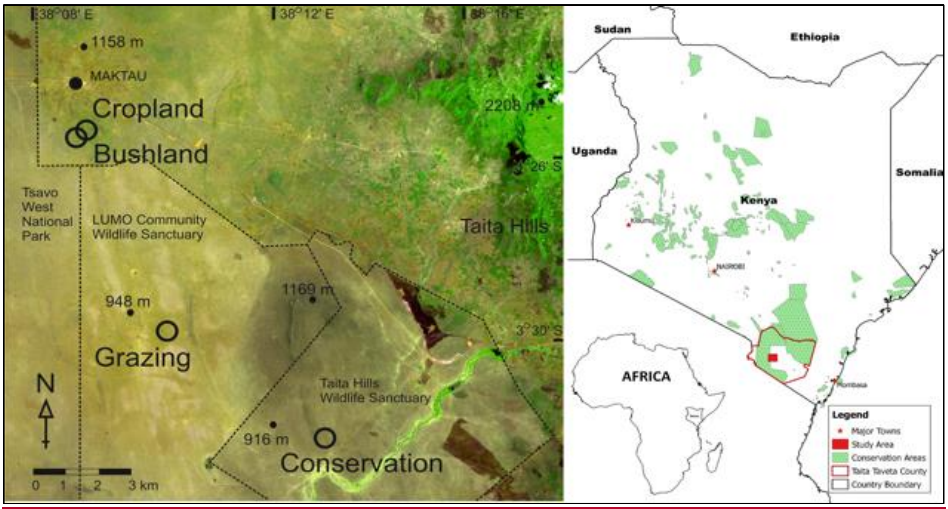


Figure 1. *Location of the study sites cropland, bushland, grazing land, and conservation land in the savanna area in the lowlands of Taita Taveta County in southern Kenya.*

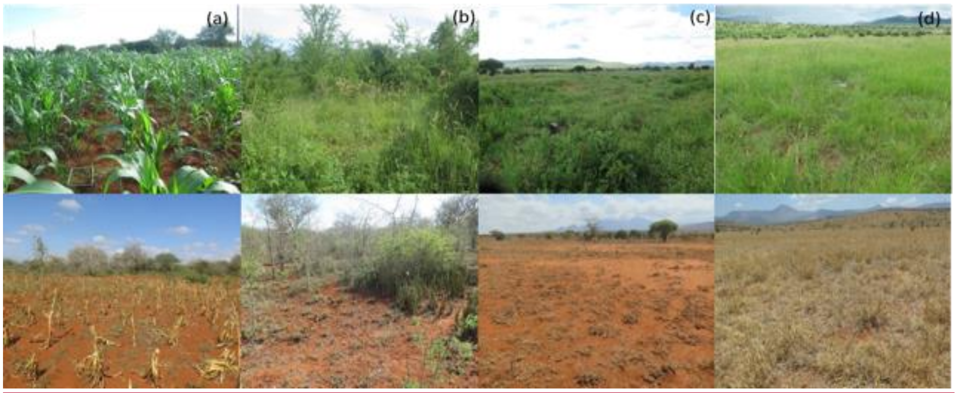


Figure 2: *The four land-use types: (a) cropland, (b) bushland, (c) grazing land, and (d) conservation land. The upper panel shows the land-use types during the wet season, while the ~~the~~ lower panel depicts the situation during the dry season. The grey plastic collars visible in upper left photo are frames for the GHG flux chambers.*

2.2. Defining the ~~Seasons~~seasons

We divided ~~the~~our campaigns into dry and wet seasons, based on ~~an~~the agro-climatic concept. ~~Therefore, the~~The onset ~~date~~ of the wet season was the first wet day of a 3-day wet spell receiving at least 20 mm without any 10-day dry spell (< 1 mm) in the ~~following~~next 20 days from ~~1st of~~1 March for the long wet season and 1st of1 September for the short wet season (Marteau et al., 2011)(Marteau et al., 2011). Equally, the end of the rainy season was the first of 10 consecutive days during whichwith no rain occurred. Thus, for this study, the long wet season (LW) was between 2 March to 4 June 2018, and the short wet season (SW) between 23 October and 26 December 2018. The two wet seasons were separated by two dry seasons, the short dry season (SD) from January to February 2018, and the long dry season (LD) from June to September 2018. We had three campaigns duringin each of the wet season: during the early days of the wet seasonseasons onset (onset-SW, onset-LW), at the peak of the of the seasons (mid-SW, mid-LW), and towardsas well as at the end of the seasons (end-SW, midend-LW).

2.3. Chamber measurements of greenhouse gas emission

Soil-atmosphere exchange of CO_2, N_2O, and CH_4 were measured in eight one-week campaigns between 29 November 2017 to 3 November 2018 using the static chamber method (Rochette, 2011; Hutchinson et al., 1981). Within each of the four sites, three locations (clusters) were randomly selected and used as replicates for soil GHG concentration measurements. In each cluster, three plastic collars (27 cm × 37.2 cm × 10 cm) were inserted (5–8 cm) into the soil at least 24 hours before the first sample was taken (see Pelster et al., 2017). The collars were left in the ground for the entire measurement period to minimize soil disturbance before the time of measurements (Søe et al., 2004). Only damaged or missing chamber bases (mostly due to livestock or wildlife activity) were replaced, at least 24 hours before the next gas sampling. During each day of a campaign, gas sampling was conducted daily between 7:00 am and 11:00 am, which represent the average flux of the diurnal cycle (Shi et al., 2012; Davidson et al., 1998).

During each gas-sampling day, grey opaque PVC lids (27 cm × 37.2 cm × 12 cm) covered with reflective tape were placed onto the collars for 30 mins. Lids were fitted with a fan for gas mixing and a vent to avoid pressure differences between the chamber headspace and outside atmosphere during gas sampling (Pelster et al.. 2017). A rubber seal was fitted along the edges of the chamber lid and paper clips were used to hold the lid and collar in place to ensure airtightness. Four gas samples were then collected every 10 minutes (time 0, 10, 20, 30 minutes) after lid deployment (Rochette, 2011). The height of each chamber collar was measured on each sampling date to derive the total chamber volume (total chamber height = height of chamber collar sticking out of the soil + height of the chamber lid). A slightly modified version of the gas-pooling method was used to reduce overall sample size while ensuring a good spatial representation of each LUT (see Arias-Navarro et al., 2013). Here, 20 ml of headspace air were collected from each of the three chambers at each time interval with polypropylene syringes (60 ml capacity), resulting in a composite gas sample of 60 ml. The first 40 ml were used to flush the vials, and the remaining 20 ml were pushed into 10 ml glass vials, leading to a slight overpressure to minimize contamination of the gas with ambient air during transportation (Rochette et al., 2003).

Following sample collection, gasSoil-atmosphere exchange of CO_2, N_2O, and CH_4 were measured in eight one-week campaigns from 29 November 2017 to 3 November 2018 using the static chamber method (Rochette, 2011; Hutchinson et al., 1981). Within each of the four sites (LUTs), three clusters were randomly selected as replicates for soil GHG concentration measurements. In each cluster, three plastic collars (27 cm × 37.2 cm × 10 cm) were inserted (5–8 cm) into the soil at least 24 hours before the first sample was taken (see Pelster et al., 2017 for further details). The collars were left in the ground for the entire measurement period to minimize soil disturbance during measurements (Søe et al., 2004). Any damaged or missing collars (mostly due to livestock or wildlife activity) were replaced, at least 24 hours before the next gas sampling. During each day of a campaign, gas sampling was conducted daily between 7:00 and 11:00 am, which is about the average flux of the diurnal cycle (Parkin and Venterea, 2010).

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Gas samples were transported to the laboratory (Mazingira Centre, mazingira.ilri.org) and analysed using a gas chromatograph (GC, model SRI 8610C gas chromatograph).). The GC was fitted with a ^{63}Ni-Electron Capture Detector (ECD) for detecting N_2O concentrations and a Flame Ionization

Detector (FID) fitted with a methanizer for CH_4 and CO_2 analysis. The GC was operated with a Hayesep D packed column (3 m, 1/8″) at an oven temperature of 70 °C, while ECD and FID detectors were operated at a temperature of 350 °C. Carrier gas (N_2) flow rate was 25 mL min^{-1} on both FID and ECD lines. In every 40 samples analysed with the GC were eight calibration gases with known CO_2, CH_4, and N_2O concentrations in synthetic air (levels of calibration gases ranged from 400 to 2420 ppm for CO_2, 360 to 2530 ppb for N_2O, and 4.28 to 49.80 ppm for CH_4). Therefore, the gas concentrations of the samples were calculated from peak areas of samples in relation to peak areas of standard gases ~~with known concentrations~~ using a linear model for CO_2 and CH_4 and a power regression for N_2O.

2.4. Greenhouse gas flux calculations

Soil GHG emissions were determined by the rate of change in gas concentration in the chamber headspace over time by linear fitting. The goodness of fit was used to evaluate the linearity of concentration increases/decreases. The dynamics of the CO_2 concentrations over the 30 min deployment period for each gas concentration was assessed to test for chamber leakage due to the typically more robust and continuous flux of CO_2 ~~(Collier et al., 2014).~~(Collier et al., 2014). If the linear model of CO_2 versus deployment time had an R^2 ~~>~~ $>$ 0.95 using all four-time points (T1, T2, T3, and T4), the measurement was considered valid and four-time points were used for analysing the CO_2, N_2O, and CH_4 emissions. However, if R^2 ~~<~~ $<$ 0.95 for CO_2 and one data point was a clear outlier, this point was discarded and the three remaining points used for the flux calculation if they showed a strong correlation of CO_2 versus time. Measurements that did not show a clear trend of CO_2 with time were considered faulty, and the entire data point series was discarded. In addition, data points that showed a decrease in CO_2 concentration over time were assumed to indicate leakage and were ~~thus~~similarly discarded (chambers were opaque, i.e. photosynthesis was inactive during chamber deployment). However, if no leakage was found, negative CH_4 and N_2O emissions were accepted as the uptake of the respective gas by the soil. Emissions were calculated according to Eq. (1):

$$F_{GHG} = \frac{(\frac{dc}{dt}) \times V_{ch} \times M_w}{A_{ch} \times Mv_{corr}} 60 \times 10^6, \quad (1)$$

~~where F_{GHG} = soil GHG flux (CO_2, N_2O, or CH_4), ∂c/∂t = change in chamber headspace gas concentration over time (i.e. slope of the linear regression), V_{ch} = volume of the chamber headspace (m^3), M_w = molar weight (g mol^{-1}) of C for CO_2 and CH_4 (12) or N for N_2O (2x N = 28), A_{ch} = area covered by the chamber (m^2) and Mv_{corr} = pressure- and temperature-corrected molar volume~~

(Brümmer et al., 2008) using Eq. (2). With 60 and 10^6 being constants used to convert minutes into hours and microgramme respectively.

Mv_{corr} =Where F_{GHG} = soil GHG flux (CO_2, N_2O, or CH_4), $\partial c/\partial t$ = change in chamber headspace gas concentration over time (i.e. slope of the linear regression), V_{ch} = volume of the chamber headspace (m^3), M_w = molar weight (g mol^{-1}) of C for CO_2 and CH_4 (12) or N for N_2O (2x N = 28), A_{ch} = area covered by the chamber (m^2) and Mv_{corr} = pressure- and temperature-corrected molar volume (Brümmer et al., 2008) using Eq. (2). With 60 and 10^6 being, constants used to convert minutes into hours and micrograms respectively. Temperature in Eq. (2) represent air temperature in the chamber headspace measured during each sampling.

$$Mv_{corr} = 0.02241 \, \frac{273.15 + Temp(℃)}{273.15} \times \frac{Atmospheric\ pressure\ at\ measurement\ (Pa)}{Atmospheric\ pressure\ at\ sea\ level\ (Pa)} \qquad (2)$$

The minimum limit of detection (LOD) for each gas was calculated following Parkin et al. (2012)Parkin et al. (2012) and levels were ± 4.9 mg CO_2-C m^{-2} h^{-1} for CO_2, ± 0.04 µg µg N_2O-N m^{-2} h^{-1} for N_2O, and ± 0.03 mg CH_4-C m^{-2} h^{-1} for CH_4. However, we included all data in the analysis, including those below LOD in line with Croghan and Egeghy (2003), who noted that including such data provides an insight on the distinct measurements, thus giving clarifying the set of environmental observations.

Field Code Changed

2.5. Auxiliary measurements

During each gas-sampling day, we measured soil moisturewater content (WC) and soil temperature (T) (at a depth of 0–5 cm) adjacent to the collar using a ProCheck handheld data logger with a GS3 sensor (Decagon DevicesProCheck METER Group, Inc. USA). Daily air temperature and precipitation data from November 2017 to November 2018 were obtained from a weather station in Maktau located within the cropland site (Tuure et al., 2019).(Tuure et al., 2019). A soil auger was used to collect soil samples (at a depth of 0–20 cm) during the wet season (22 May 2018) fromin each land-use typesite for soil chemical and physical property analysis. For bulk density, we collected a combination of three samples from each cluster close to each chamber collar at depths of 0–10 cm and 10–20 cm using a soil bulk density ring (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands). Samples were stored in airtight polyethylene bags and kept in a cooler box with ice packs before transportation to the laboratory for further analysis. In the laboratory, samples were stored in a refridgeratorrefrigerator (4 °C) and analysed within 10 days.

The samples were sieved at < 2 mm before analysis. Soil water content was measured by drying soil at 105- °C for 48- h. Soil pH was determined in a 1:2.5 (soil: : distilled water) suspension using an electrode pH meter (3540 pH and conductivity Meter, Bibby scientificScientific Ltd, UK). We measured) and soil texture using the hydrometer technique (Scrimgeour, 2008; Reeuwijk, 2002).(Scrimgeour, 2008; Reeuwijk, 2002). Total soil C and N content were analysed using a C/N elemental analyser as follows. A, a duplicate of 20 g of fresh sample was oven-dried at 40 °C for 48 hours and ground into a fine powder using a ball mill (Retsch MM400). Approximately 200 mg of the dry sample waswere measured by elemental analysis (Vario MAX Cube Analyzer Version 05.03.2013).

2.6. Statistical Analysis

All statisticalStatistical analyses were carried out using R Statistical Software (R 3.5.2 (, R Core Team). Spearman correlation coefficients were performed among the variables followed by the Kruskal Wallis test to assess- significant differences- of soil GHG emissions between the land use typesLUTs and across seasons. A post-hoc analysis involving pairwise comparisons using the Nemenyi test was performed for gases where significant differences existexisted. Significance level was set at $p < 0.05$.

We used several functions to assessassessed the correlation between soil GHG (CO_2 and N_2O) with soil temperature and soil water content emissions with T and WC using several functions based on the coefficient of determination (R^2), root-mean-square error (RMSE) and Akaike's information criterion (AIC). There being no difference in the outputs, we present results from the Gaussian function (O'Connell, 1990)(O'Connell, 1990) for the correlation between soil GHG (CO_2 and N_2O) emissions and soil temperatureT using Eq. (3), and a quadratic function for correlation with soil water contentWC using Eq. (4). We also evaluated the combined effect of T and WC on soil GHG emissions by combining Eq. (3) and Eq. (4) into Eq. (5) to assess the effect of these two variables on the emissions.

$$Rs = ae^{(bT+cT^2)} \quad (3)$$

$$Rs = a + bWC + cWC^2 \quad (4)$$

We also evaluated the combined effect of soil temperature (*T*) and soil water content (*WC*) on soil GHG (CO_2 and N_2O) using several functions. Having also found no significant difference in the

~~function result outputs, we combined Eq. (3) and Eq. (4) into Eq. (5) to assess the combined effect of these two predictors on soil emissions.~~

$$Rs = e^{(aT+bT^2)} \times (cWC + dWC^2) \quad (5)$$

Where *Rs* is soil GHG (CO_2 and N_2O) emissions, *T* is soil temperature (°C), and *WC* is soil water content ($m^3\ m^{-3}$), while *a*, *b*, *c*, and *d* represent the model coefficients.

After no correlation with ~~soil water content and soil temperature was~~T and a weak correlation with WC were observed, we included ~~information on~~ vegetation cover~~ as a predictor. We~~. For this, we used Normalized Difference Vegetation Index (NDVI) ~~products (MOD13Q1)~~ from ~~MODIS~~ ~~(~~Moderate Resolution Imaging Spectroradiometer (MODIS) from~~-~~ https://ladsweb.modaps.eosdis.nasa.gov. NDVI quantifies vegetation vigour by measuring the difference between reflectance in near~~-~~ infrared (which green chlorophyll-rich vegetation strongly reflects) and red wavelength areas (which vegetation absorbs) computed using Eq. ~~(6):~~(6). MOD13Q1 products from MODIS are NDVI data generated from a 16-day interval at a 250 m spatial resolution as a Level 3 product (Didan, K, 2015).

$$NDVI = \frac{NIR+Red}{NIR+Red} \quad (6)$$

~~MODIS NDVI is generated from a 16 day interval at a 250 m spatial resolution as a Level 3 product.~~ To cover our study period, we selected NDVI data ~~that were~~ within the ~~dates of~~ campaign~~. However, if~~ dates. If no~~ NDVI~~ data fitted within our dates, we used data that were~~ from~~ less than five days before or after the campaign dates, assuming that no significant increase or decrease would occur in the vegetation. The pixels containing the study sites were extracted based on the latitude and longitude of each site. ~~When comparing various functions, linear~~Linear functions were applied to the seasonal datasets of ~~soil GHG emissions~~Rs with NDVI to assess the contribution of vegetation ~~indices~~on soil emissions using Eq. (7) and a combined effect of WC and NDVI on soil ~~GHG~~CO_2 emissions (Rs) using Eq. (~~7): ~~8).

$$Rs = a + bNDVI \quad (7)$$

~~We also assessed the combined effect of WC and NDVI on soil CO_2 emissions using Eq. (8).~~

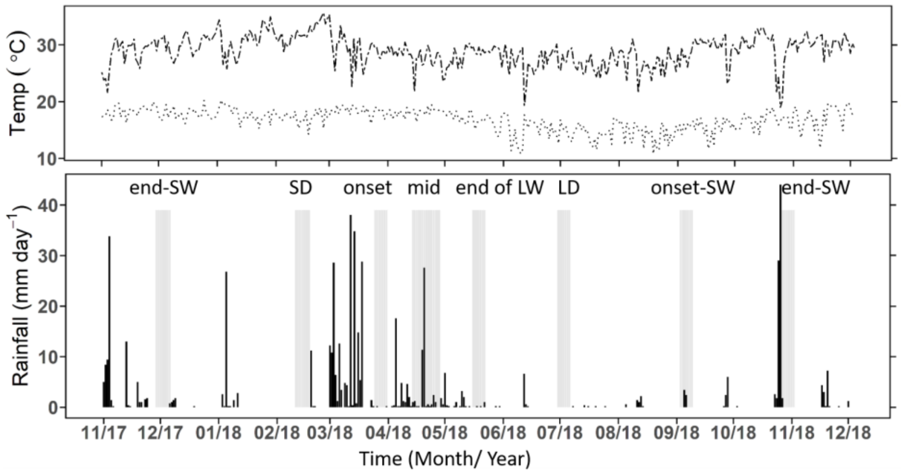
$$Rs = a + bNDVI + (cWC + dWC^2) \quad (8)$$

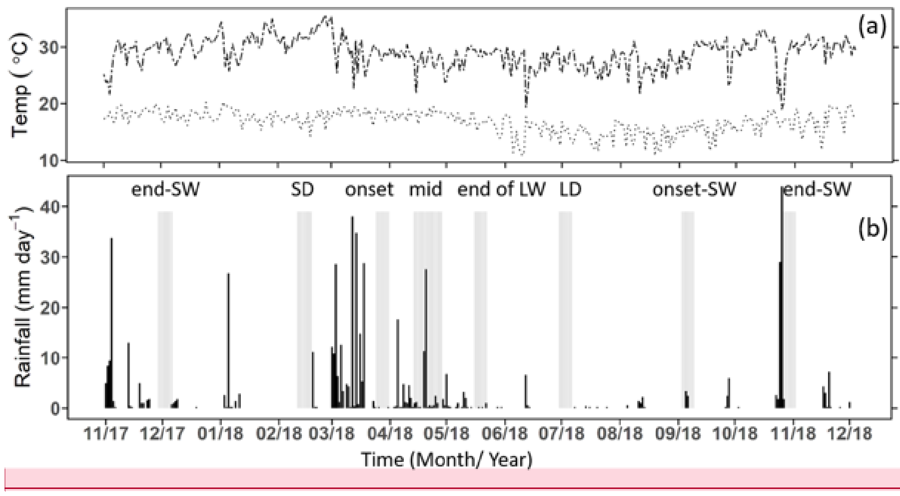
~~where *Rs* is soil GHG (CO_2 and N_2O), *T* is soil temperature, and *WC* soil volumetric water content (m^3 m^{-3}) while *a, b, c,* and *d* are model coefficients.~~

3. Results

3.2. Meteorological data

During the 12~~-~~-month study period, the long ~~rainy periods were observed~~rains lasted from early March to the end of May, while short ~~rainy periods were observed~~rains occurred between early September and ~~October~~December (Fig. 3). The total annual rainfall was 550 mm, which ~~was~~is within the average rainfall ~~quantity~~ expected in the area (CIDP, 2014). ~~Mean~~The mean annual air temperature was 22.7 °C (min=16.7 °C, max=30.5 °C). January was the hottest month (min=17.4 °C, max=31.9 °C), while June and July (min=14.5± 0.2 °C, max=27± 0.1 °C) were the coolest.





Commented [WS17]: RC: Label Fig. 3 as a and b
AC: *Done*

Figure 3: *(a) Daily maximum and minimum air temperature and (b) daily rainfall from lowland in southern Kenya between November 2017 to October 2018 recorded at Maktau weather station. Total annual recorded rainfall was 550 mm. Highlighted grey bars show the days of the sampling campaigns (the season above the grey bars denote SW and LW for the short and long wet season with corresponding onset, mid and end of the wet season, and SD for the short dry season and LD for the long dry season).*

3.3. Soil characteristics

~~Sand was the main component of the soils atall sites (Table 2).~~ Sand content was ~~slightly higher~~highest in cropland (77±8 %) compared to the conservation ~~area~~land and bushland (ca. 72±1 ~~%).Sand proportion was lower in the~~ %) and lowest in grazing land (64.3 ±0.4 ~~%), while~~ %) (See Table 2). Grazing land had the highest clay content ~~was higher~~ (31.7±0.5 ~~%) than in the conservation area (26 ± 2 %), bushland (23.7±0.7 %), and~~ %) while cropland (19±2 ~~%).~~ %) had the lowest. Soil pH ranged between slightly acidic in the grazing land (6.3 ± 0.3), neutral in the bushland (7.2±0.4), and slightly alkaline in the conservation ~~area~~land and cropland (7.5±0.1 and 7.9±0.2 respectively). Carbon content ranged from 0.93 % in the conservation land to 0.60 % in the cropland. Nitrogen content did not vary significantly between sites (mean=0.08±0.01 %).

Commented [WS18]: Rephrased based on RC2

Table 1: Soil characteristics of the topsoil (a depth of 0–20 cm) from the four land-use types investigated in this study. Values are given as mean ± SE.

Land Use	% N	% C	Bulk Density (g cm^{-3})	pH	Soil Texture % Clay	% Sand	% Silt
Bushland	0.08 (0.03)	0.77 (0.5)	1.31 (0.2)	7.2 (0.4)	23.7 (0.7)	71.6 (2.2)	4.7 (2.3)
Conservation land	0.09 (0.02)	0.93 (0.7)	1.27 (0.4)	7.5 (0.1)	26.4 (2.2)	71.6 (0.5)	2.0 (0.0)
Cropland	0.07 (0.04)	0.60 (0.2)	1.26 (0.3)	7.9 (0.2)	19.1 (2.4)	76.9 (8.1)	4.0 (5.1)
Grazing land	0.08 (0.02)	0.83 (0.4)	1.23 (0.5)	6.3 (0.3)	31.7 (0.5)	64.3 (0.4)	4.4 (0.4)

3.4. Soil greenhouse gas emissions

3.4.1. Soil carbon dioxide (CO_2) emissions

Mean annual soil CO_2 emissions were ~~significantly higher~~highest in the conservation land (75±6 mg CO_2-C m^{-2} h^{-1}~~) compared to the other three sites.~~). Concurrently, no significant differences occurred ~~in CO_2 emissions~~ between grazing land (50±5 mg CO_2-C m^{-2} h^{-1}), cropland (47±3 mg CO_2-C m^{-2} h^{-1}), and bushland (45±4 mg CO_2-C m^{-2} h^{-1}). We observed no significant difference in ~~the~~ CO_2 emissions between the first three seasons, namely SD~~ in February, and~~, onset-LW ~~in March~~ and mid-LW~~ in April~~. However, ~~toward~~towards the end of the wet season (end-LW) in May, CO_2 emissions ~~from~~in the conservation land and grazing land were significantly higher than ~~emissions from~~ cropland and bushland ($p<0.05$). Through LD, onset-SW, and mid-SW, CO_2 emissions in the conservation land remained significantly higher~~ than emissions from the other three sites~~, while ~~emissions~~those from grazing land dropped during LD and were not different from bushland or cropland emissions thereafter.

Generally, CO_2 emissions were higher ~~during~~in the wet ~~season~~seasons than in the dry ~~season~~seasons at all sites~~, showing a bimodal pattern~~ (Fig. 4c). ~~Just after~~At the onset of the rainy season in early March, CO_2 emissions increased at all sites by over 200% from SD to LW and dropped during LD by approximately 70% in grazing land, bushland, and cropland. In the conservation land, the drop from LW to LD was about~~. 20%. On average, the highest seasonal mean fluxes were observed during the wet season.~~ 20%. In the bushland, the highest seasonal mean fluxes were reached in mid-LW (98±6 mg CO_2-C m^{-2} h^{-1}) ~~in early March. However,~~while in the conservation land (239±11 mg CO_2-C m^{-2} h^{-1}), grazing land (160±16 mg CO_2-C m^{-2} h^{-1}), and cropland (84±12 mg CO_2-C m^{-2} h^{-1}), the highest ~~seasonal mean fluxes~~ were observed during end-LW towards the end May. ~~On the other hand, the~~The lowest seasonal mean CO_2 emissions at all sites were observed during the SD campaign (below 20 mg CO_2-C m^{-2} h^{-1}, Fig 4).

When comparing ~~between~~ the two wet seasons (LW and SW), CO_2 emissions were 45 % (bushland), 55 % (conservation land), 56 % (cropland), and 57 % (grazing land) higher ~~during the long wet~~

Commented [WS19]: RC: Different terms are being used, soil respiration; soil CO_2 emissions, ecosystem soil respiration (?) Make this consistent.
AC: *We only use the term "soil CO_2 emission".*

Commented [WS20]: SC: N2O fluxes are sometimes given in µg N2O-N m^{-2} h^{-1} (e.g. l. 295 or 420) and in some graphics they are given in N2O (µg m^{-2} h^{-1}) (e.g. figure 4 or figure 5). This is the same for CO_2. Units should be used consistent, so that you can compare the fluxes.
AC: *We made the necessary correction. CO_2 (mg CO_2-C m^{-2} h^{-1}) N_2O (µg N_2O-N m^{-2} h^{-1}) and CH_4 (mg CH_4-C m^{-2} h^{-1}).*

Commented [WS21]: RC: Ln 365 – What are the errors on the fluxes? They are so small for soil CO_2 fluxes. Report error and sample size.
AC: *The sample size per season is seven daily average values derived from three flux values per day from each land use type. The error bar presented here is the standard error of the three flux values per day.*

~~season~~ in LW than ~~during the short wet season~~SW (Fig. 5a). For the two dry seasons, CO_2 emissions were ~~also~~ significantly higher in LD than SD across all the sites (in SD all sites recorded emission below 20 mg CO_2-C m^{-2} h^{-1}). ~~However, during~~During the LD, CO_2 ~~emission~~emissions were 29 % (bushland), 38 % (cropland), 40 % (grazing land), and 77 % (conservation) higher than during SD ~~(Fig. 5a). While~~. As much as CO_2 emissions in cropland, bushland, and grazing land ~~had~~ dropped ~~below~~to less than 30 mg CO_2-C m^{-2} h^{-1} during LD, ~~CO_2 emissions were still high (118±6 mg CO_2-C m^{-2} h^{-1})~~ in the conservation land~~, even more than during onset LW (63±9~~ (118±6 mg CO_2-C m^{-2} h^{-1}) ~~and mid-LW (79±5 mg CO_2-C m^{-2} h^{-1}~~the emissions remained high (Fig 4c).

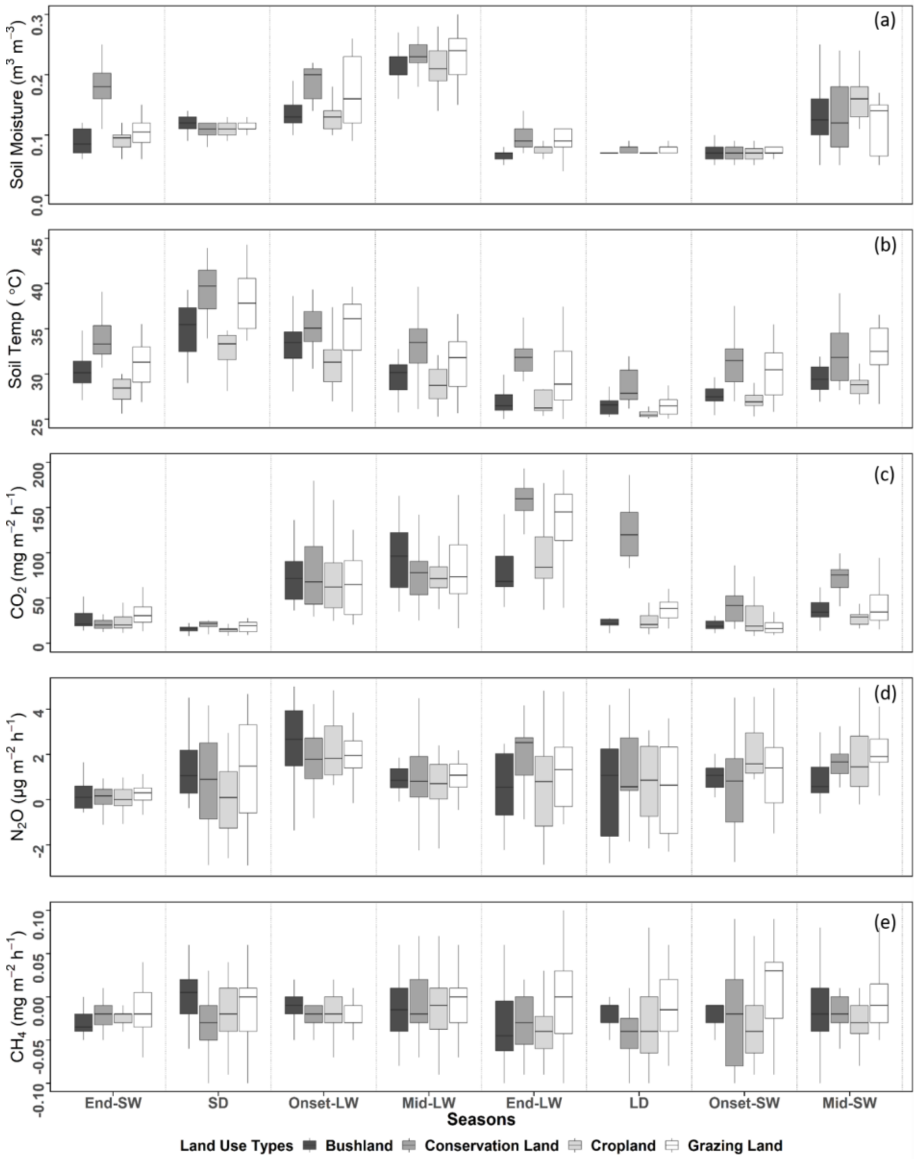
3.4.2. Soil nitrous oxide (N_2O) emissions

Mean annual N_2O emissions were very low (< 5 μg N_2O-N m^{-2} h^{-1}) at all four sites (Fig. 4d). ~~Mean N_2O emissions were higher in the cropland~~Cropland (2.~~65~~7±0.~~06~~6 μg N_2O-N m^{-2} h^{-1}) recorded the highest mean N_2O emissions than ~~in the~~ conservation land (1.~~59~~6±0.~~04~~4 μg N_2O-N m^{-2} h^{-1}), grazing land (1.~~49~~5±0.~~04~~4 μg N_2O-N m^{-2} h^{-1}), and bushland (1.~~16~~2±0.~~04~~4 μg N_2O-N m^{-2} h^{-1}). N_2O ~~fluxes~~emissions did not show a clear temporal pattern as observed for CO_2 emissions. ~~Mean seasonal N_2O emissions were very low during both the wet and dry seasons.~~ Within each season, no significant differences in N_2O emissions were observed among the sites. ~~At~~However, at the onset of the rainy season (onset-LW), there were observable increases in N_2O emissions from all the sites. During this period, mean N_2O emissions at all the sites were ca. 2.6±0.4 μg N_2O-N m^{-2} h^{-1}). By mid-LW and end-LW periods, N_2O emissions had dropped ~~to nearly zero (<~~ (<1 μg N_2O-N m^{-2} h^{-1}) at all sites. ~~However,~~In June during LD ~~in June~~, N_2O emissions ~~in~~from the cropland were significantly higher than at the other three sites (2.35±0.03 μg N_2O-N m^{-2} h^{-1}, $p < 0.05$). During this period, the farmer had just harvested his crops.

When comparing the two wet seasons, N_2O emissions did not differ between LW and SW at all sites (Fig. 5b). However, short N_2O emission pulses were observed during both seasons. A notable peak of ~~apprximately~~about 70 μg N_2O-N m^{-2} h^{-1} was observed in the cropland on 7 April 2018, ~~which was~~a week after ~~the application of~~ livestock manure ~~a week before the sampling campaign.~~application. It had also rained the night before the sampling day. At the same site, we also recorded a peak of 55.2 μg N_2O-N m^{-2} h^{-1} on 30 September 2018, likely also due to manure application (personal communication from the farmer Mwadime Mjomba). Other notable peaks were 29.9 μg N_2O-N m^{-2} h^{-1} (in the bushland on ~~03~~3 September 2018) and 26.~~59~~ 6 μg N_2O-N m^{-2} h^{-1} (in grazing land on 4 September 2018). These were observed during the SW from chambers with animal droppings within the chambers on these dates. During. For the dry seasonseasons, N_2O emissions did not differ between SD and LD in the bushland, conservation land, and grazing land, while N_2O emissions in the cropland were significantly higher during LD than SD (Fig. 5b).

3.4.3. Soil methane (CH_4) emissions

Throughout the study period, CH_4 emissions did not vary significantly among sites and seasons (Fig. 4e and Fig.– 5c). The studied sites were mostly CH_4 sinks rather than sources, and CH_4 emissionsfluxes were very low, ranging from -0.03 to 0.9 mg CH_4-C m^{-2} h^{-1} (Fig.- 4e), and were often below the LODlimit of detection (0.03 mg CH_4-C m^{-2} h^{-1}).



(a)
(b)
(c)
(d)
(e)
Soil Moisture (m^3 m^{-3})
Soil Temp (°C)
CO_2 (mg m^{-2} h^{-1})
N_2O (µg m^{-2} h^{-1})
CH_4 (mg m^{-2} h^{-1})
End-SW
SD
Onset-LW
Mid-LW
End-LW
LD
Onset-SW
Mid-SW
Seasons
Land Use Types
Bushland
Conservation Land
Cropland
Grazing Land

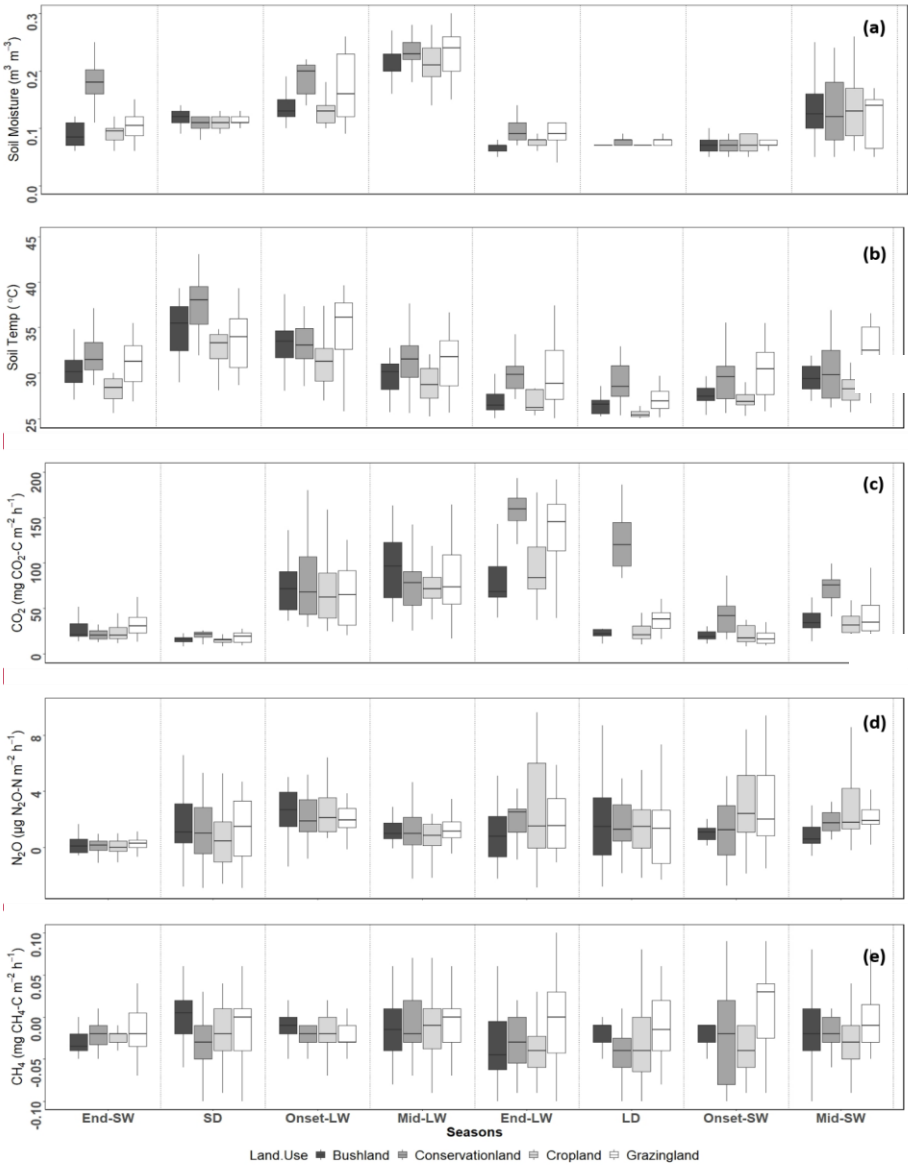
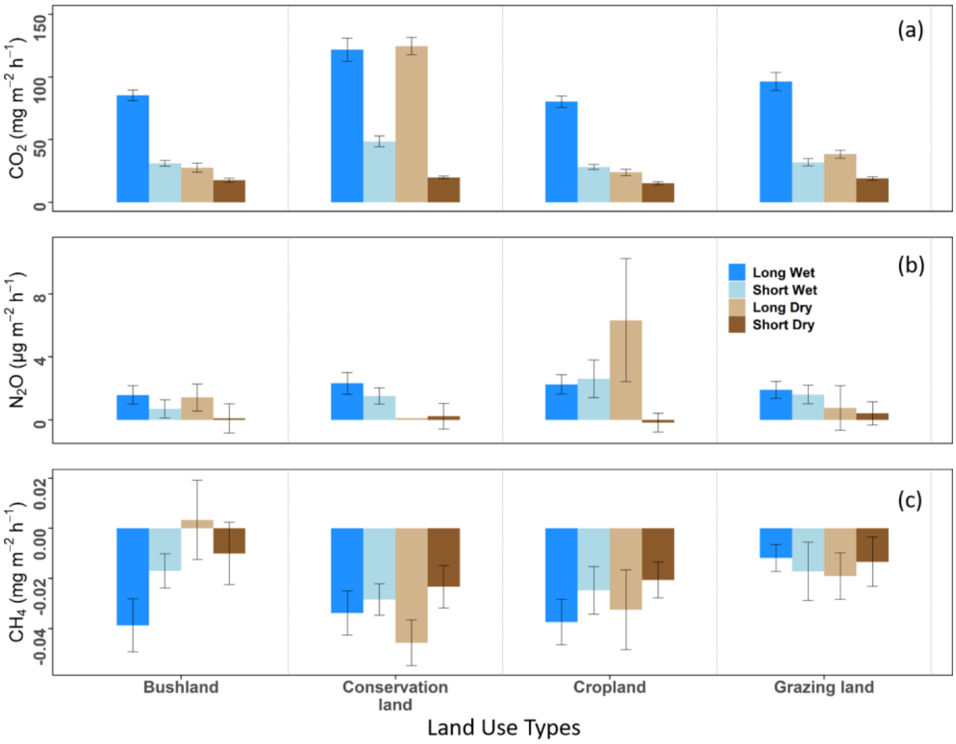


Figure 4: *Box plots showing differences in seasonal means for (a) soil moisture, (b) soil temperature, and soil emissions of (c) CO_2, (d) N_2O, and (e) CH_4 for each site from November 2017 to October 2018. Season abbreviations on the x-axis denote SW for the short wet season and LW for*

Commented [WS22]: RC: Figures 4 and 5 are good. Keeping the color scheme, the same would be helpful.
AC: *The two figures provide different information and having them in the same color scheme might be misleading. Figure 4 shows the difference in emissions between the land uses types while figure 5 gives the differences in emission between the wet and dry season.*

the long wet season with corresponding onset, mid and end of the wet season, along with SD for the short dry season and LD for the long dry season.



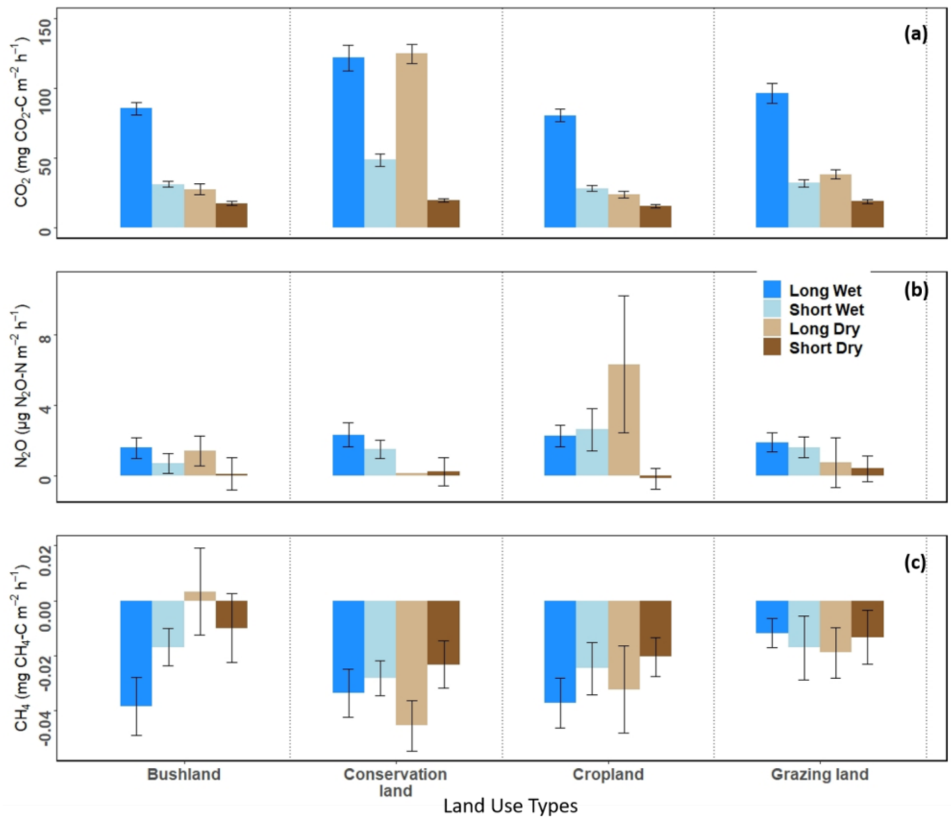


Figure 5: *Seasonal differences in mean (a) CO_2, (b) N_2O, and (c) CH_4 emissions between the long and short wet seasons and the long and short dry season for the four land-use types.*

3.5. Effects of soil temperature, soil water content, and vegetation indices on soil GHG emissions

Soil water content (WC) was highest during the wet season, ranging between (mean 0.13 to 19±0.25 06 m^3 m^{-3}) and lowest during the dry season, ca (mean. 0.07±0.02 m^3 m^{-3}) at all sites (see Fig. 4a). Soil temperature (T), on the other hand, were higherhighest during the SD (36.7±2.1 ^oC) at all the sites and lowest (24.5±0.6 ^oC) duringin LD in July (Fig.4b). Throughout all the campaigns, mean WC and mean T were highest in the conservation land, followed by grazing land, bushland, and were lowest in the cropland.

Results from the nonlinear regression analyses Regression results on soil CO_2 and soil N_2O emissionemissions against T and WC are shown in Table 2. The results showed positive correlations between soil CO_2 emissions and WC (p <0.05). However, the R^2 was very weak at all sites. Conversely, CO_2 emissions showed no correlation with T (P < 0.05). There wasWe observed no correlation between N_2O and CH_4 emissions with botheither WC or T (p <0.05). Separating data into the wet and dry season did not improve any of the correlations as we had expected. However, we observed an increase in both CO_2 and N_2O emissions at the onset of the rainy season in March. .

Table 2: Soil water content (WC) and soil temperature (T) control on carbon dioxide (CO_2) and nitrous oxide (N_2O). Soil CO_2 and N_2O emissions are) denoted by *Rs*, while *a, b,* and *c* represent the model coefficient

Predictors	**Land Use**	**CO_2-C mg m^{-2} h^{-1}**		**N_2O-N ug m^{-2} h^{-1}**	
Soil water content (WC)		$Rs = a + bWC + cWC^2$			
	Bushland	$6.12WC + 0.92WC^2$	R^2= 0.26***	$19.02WC - 64.11WC^2$	R^2= 0.008
	Conservation land	$135.27WC - 0.57WC^2$	R^2= 0.07**	$11.63WC - 7.736WC^2$	R^2= 0.009
	Cropland	$17.83WC + 0.67WC^2$	R^2= 0.04***	$28.48WC - 66.63WC^2$	R^2= 0.005
	Grazing land	$15.03WC + 0.79WC^2$	R^2= 0.11***	$19.81WC - 53.56WC^2$	R^2= 0.002
Soil Temperature (T)		$R = ae^{(bT+cT^2)}$			
	Bushland	$1.078e^{0.26T-0.004T^2}$	R^2= 0.008	$360.25e^{-0.29T-0.004T^2}$	R^2= 0.008
	Conservation land	$0.001e^{0.81T-0.014T^2}$	R^2= 0.015**	$0.007e^{0.45T-0.008T^2}$	R^2= 0.015
	Cropland	$4.568e^{-0.13T+0.002T^2}$	R^2= 0.008*	$0.007e^{-0.05T+2.42T^2}$	R^2= 0.008*
	Grazing land	$4.136e^{0.18T-0.003T^2}$	R^2= 0.015	$2.366e^{0.05T-0.001T^2}$	R^2= 0.015

***: p<0.0001, **: p<0.001, *: p<0.05

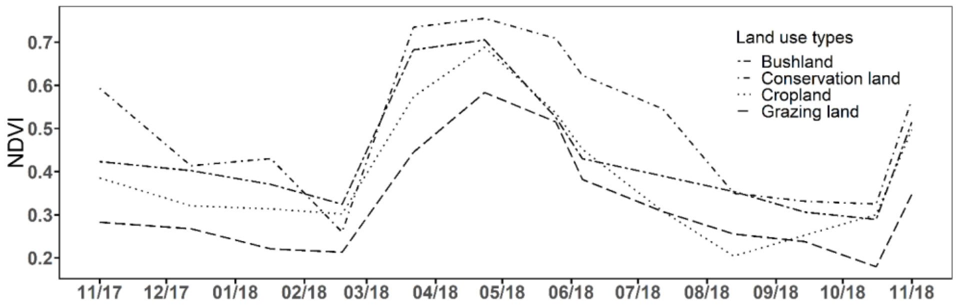
Results from combined soil water contentWC and soil temperatureT on soil CO_2 and N_2O emissions did not improve the correlation, as shown in Table 3. We concluded that soil emissions could be an overall effect of other factors than these two parameters. Thus, we chose to includeincluded vegetation indices in our model.

Table 3: Combined effects of soil water content (WC) and soil temperature (T) control on soil CO_2 and N_2O emissions. Soil CO_2 and N_2O emissions denoted by *Rs*, while *a, b, d,* and *e* represent the model coefficient, (R^2) the coefficient of determination, and AIC the Akaike's information criterion

Functions	Land use	a	b	d	e	R^2	AIC
CO_2-C mg m^{-2} h^{-1}							
$Rs = e^{(aT+bT^2)} \times (dWC + eWC^2)$	Bushland	-0.12	0.001	52.774	-0.527	0.31***	1888
	Conservation land	0.90	-0.016	0.0001	0.000	0.10***	2156
	Cropland	-0.39	0.006	3701.901	-84.001	0.08**	1886
	Grazing land	0.14	-0.003	0.842	-0.008	0.12***	2024
N_2O-N ug m^{-2} h^{-1} $Rs = e^{(aT+bT^2)} \times (dWC + eWC^2)$	Bushland	-0.50	0.007	2008.345	-58.559	0.009	785
	Conservation land	0.56	-0.010	0.000	0.000	0.003	811
	Cropland	0.67	-0.017	0.003	-0.0001	0.089	911
	Grazing land	0.11	-0.003	0.187	-0.005	0.003	770

***: p<0.0001, **: p<0.001, *: p<0.05

The annual change in vegetation cover ~~and during~~at each ~~campaign in the study area~~site are shown in Fig. (6~~) and Fig (7) respectively.~~). The highest NDVI values were observed during the LW in April (ranging from 0.58 to 0.76) and the lowest during the ~~dry season (below~~SD (< 0.26). Vegetation greenness increased rapidly from mid-March at all sites~~, which coincided~~ coinciding with the onset of the rainy season and remained high (Fig.6~~ and Fig. 7). However, at~~). At end of the rainy season, NDVI gradually dropped. Highest NDVI values occurred in the conservation land (0.51±0.05~~),~~); followed by bushland (0.44±0.05), cropland (0.41±0.05), and the lowest ~~values~~ were recorded in the grazing land (0.33±0.05).



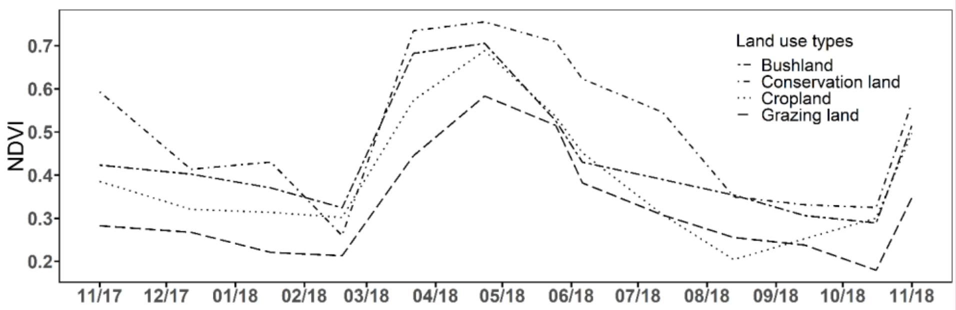


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Figure 6: *Monthly NDVI time series showing the annual trend in vegetation cover from November 2017 to November 2018 for the four land-use types.*

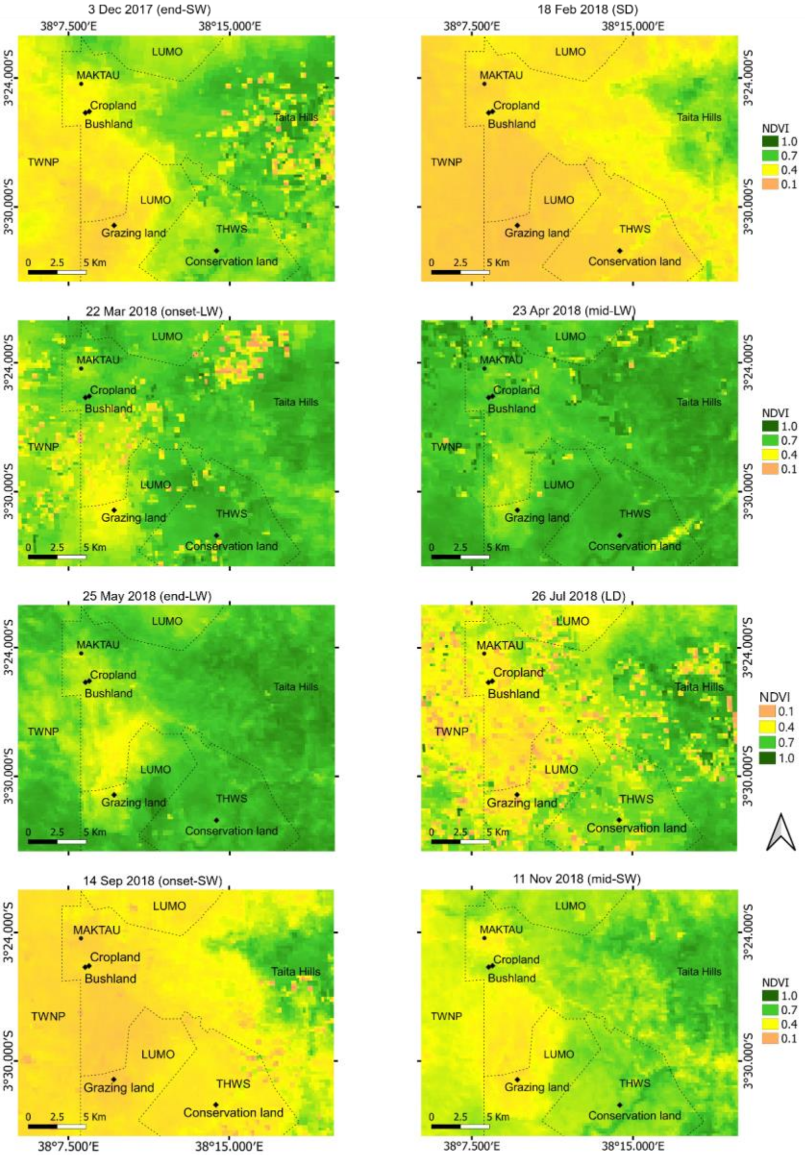
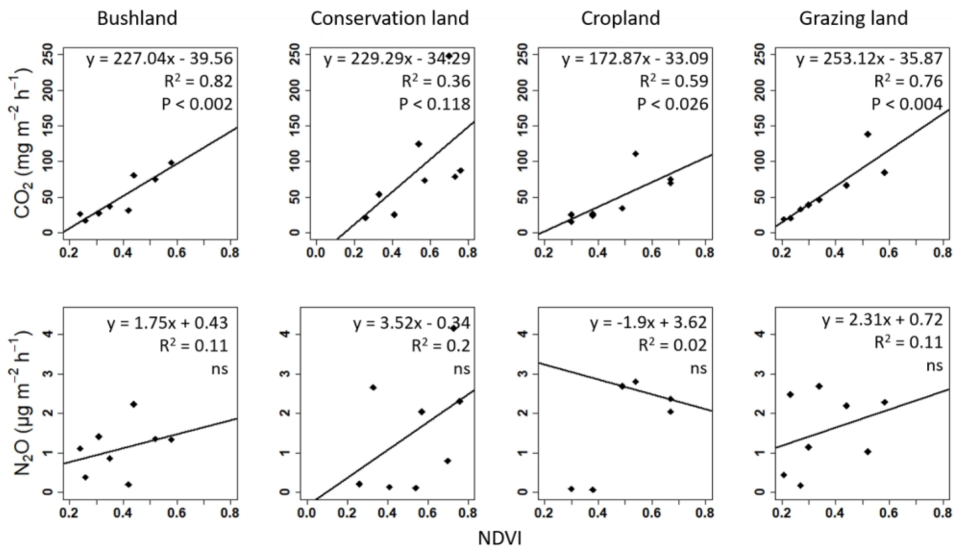
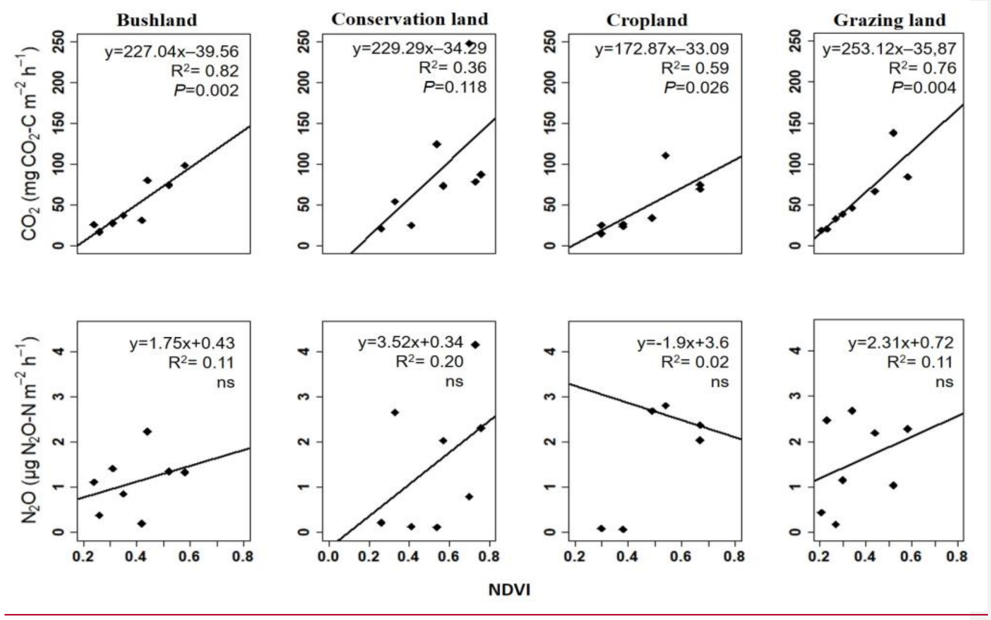


Figure 7: *Normalized difference vegetation index (NDVI) maps for each campaign (SW and LW denotes short and long wet seasons with corresponding onset, mid and end of the season, and SD and LD for short and long dry season) from November 2017 to November 2018. LUMO is the LUMO community wildlife sanctuary, TWNP stands for the Tsavo west National Park and THWS for Taita Taita hills wildlife sanctuary*

OurRegression analysis results show that NDVI was capable of explaining a large degree in the variation of shows a positive correlation between NDVI and seasonal soil CO_2 emissions inat all the bushland, grazing land, and croplandsites (see Fig. 8). However, 7). Combined WC and NDVI improved the correlation in the conservation land was noteven further as shown in Table 4. No significant. We also correlation was observed no significant correlation withbetween N_2O at all the sites.emissions and NDVI (Fig. 7).





ns= not significant

***Figure ~~8~~7:** Linear regression analyses of the measured seasonal means for soil CO_2 and soil N_2O emissions during the campaign from November 2017 to November 2018 plotted against NDVI data acquired during each campaign.*

Results from combined WC and NDVI improved the correlation outputs further (Table 4). These results highlight the importance of WC and vegetation cover (as represented by NDVI) on soil CO_2 emissions in the study areas.

Table 4: Combined effects of soil water content (WC) and NDVI on soil CO_2 emissions. Soil CO_2 emissions denoted by *Rs*, while *a, b, c,* and *d* represent the model coefficient and (R^2) the coefficient of determination.

	Land use	a	b	c	d	R^2
CO_2-C mg m^{-2} h^{-1}						
$Rs = a + bNDVI + (cWC + dWC^2)$	Bushland	-29.69	196.47	-83.74	781.29	0.86***
	Conservation land	6.48	382.96	-861.98	-256.66	0.82***
	Cropland	26.94	244.54	-1250.22	3269.46	0.79***
	Grazing land	-97.19	396.41	575.60	-3440.80	0.96***

***: p<0.0001, **: p<0.001, *: p<0.05

4. Discussion

4.1. Soil CO_2 emissions

CO_2 emissions from the soil differed significantly between the land-use types. Higher CO_2 emissions were particularly observed in the conservation land followed by grazing land and bushland, while lowest levels were recorded from the cropland. We observed the same trend with SOC, and thus we attributed the difference in CO_2 emissions between the land uses to SOC as observed (see Table 1). This is in line with a similar study by La Scala et al. (2000), which recognized SOC as a key driver of CO_2 emissions from the soil, as it is the primary source of energy for soil microorganisms (Lal, 2009).

The differences in CO_2 emissions and SOC among our land-use types can be linked to the difference in vegetation cover type, which can alter both biotic and abiotic factors that drives soil CO_2 emissions (Raich and Tufekcioglu, 2000; Pinto et al., 2002) and net carbon assimilation (La Scala et al., 2000). Vegetation types directly influence soil physicochemical properties, which modify soil microbial activities (Raich and Tufekcioglu, 2000). This also affects the quantity of plant carbon allocated belowground (Metcalfe et al., 2011). Vegetation additionally affects root respiration by determining root biomass, and litter quality and quantity (Fanin et al., 2011; Rey et al., 2011). Root respiration and the associated microbial components are important in ecosystem soil respiration. Active roots add directly to soil respiration, while the dead roots and exudates from the roots provides carbon as a source of energy and nutrients for microbial biomass (Tufekcioglu et al., 2001).

In the conservation land, thick grasses formed a closed ground cover, especially during the wet seasons (also confirmed by NDVI values). This translated into higher soil respiration due to higher root respiration due to a more active root network and litter production compared to the other sites (Raich and Tufekcioglu, 2000). Besides this, grazing here was low and only occurred by random elephants and other wild mammals. We observed less damage to grass cover in the conservation area compared to grazing land (which was mostly bare due to overgrazing) and bushland. Abdalla et al. (2018) found higher grazing intensity to reduce SOC stocks due to the modification of vegetation cover, which affects litter accumulation and decomposition (Wilsey et al., 2002). This could be the case with the grazing land, which was under heavy grazing by livestock, and also by wildlife. This explains the difference in mean CO_2 emissions between conservation land and grazing land.

In the bushland, grazing can be considered moderate when compared to the conservation land and grazing land, as only the farmer's livestock grazed the land. However, the lower CO_2 emissions and lower SOC compared to the grazing land can be a consequence of the higher clay content observed in grazing land (see Table 1). The presence of polyvalent cations in clay forms organo-mineral complexes that protect SOC from microbial and enzymatic decay, which in turn increases SOC storage (Amanuel et al., 2018).

Soil CO_2 emissions and mean SOC were lowest in cropland. Root respiration in cropland depends on periods of live roots in annual crop fields and on the biomass of roots during the initial growing season (Raich et al., 2000). Therefore, the continued removal of crop residues during harvesting and frequent tillage affected both root respiration and SOC. As much as crop residues contribute to carbon stocks through their mineralization (Nandwa, 2001), most maize residues were used as livestock feed and sometimes as fuel, while bean residues were removed completely during the harvest and burned.

Manure inputs provide easily degradable substrates of C and N catalyzing soil emissions (Janssens et al., 2001; Davidson and Janssens, 2006). However, manure input in cropland was very low (approximately 20 kg in a 1.5 hectare farm per month) and thus no measurable effects in CO_2 emissions were detected. This was opposite to our hypothesis. Another reason could be that soil fertility was too low to have a detectable influence on CO_2 emissions (Pelster et al., 2017). Our results are in the same magnitude with those of Rosenstock et al. (2016); Farai Mapanda et al. (2011), and Pelster et al. (2017), who also did not detect any change in CO_2 emissions after manure application and attributed this to the low input of manure from the maize and sorghum plots.

On average, CO_2 emissions were higher during the wet season than during the dry season. At the start of both rainy seasons, CO_2 emissions increased significantly in all land-use types. The emission from the conservation land and grazing land are comparable with those in Brümmer et al. (2008), who observed CO_2 emissions ranging between 100 and 250 mg C m^{-2} h^{-1} in a natural savanna in Burkina Faso. Several other studies from similar ecosystem have also documented comparable changes in CO_2 emissions with the onset of the rainy seasons (Castaldi et al., 2006; Livesley et al., 2011; Pinto et al., 2002).

In the cropland, our results during the wet season are similar with those that Rosenstock et al. (2016) measured during the wet season, which ranged between 50 to greater than 200 mg C m^{-2} h^{-1}. We attributed the increase in CO_2 emissions during the wet season to the response of soil microbes to soil moisture producing an increase in ecosystem respiration (Livesley et al., 2011; Otieno et al., 2010). Soil moisture allows for soluble substrates and oxygen, both needed by soil microbes, and increasing microbial activity such as decomposition and soil respiration (Davidson et al., 2006; 2009; Grover et al., 2012).

Consequently, higher soil CO_2 emissions during the wet season can be a result of increased root respiration due to more active plant and root growth (Macdonald et al., 2006). Grass sprouts rapidly after the rains, increasing in root network density to maximize the use of available soil moisture on the soil surface (Merbold et al., 2009). This is one explanation for the higher CO_2 emissions in the grassy conservation land, grazing land, and bushland compared to cropland without the grasses. The lower CO_2 emissions in bushland compared to conservation land and grazing land were attributed to the presence of more trees and shrubs, which according to Merbold et al. (2009), respond more slowly than grasses to changes in soil moisture. Therefore, grass production belowground in the conservation land and grazing land was probably more than in the bushland, leading to higher autotrophic respiration and also heterotrophic respiration (Janssens et al., 2001).

To our surprise, the highest seasonal mean CO_2 emissions in conservation land, grazing land, and cropland were observed at the end rather than the at the peak of the wet season. During this time, both documented soil moisture and soil temperature had dropped in all land-use types. Thus, we credited the relatively high CO_2 emissions to root respiration that could tap moisture from deeper profiles than microbial activity in the soil (Carbone et al., 2011). According to Carbone et al. (2011), microbial respiration peaks first with surface soil moisture, whereas root respiration continues to increase throughout the wet season, controlling emissions as temperatures increass and surface soil moisture gradually drops. Most microbial activities are found on the soil surface, which are first to wet-up and dry-down with rainfall, while roots are located deeper, with access to more water reserves that take longer to be exhausted (Carbone et al., 2011).

1.1. N_2O emissions

Soil N_2O emissions can vary highly over time, as regulated by factors such as soil moisture, temperature, aeration, ammonium and nitrate concentrations, pH, and mineralizable carbon (Butterbach-Bahl et al., 2013). However, we did not document any significant difference in N_2O emissions between the four land uses. At all the sites, N_2O emissions were very low, and this we attributed to the observed low soil N content (see Table 1). According to Pinto et al. (2002) and Grover et al. (2012), savanna ecosystems have a very tight N cycling, which transcends to low N availability. Thus, available N is taken up by vegetation, leaving very little for denitrification (Castaldi et al., 2006; Mapanda et al., 2011). Our results are consistent with low N_2O emissions observed in a Brazilian savanna (cerrado) by Wilcke et al. (2005), who also reported low N levels in their study area. Very low N_2O emissions due to poor nutrient availability have also been observed in other savanna landscapes (Scholes et al., 1997; Castaldi et al., 2016). Soil N_2O in cropland match those of Rosenstock et al. (2016), who also attributed the low soil N_2O emissions to poor nutrient availability in the soil.

We did not detect seasonal variations in N_2O emissions. The only exception to otherwise very low N_2O emissions was after the onset of the rainy season, when N_2O emissions slightly increased at all sites. Such a pattern has previously been shown by Scholes et al. (1997) in South Africa. Several other studies have reported a comparable increase in N_2O emissions after the rainy season (Scholes et al., 1997; Pinto et al., 2002; Castaldi et al., 2006; Livesley et al., 2011). Soil moisture in the savanna ecosystem controls soil gas diffusion, oxygen (O_2) availability for microbial use and the availability of substrate for microbial communities (Davidson et al., 2000; Butterbach-Bahl et al., 2013). Therefore, the increase in N_2O emissions at the onset of the wet season is possibly a response of microbial communities to variation in soil moisture (Rees et al., 2006). In addition, the decomposition of litter and plant residue facilitated by soil moisture may have further increased N availability.

Rosenstock et al. (2016) also recorded low N_2O emissions with average fluxes typically less than 12 µg N_2O-N m^{-2} hr^{-1} in rainy Kenyan highlands. In cropland, mean N_2O emissions are close to those in Mapanda et al. (2010) in Zimbabwe, who reported an average of 3.3-3.4 µg N_2O-N m^{-2} hr^{-1}. In June and July, the slight increase after the maize and bean harvests could be due to there being no plants to take up the available N and thus some was lost as N_2O.

Negative N_2O emissions were detected during the dry season. Such observations could result from the poor N levels observed at all sites. Soil denitrifiers may therefore use N_2O as an N substrate in the absence of NO_2^- and NO_3^- (Rosenkranz et al., 2006). Negative N_2O emissions have also been reported in other tropical savanna soils under similarly dry conditions (Donoso et al., 1993; Castaldi et al., 2006; Livesley et al., 2011).

Application of manure in the cropland did not show any significant differences, which is the opposite of what we expected. Several studies have shown both organic and inorganic fertilisers in agricultural land to increase N_2O emissions (Davidson, 2009; Butterbach-Bahl et al., 2013; Hickman et al., 2014). Due to low nutrient levels, as observed, the addition of manure to these soils may not have been sufficient to stimulate high N_2O emissions. However, manure input by the farmer was also very low (less than 12 kg of N for the crop-growing season). Our conclusion here is that the maize took most of the available N that was added, thus diminishing the pool of N to be lost as N_2O. According to the Taita Development plan, this is a common scenario in the county, which translates to very low yields (CIDP, 2014). Our results are similar to those in Pelster et al. (2017) (generally < 10 µg N_2O-N m^{-2} hr^{-1}), who also observed no detectable influence of manure application (which they noted was low, between 1–25 kg N ha^{-1}) on N_2O emissions. Increased nutrient inputs and improved management are required to improve yield and livelihoods, but this may simultaneously lead to increased soil N_2O emissions. Nevertheless, Hickman et al. (2015) suggested that managed agricultural intensification in western Kenya could increase crop yields without immediate increases in N_2O emissions, if application rates remained at or below 100 kg N ha^{-1}. We believe this could also be the case in our study area.

Deposition of faeces and urine by animals while grazing in the grazing land and bushland did not show any statistical difference with cropland and conservation land, as we expected. We found faeces in and close to chambers for most of the sampling days in the grazing land, although we did not see any animal urine in the chambers. In addition, on each sampling day, we also observed animal footprints in our chamber or close by in the same site in the bushland. In the conservation area, as much as animal were grazing, we never observed faeces in or close to our chambers throughout the campaign period. We only noted the presence of animals close to our chamber from the footprints and the destruction of our chamber from time to time.

1.2. CH_4 emissions

Methane emissions did not vary between the land-use types or with seasons. Most values were below the LOD at all the sites, which is similar to observations made by Rosenstock et al. (2016) and Wanyama et al. (2019).

Soil CO_2 emissions differed significantly between the four LUTs. The highest mean CO_2 emissions were observed in the conservation land followed by grazing land and bushland, and the lowest from cropland. Soil C content, which is the primary source of energy for soil microorganisms that contribute to soil CO_2 emissions (Lal, 2009) also showed the same trend (conservation land > grazing land > bushland > cropland). Therefore, the difference in land use and land-use management activities between our sites played a vital role in modifying both biotic and abiotic factors that drive both soil C content and soil CO_2 emissions (Pinto et al., 2002).

Due to the difference in land use and management, vegetation type and cover differed between our sites. The dense grass network in the conservation land formed an almost closed ground cover, especially in the wet seasons (further confirmed by NDVI values). Being a private sanctuary, only wild mammals (no livestock allowed) grazed and browsed there, and thus we observed less damage on the grass cover throughout all the campaigns as compared to the grazing land (which had large patches of bare soil due to overgrazing) and bushland. This provides a good explanation for the difference in mean CO_2 emissions between these three LUTs, as vegetation is known to affect soil C concentration and root and microbial respiration that directly contribute to soil CO_2 emissions (Fanin et al., 2011; Rey et al., 2011).

With the lowest CO_2 emissions being measured in the cropland, we attribute this observation to the continued tillage and removal of crops and crop residues during land preparation, weeding and harvesting, which affects both root respiration and soil C content (Raich et al., 2000; Nandwa, 2001). In East Africa and especially in smallholder farming systems, most of the crop residues are used as livestock feed and fuel. In addition, manure inputs in cropland are very low (about 20 kg per month on a 1.5 ha farm) and thus no measurable difference in CO_2 emissions was detected before and after manure input, and with the other LUTs. Several other studies observed the same scenario from low

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manure input in maize and sorghum plots (Rosenstock et al., 2016; Mapanda et al., 2011, and Pelster et al. 2017).

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On average, CO_2 emissions were higher during the wet season than during the dry season. At the start of both rainy seasons (SW, LW), CO_2 emissions increased significantly in all LUTs. Emissions from the conservation land and grazing land are comparable to those in Brümmer et al. (2008), who observed CO_2 emissions ranging between 100 and 250 mg CO_2-C m^{-2} h^{-1} in a natural savanna in Burkina Faso. Several other studies from similar ecosystem have also documented comparable changes in CO_2 emissions with the onset of the rainy seasons (Castaldi et al., 2006; Livesley et al., 2011; Pinto et al., 2002). In the cropland, results in the wet season are similar to those measured by Rosenstock et al. (2016), ranging from 50 to > 200 mg m^{-2} h^{-1}. We attributed the increase in CO_2 emissions in the wet season to the response of soil microbes and vegetation to soil moisture (Livesley et al., 2011; Otieno et al., 2010). Soil moisture connects microorganisms with soluble substrates (Moyano et al., 2013) and increases microbial activity (Davidson et al., 2006; 2009; Grover et al., 2012) and thereby soil CO_2 emissions.

Furthermore, an increase in soil CO_2 emissions during the wet season can also be a result of increased root respiration due to more active plant and root growth (Macdonald et al., 2006). Grasses sprout more rapidly than trees and shrubs with the first rains (Merbold et al., 2009). This provides a possible explanation for the higher CO_2 emissions in the grassy conservation land, grazing land, and bushland compared to cropland during the rainy season. However, grazing land recorded higher CO_2 emissions than bushland (only the farmer's livestock grazed here). The main difference between these two sites – apart from grazing intensity – was that bushland had more trees (*Acacia spp.*) and shrubs (*Commiphora spp.*) and less herbaceous undergrowth than the grazing land, thus providing shade that might have interfered with growth and regrowth of plants below the canopy. Therefore, grass root production in the open conservation land and grazing land was likely higher than in the bushland (Janssens et al., 2001), although we cannot confirm this because root biomass was not determined in this study. In cropland, all grasses and weeds were cleared during regular weeding and therefore did not play a role in root respiration.

To our surprise, the highest mean seasonal CO_2 emissions in conservation land, grazing land, and cropland were observed at the end rather than at the peak of the wet season. During this time, both soil moisture and soil temperature had dropped in all LUTs. However, our data was only recorded up to a depth of 5 cm, but roots of perennial grasses, shrubs and trees can tap moisture from greater soil depths (Carbone et al., 2011). According to Carbone et al. (2011), while microbial activity is highest

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and most variable in the upper soil layers, which are first to wet-up and dry-down, roots can access water reserves in deeper soil layers that take longer to be exhausted, and therefore remain active at the end of the wet and into the dry season.

4.2. Soil N_2O emissions

Our results showed very low N_2O emissions from all LUTs, which we attributed to low soil N content observed in all the sites (see Table 1). Savanna ecosystems are characterized by very tight N cycling, which transcends to low N availability (Pinto et al., 2002 and Grover et al., 2012), and most of this N is rapidly taken up by vegetation, leaving very little for denitrification (Castaldi et al., 2006; Mapanda et al., 2011). The N_2O flux results observed from conservation land, grazing land and bushland are consistent with those observed in a Brazilian savanna by Wilcke et al. (2005), and other studies from similar ecosystems reported comparable N_2O flux magnitudes (Scholes et al., 1997; Castaldi et al., 2016; Mapanda et al., 2010). The higher N_2O emissions observed in June and July from our cropland site after the maize and bean harvests likely occurred due to the disturbance and following absence of live plants, which led to higher soil N availability because of less N uptake by plants and increased root decomposition.

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In contrast to the patterns observed for CO_2 emissions, we did not detect any seasonal variations in N_2O emissions. The only exception to the otherwise very low N_2O emissions was after the onset of the rainy season, when N_2O emissions slightly increased at all sites. Such patterns have previously been shown by several similar studies (Scholes et al., 1997; Pinto et al., 2002; Castaldi et al., 2006; Livesley et al., 2011). The increase in N_2O flux at the onset of the rains has been attributed to an increase in microbial activity and therefore faster decomposition of litter and plant residue facilitated by an increase in soil moisture, thus increasing N availability (Rees et al., 2006). Furthermore, according to Davidson et al., (2000) and Butterbach-Bahl et al., (2013), soil moisture affects soil gas diffusion, oxygen (O_2) availability, and the movement of substrate necessary for microbial growth and metabolism.

Negative N_2O emissions were detected during the dry season. Such observations could result from the low N contents observed at all sites coupled with low soil moisture in the dry season, which facilitates diffusion of atmospheric N_2O into the soil. Soil denitrifiers may, therefore, use N_2O as an N substrate in the absence of NO_2^- and NO_3^- (Rosenkranz et al., 2006). Negative N_2O emissions have also been reported in other tropical savanna soils under similarly dry conditions (Castaldi et al., 2006; Livesley et al., 2011).

Manure application in the cropland was very low (< 12 kg of N in 1.5ha for the crop-growing season), and thus N_2O emissions from cropland were low and not different from the other LUTs, which was in contrast to what we had hypothesized. Due to low soil N levels in the cropland, the low amount of manure added was not sufficient to stimulate N_2O emissions, likely because soil N availability was still limiting for plant and microbial growth (Castaldi et al., 2006). Traditional farming systems in smallholder farms in Africa involve repeated cropping with no or very low N inputs that leads to soil N mining over time (Chianu et al., 2012). In line with this, in our cropland site maize and beans are grown during every wet season with no fallow in between years. In addition, the farmer did not use any chemical fertilizer to increase soil N, and the N input from biological N fixation into the soil was likely small because beans were harvested for consumption and bean plant residues were used as livestock feed and not incorporated into the soil. Therefore, the small quantities of manure applied and legume N fixation may have likely been insufficient to compensate for N loss through leaching and crop harvests. According to the Taita Development plan, this is a common scenario in the county, which translates to very low crop yields in this region (CIDP, 2014). Another possible explanation for not detecting the influence of manure on N_2O emissions could be the fact that we did not manage to sample immediately after manure application and therefore might have missed the instant impact of manure application on N_2O emissions. However, similar studies by Pelster et al. (2017) and Rosenstock et al. (2016) also did not see any influence of manure application on soil N_2O emissions and reported N_2O emission values that were generally < 10 µg N_2O-N m^{-2} h^{-1}). Equally, the deposition of dung and urine by animals in the grazing land and bushland did not have any measurable influence on soil N_2O emissions.

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4.3. Soil CH_4 emissions

Methane emissions did not vary between the land-use types or with seasons. Most values were below the LOD at all the sites. Soil water content in our study is clearly the limiting factor for methanogenesis, which needs anoxic conditions for a certain period until methanogenic archaea are established (Serrano-silva et al. 2014). Furthermore, soil compaction by animal trampling may have limited CH_4 diffusion into the soil thus limiting CH_4 consumption by oxidation (Ball et al. 1997). In cropland, continuous tillage interferes with soil structure thus affecting the microenvironment that favours methanotrophic (Jacinthe et al. 2014). Additionally, low soil C as observed in all the sites generally leads to low abundance of soil microorganisms and consequently also methane oxidisers (Serrano-silva et al. 2014). Nevertheless, soils around lakes, waterholes and rivers can be CH_4 sources in semi-arid savanna ecosystems, but those were not investigated during this study.

4.2.4.4. Effects of soil moisture, soil temperature, and vegetation indices on GHG emissions

Soil moisture and soil temperature are known to be important drivers of soil CO_2 production, and they may change across seasons. Seasonal variations in T were very minor and thus changes in WC were considered to be the main driver of CO_2 emissions in our study, as previously highlighted by Grover et al. (2012). Brümmer et al. (2009) and Livesley et al. (2011) also found that WC controlled CO_2 fluxes from savanna soils, rather than T. Soil moisture determines the rate of soil respiration, including heterotrophic and autotrophic processes that are highly moisture reliant (Ardö et al., 2008; Grover et al., 2012).

Soil temperature and soil moisture are also vital for nitrification and denitrification, as they control the activities of soil microbes and O_2. However, we did not observe a significant relationship between N_2O emissions with both WC and T. Only in the cropland area did we observe a positive correlation with T ($p < 0.05$). As much as previous results have shown a positive relationship between T and N_2O emissions (Castaldi et al., 2010), we did not observe such a relationship in our study. Other studies carried out in savannas by Scholes et al., (1997) and Brümmer et al. (2008) were also unable to link N_2O emissions to variations in T. In fact, N_2O emissions were very low during both the wet and dry seasons, as in (Castaldi et al., 2004), Pelster et al. (2017), and Rosenstock et al. (2016**).** The most likely clarification for the lack of seasonality would be the low N levels observed at all the sites (Grover et al., 2012).

The vegetation and its status are other important drivers of GHG emissions from soils. NDVI measures the status of vegetation (with a value range of -1 to 1). High NDVI values correspond to high vegetation cover, while low NDVI corresponds to less or no vegetation (Gamon et al., 1995; Butt et al., 2011). Therefore, the drop in NDVI values at the end of the rainy season was a result of the reduction in vegetation cover in the land-use types. In the cropland area, this coincided with the harvesting of beans and the drying of the maize plant occurring in June and July. The conservation land showed the highest mean NDVI, mainly due to the dense grassy vegetation, especially during the rainy season. Lowest NDVI values were observed in the grazing land, which was expected because the land is mostly bare caused by overgrazing. Results from the linear regression showed a positive correlation with soil CO_2 emissions with NDVI ($p < 0.05$), explaining between 35 % and 82 % of the variation in soil CO_2 emissions at the four sites. We therefore observed high CO_2 emissions when NDVI was high, which is an indication of more vegetation cover. Several studies have shown that vegetation can affect soil respiration by intercepting radiation, modifying the soil moisture regime, adding litter onto the soil surface, and affecting both plant and root respiration (Myneni et al. 1995; Almagro et al., 2013;). Thus, the inclusion of both NDVI and WC is essential for predicting soil CO_2 emission from savanna soils. Our results confirm the importance of vegetation variability in addition to WC as a key driver of productivity in savannas and is consistent with other studies (Reichstein et al., 2003; Anderson et al., 2008; Lees et al., 2018). Concurrently, the same relationship between NDVI and N_2O emissions could not be proven. Our conclusion was that the low N level played a major impact on overall N_2O emissions in this study.

As is common for sub-tropical regions, seasonal variation in soil temperature was small in the study region and therefore soil temperature did not play a big role in modifying soil GHG emissions. Instead, changes in soil moisture were considered to be the main driver of CO_2 emissions in our study, as has previously been highlighted also by other studies (Grover et al. (2012), Brümmer et al. (2009) and Livesley et al. (2011)). However, we did not observe any significant relationship between N_2O emissions with either soil moisture or temperature apart from in the cropland, where we found a positive correlation between N_2O and soil temperature ($p <0.05$). As much as previous results have sometimes shown a positive relationship between temperature and N_2O emissions (Castaldi et al., 2010), our results are in line with others (Scholes et al., (1997), Brümmer et al. (2008) who were also unable to link soil N_2O emissions to variations in soil temperature. In fact, N_2O emissions were very low during both the wet and dry seasons, which is similar to the findings of Castaldi et al., (2004). The most likely explanation for the lack of seasonality effects on N_2O emissions would be the low soil N levels observed at all the sites, which was probably the most limiting factor for N_2O emissions and thus overruled all other potential controlling factors (Grover et al., 2012).

The vegetation cover as depicted by NDVI represents the status of the vegetation (value range from -1 to 1). High NDVI values correspond to high vegetation cover, while low NDVI correspond to little or no vegetation (Gamon et al., 1995; Butt et al., 2011). Therefore, the increase in NDVI that we observed at the onset of the rainy season indicates sprouting and regrowth of vegetation at that time, while the drop in NDVI values at the end of the rainy season indicates reduction in vegetation cover due to plant senescence and grazing. In the cropland area, low NDVI coincided with the harvesting of beans and the drying of the maize plants in June and July. Highest mean NDVI values were observed in the conservation land, mainly due to the dense grassy vegetation, while the lowest NDVI values were found in the grazing land, which we had expected because this area has large spots without vegetation due to overgrazing. Results from linear regression analysis showed a strong positive correlation of soil CO_2 emissions with NDVI ($p< 0.05$), explaining between 35 % and 82 %

of the variation in soil CO_2 emissions at the four sites. This means that CO_2 emissions were highest when NDVI (i.e. vegetation cover) was high Thus, the inclusion of both NDVI and soil moisture measurements is essential for reliably predicting soil CO_2 emission from savanna soils, which is consistent with other studies (Reichstein et al., 2003; Anderson et al., 2008; Lees et al., 2018). Concurrently, the same relationship between NDVI and N_2O emissions could not be proven in our study.

5. Conclusion

The ~~land-use management system plays an important role in~~ magnitude and temporal and spatial variability of soil GHG emissions ~~due to changes in vegetation, soil, hydrology, and nutrient availability. However, the effects on GHG emissions change remain uncertain due to limited data being available in~~in most developing countries have large uncertainties due to a lack of data, especially in dry areas and ecosystems facing ~~diverse~~ land-use change. In our study, we quantified soil GHG emissions from four dominant LUTs in the dry ~~lowland~~lowlands of southern Kenya, namely bushland, conservation land, cropland, and grazing land. Our results showed significant variation between seasons and the respective ~~land-use types.~~LUTs. CO_2 emissions, in particular, were higher during the wet season ~~than the dry season. The lowest seasonal mean CO_2 emissions were observed in the SD~~, when soil moisture was ~~very low while soil temperature was very~~ high~~.~~, compared to the dry season. Most of the variation in CO_2 emissions ~~was~~could be explained by soil moisture and NDVI ~~and soil moisture~~, highlighting the ~~fact~~importance of including proxies ~~of~~for vegetation cover in soil GHG ~~emission~~emissions studies in savannas. N_2O emissions and CH_4 emissions were of minor importance at all sites. However, we ~~may~~acknowledge that we might have missed some episodes of ~~the~~elevated soil N_2O emissions, as these are often episodic~~, i.e.~~ and of short duration, for examples after fertilization or precipitation events. ~~These can easily be missed unless a continuous measurement and monitoring programme is in place.~~ Following ~~theseresults~~these results, there is still need for more continuous studies to cover spatial and temporal ~~variations in soil emissions from diverse land-use types across seasonal and management gradients. Furthermore, continuous measurements allow the detection changes in GHG emission patterns following intensification.~~variation in soil GHG emissions, as well as the inclusion of other LUTs than the ones examined in this study (e.g. wetlands). Nevertheless, we believe that our results are ~~useful for deriving~~important to reduce uncertainties in GHG emission baselines and to identify reliable and meaningful climate change mitigation interventions by informing the relevant policies.

6. Data availability

The data associated with the manuscript can be obtained from the corresponding author upon request.https://figshare.com/articles/Final_data_for_Soil_Greenhouse_Gas_Emissions_under_Different_Land-Use_Types_in_Savanna_Ecosystems_of_Kenya_/11673579

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REVIEWERS COMMENTS

Soil Greenhouse Gas Emissions under Different Land-Use Types in Savannah Ecosystems of Kenya

Authors Response:

The manuscript has been reviewed by 2 reviewers and an additional comment was made in the open discussion. Before, responding to each reviewer and comment individually, we would like to thank for the constructive comments and informative feedback.

The document is structured as follows: each of the reviewer's comment (indicated by RC) is first repeated followed by our response (indicated as AC and in italic). Where relevant we either include a rephrased sentence already or explain on how we intent to implement suggested changes.

Anonymous Referee #1

Overall comments:

RC: The manuscript describes a study in four typical land use types in Kenya, Africa. Soil fluxes of CO_2, N_2O, and CH_4 were measured manually eight times over the course of a year. The main strength of the manuscript is that it produces flux estimates of these greenhouse gasses in under-represented ecosystems. Correlations with driving factors of moisture, soil C content, and vegetation activity (NDVI) were explored. The main weakness of the manuscript is the sampling campaign and methods are very limited and coarse, and thus interpretation of the driving factors of the fluxes are much more speculative than could be with greater initial and supporting data. My suggestion would be to reduce the length of the manuscript to focus just on the data collected and acknowledge the weaknesses in the data set. A shorter, more concise, manuscript would be much more effective to get the data out there.

AC: *Once again, we thank the reviewer for pointing out both, the strengths and the limitations in the originally submitted manuscript. Following the concern made on the length of the paper, we will reduce the revised manuscript, focus only on the important issues, and not compromise the quality of the manuscript.*

Abstract

RC: Ln 25 – the N2O flux was more than double the cropland than bushland, why do you say is was not different between the four sites?

AC: *We thank the reviewer for pointing this out. Actually the difference in annual mean N_2O emissions were significantly higher in the cropland (2.7±0.6 µg m^{-2} h^{-1}) than in the conservation land (1.6±0.4 µg m^{-2} h^{-1}), grazing land (1.5±0.4 µg m^{-2} h^{-1}), and bushland (1.2±0.4 µg m^{-2} h^{-1})(Kruskal-Willis rank test). In contrast, no difference was observed between the other three sites.*

RC: Ln 31 – Over the course of the measurement period or between sites, CO_2 was correlated with soil moisture?

AC: *In all our study sites and across the seasons, soil CO_2 emissions were positively correlated with soil moisture.*

RC: Ln 30-40 - The abstract does not have a clear message. Soil C is important, but soil moisture is driving fluxes, but NDVI is correlated. What is the take home point?

AC: *We will rephrase the abstract as follows in order to provide a clearer message.*

"Based on our results, soil C and soil moisture are key drivers of soil GHG emissions in all land use types. In addition, vegetation cover explained the seasonal variation of soil CO_2 emissions as depicted by the strong positive correlation of between NDVI and CO_2 emissions. We conclude that with more green (active) vegetation cover higher CO_2 emissions occur due to enhanced root respiration compared to drier periods in the year.

Introduction

RC: The introductory paragraph never says what produces and consumes GHGs from the soil?

AC: *We will include the following information into the introduction of the revised manuscript. Each of the GHGs observed is either consumed or produced via biogeochemical processes. For instance, methane is produced by methanogenesis process under anaerobic conditions and consumed by methanotrophic microorganisms under aerobic conditions (Serrano-Silva et al., 2014). CO_2, is in our case (dark chambers) produced in the soil during decomposition of organic matter and root respiration which produces CO_2. Similarly, CO_2 is produced via plant respiration in the case plants were present in the chamber (Oertel et al. 2016). N_2O on the other hand is produced as an intermediate product of denitrification and nitrification processes amongst others (Butterbach-Bahl et al., 2013).*

RC: ASALs is an acronym that could be avoided by using drylands, or arid ecosystems. Overall there are many acronyms used that could be avoided.

AC: *We thank the reviewer for this suggestion. Overall, we will have a look at the use of abbreviations. In the case of ASAL, we will use drylands in the revised manuscript. A similar point was made by reviewer 2.*

Methods

RC: Ln 187 – ssp

AC: *Corrected to spp*

RC: Ln 240 – This is a large assumption. Does the sampling really represent the average flux of the day for your ecosystem? At least one of those references is for a temperate forest where they did measure the 24-hour cycle, which likely has a very different cycle than these ecosystems due to differences and vegetation type and environmental variables.

AC: *We agree that this is partially an assumption, and yet one has to compromise, as a more frequent sampling was impossible. Overall, the theory of sampling in the respective morning hours is sound (Parkin and Venterea, 2010), as temperatures increase during the day and thus microbial processes similarly are enhanced. Of course, the fact that moisture and other factors are essential drivers following our results this may be misleading and yet again the drivers suggested are for the whole dataset, i.e. across seasons and not necessarily aiming at explaining diurnal variations. We have done diurnal GHG measurements in other regions in Kenya with a portable laser absorption spectrometer where we found clear temperature dependencies during the course of the day (data not shown here, as this is part of another study, Butterbach-Bahl in prep.).*

RC: Ln 252 – The pooling method reduces the sample # to 3 for each LUT time period instead of 9?

AC: *This is correct, the three gas flux estimates that we have at the end of the day for each LUC type is thanks to the pooling method derived from 9 distinct locations (chambers). With this approach, one can still account for spatial heterogeneity while reducing the overall number of GHG samples to be analysed in the laboratory* (Arias-Navarro et al., 2013).

RC: Ln 290 – was temperature measured in the chamber?

AC: *We recorded the air temperature in the headspace of each chamber at the same interval as gas pooling (recorded at T1, T2, T3 and T4). This temperature is then used to correct the gas flux during flux calculation.*

Results

RC: Ln 385 – What are the errors on the fluxes? They are so small for soil CO_2 fluxes. Report error and sample size.

AC: *The sample size per season is seven daily average values derived from three flux values per day from each land use type. The error bar presented here is the standard error of the three flux values per day.*

RC: Figures 4 and 5 are good. Keeping the color scheme, the same would be helpful.

AC: *The two figures provide different information and having them in the same color scheme might be misleading. Figure 4 shows the difference in emissions between the land uses types while figure 5 gives the differences in emission between the wet and dry season.*

RC: Figure 6 – put in same color scheme.

AC: *This is a relevant point and we tried to have them in the same color scheme of figure 4. However, this then made it very difficult to differentiate between the LUC types***.**

RC: Figure 7 – this is at such a large scale, I don't find it very informative. Fig 6 shows the data used.

AC: *We agree and we will move Figure 7 into the appendix and keep Figure 6 in the revised manuscript.*

Discussion

RC: Different terms are being used, soil respiration; soil CO_2 emissions, ecosystem soil respiration (?) Make this consistent.

AC: *We thank the reviewer for pointing this out. In the revised manuscript, we will only use the term "soil* CO_2 *emission".*

RC: There is quite a bit of speculation in the discussion. It would be better shortened and more focused on the data collected, not the data lacking that could explain the patterns. This is true for CO2 and N2O sections.

AC: *Following this suggestion and a similar point being raised by Reviewer 2, we will make the discussion shorter and more concise – some examples are:*

Example 1

Original *-* CO_2 *emissions from the soil differed significantly between the land-use types. Higher* CO_2 *emissions were particularly observed in the conservation land followed by grazing land and bushland, while lowest levels were recorded from the cropland. We observed the same trend with SOC, and thus we attributed the difference in* CO_2 *emissions between the land uses to SOC as observed (see Table 1). This is in line with a similar study by La Scala et al. (2000), which recognized SOC as a key driver of* CO_2 *emissions from the soil, as it is the primary source of energy for soil microorganisms (Lal, 2009).*

Revised *- Highest mean* CO_2 *fluxes were observed from the conservation land followed by grazing land and bushland, and the lowest from cropland. Soil C content also showed the same trend (conservation land > grazing land > bushland > cropland), which is the primary source of energy for soil microorganisms (Lal 2009) and thus affecting* CO_2 *emissions. Therefore, we attributed this variance to the difference in land use and management activities playing a major role in modifying both biotic and abiotic factors (Pinto et al., 2002).*

Example 2

Original *- Soil* CO_2 *emissions and mean soil C content were lowest in cropland. Root respiration in cropland depends on periods of live roots in annual crop fields and on the biomass of roots during the initial growing season (Raich et al., 2000). Therefore, the continued removal of crop residues* *during harvesting and frequent tillage affected both root respiration and SOC. As much as crop residues contribute to carbon stocks through their mineralization (Nandwa, 2001), most maize residues were used as livestock feed and sometimes as fuel, while bean residues were removed completely during the harvest and burned.*

Revised *- With the lowest CO_2 emissions being reported from the cropland, we attribute this observation to the continued tillage and removal of crop and crop residues during land preparation, weeding and harvesting, affecting both root respiration and soil C content (Raich et al., 2000; Nandwa, 2001). In East Africa and in smallholder farming systems, most of the crop residues are used as livestock feed and fuel.*

Example 3

Original *- Manure inputs provide easily degradable substrates of C and N leading to enhanced soil CO_2 emissions (Janssens et al., 2001; Davidson and Janssens, 2006). However, manure input in cropland was very low (approximately 20 kg in a 1.5 ha farm per month) and thus no measurable effects in CO_2 emissions were detected. This was opposite to our hypothesis. Another reason could be that soil fertility was too low to have a detectable influence on CO_2 emissions (Pelster et al., 2017). Our results are in the same magnitude with those of Rosenstock et al. (2016); Farai Mapanda et al. (2011), and Pelster et al. (2017), who also did not detect any change in CO_2 emissions after manure application and attributed this to the low input of manure to the maize and sorghum plots.*

Revised *- Manure inputs in cropland were very low (about 20 kg per month on a 1.5 ha farm) and thus no measurable difference on CO_2 emissions were detected. Several other studies observed the same scenario from low manure input in maize and sorghum plots (Rosenstock et al., 2016; Farai Mapanda et al., 2011, and Pelster et al. 2017).*

Example4

Original *- Soil N_2O emissions can vary highly over time, as regulated by factors such as soil moisture, temperature, aeration, ammonium and nitrate concentrations, pH, and mineralizable carbon (Butterbach-Bahl et al., 2013). However, we did not document any significant difference in N_2O emissions between the four land uses. At all the sites, N_2O emissions were very low, and this we attributed to the observed low soil N content (see Table 1). According to Pinto et al. (2002) and Grover et al. (2012), savanna ecosystems have a very tight N cycling, which transcends to low N availability. Thus, available N is taken up by vegetation, leaving very little for denitrification (Castaldi et al., 2006; Mapanda et al., 2011). Our results are consistent with low N_2O emissions 610 observed in a Brazilian savanna (cerrado) by Wilcke et al. (2005), who also reported low N levels in their study area. Very low N_2O emissions due to poor nutrient availability have also been observed in other savanna landscapes (Scholes et al., 1997; Castaldi et al., 2016). Soil N_2O in cropland match those of Rosenstock et al. (2016), who also attributed the low soil N_2O emissions to poor nutrient availability in the soil*

Revised *- Our results showed low N_2O emissions from all the LUTs, which we attributed to the low soil N content observed (see Table 1). Savanna ecosystems are characterized by very tight N cycling,* *which transcends to low N availability (Pinto et al., 2002 and Grover et al.,2012) and most of this N is taken up by vegetation, leaving very little for denitrification (Castaldi et al., 2006; Mapanda et al., 2011). The flux results observed from the conservation land, grazing land and bushland are consistent with those observed in a Brazilian savanna by Wilcke et al. (2005). Many other studies from similar ecosystem reported comparable N_2O flux magnitudes (Scholes et al., 1997; Castaldi et al., 2016; Mapanda et al., 2010). The higher N_2O emissions observed in June and July from our cropland site after the maize and bean harvests are likely occurring due to the absence of plants.*

RC: Interesting CH_4 just gets one sentence because it is small: : : but this is important too!

AC: *For the completeness of the paper, methane emissions have to be mentioned. Even though Reviewer 2 suggested to remove everything related to CH_4, we decided to keep this information in the manuscript for 2 reasons: (1) completeness in terms of greenhouse gases, and (2) even if the contribution of CH_4 is low, this is an important results and similar measurements may not have to be repeated.*

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Authors Response:

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RC 2

D. Otieno (Referee)

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Received and published: 21 November 2019

RC: This is interesting study conducted in semi-arid parts of Kenya, where similar data are quite scarce. The set-up is an area characterized by a series of activities. It is a surprised that there is some form of cultivation/farming in an area that looks more like Tsavo national Park. Nonetheless, the study provides valuable data that extend our knowledge of ecosystem gas fluxes in this part of the world.

AC: *We would like to thank Mr. Otieno for this review and his valuable comments.*

RC: The study was conducted in a relatively poor soil. What the authors failed to mention, especially for the cropped and grazed sites was the slope of the field. I tend to imagine that erosion must be playing a critical role in mineralization processes in this place. It looks like the organic/humus, top soil layer is completely gone and what remains is mainly the mineral soils. Unfortunately, the paper is already too long and I will not recommend inclusion of more information on land use history, which would have been helpful in understanding/interpreting these results.

AC: *The study area are located is the lowland of the Taita Taveta county, which is very flat. The cropland is at 1070 m a.s.l, bushland at 1076 m a.s.l, grazing land at 970 m a.s.l, and conservation land at 928 m a.s.l. The cropland is received very small quantities of manure and no chemical fertilizer inputs and thus no significant difference in soil C content with the other land use types. In the grazing area, overgrazing was evident as most of the soil was bare especially in dry season. This contributes to soil erosion and compaction of the land by wind and rain and even the livestock while grazing. We will add this information briefly in the revised manuscript.*

RC: It's very surprising that temperature and soil moisture had no influence on soil CO2 fluxes. Could it be the method of data collection, with significant data collection gaps that led to this?

AC: *Soil CO_2 emissions were positively correlated to soil moisture. However, variation in soil temperature for the time of measurements during the day in both dry and the wet season were minor, and thus we found no statistically significant effect of soil temperature upon CO_2 emissions for the dataset. Other studies by Brümmer et al. (2009) and Livesley et al. (2011) also found that soil moisture controlled CO_2 emissions from savanna soils, rather than soil temperature. However, if we have had the opportunity to measure more frequently – i.e. following a diurnal course – we are confident that an effect of temperature exists. For instance, we found such diurnal course in GHG emissions in a similar ecosystem in Kenya. This was part of another project and is consequently not shown here.*

RC: For future, the authors need to consider higher frequencies of data collection. In such arid ecosystems, evaporation is quite high and it is likely that critical information is lost by not collecting data more regularly.

AC: *For this study, the sampling frequency was based on seasonal variation, thus the campaigns were targeting the wet, transition and dry season and when moisture and/or management practices are likely to impact GHG emissions. Certainly, we would have preferred more frequent measurements, though given the research question asked and the available resource for this project, we had to make a compromise. However, there is a follow-up study in other Land Use Types with measurements that are more frequent.*

RC: CH_4 seems to contribute little to this paper, why not exclude it completely? I do not see the two lines of discussion on CH_4 are of major benefit to the readers. The paper is already too long and probably removing all the descriptions on CH_4 could reduce the number of pages.

AC: *We agree that the importance of methane emissions is negligible when compared to the other gases. However, our aim was to look at all three GHGs in this study and due to the lack of available GHG emissions data from such land cover types in this region of the world we still think its beneficial to report these here. Certainly, in order to not further lengthen the paper, we decided to keep this information as short as possible.*

RC: The word "Soil Organic Carbon SOC" is introduced in the introductory part of the Ms. In the methods, there is total soil carbon and in the results, I met Soil Carbon. In the discussions, SOC becomes the main discussions line. The authors need to be consistent in the use of these terms, otherwise the readers get confused.

AC: *We thank the reviewer for pointing this out and we will harmonize in the revised manuscript accordingly.*

RC: Ln 65. Not all savannah belongs to the ASALs. The humid savannas are relatively wet, with green vegetation almost throughout the year. It is therefore not right to make such a sweeping statement.

AC: *Noted with thanks and we adjust the revised manuscript accordingly and use drylands instead of ASALs.*

Specific comments

RC: Ln 67. Note that shrubs are woody vegetation

AC: *Noted with thanks.*

RC: Ln 88. Revise the sentence. Overstocking leads to grazing pressure. The way the sentence is written is redundant.

AC: *Done*

RC: Ln 96-7. ---Croplands are still being cleared from natural vegetation----re-write the sentence, it's not making the intended meaning.

AC: *Done. Revised --Natural vegetation is being cleared to make way for the expansion of cropland*

RC: Ln 104, what's "cropland farming"?

AC: *Here we refer to cropping agriculture in the savanna.*

RC: Ln 153. The authors need to be clear on the physiognomic characterization of the vegetation they are studying. Here you have woodlands, bushlands and on line 155 you have wood bushlands, which is which?

AC: *We harmonize this in the revised manuscript to bushland as found in Tsavo East and West national park.*

RC: Ln 156 are Lions also grazers?

AC: *Lion are not grazers. On this line, we were mentioning the fauna that the ecosystem supports in general to highlight the importance and the functions of the park.*

RC: Ln 160 –other important land use(s)

AC: *Corrected*

RC: Ln 173. Is the farm rain-fed or not? Are there other sources of moisture input apart from rain?

AC: *The farm is totally rain fed.*

RC: Ln 237, how deep was the collar inserted into the soil?

AC: *The collars we inserted between 5cm to more than 8cm into the soil. We ensured the collars were inserted so the extend above the surface did not hold water during the rainy season and the collars were less likely to be trampled on and broken by large animals*

Result

RC: Label Fig. 3 as a and b

AC: *Done*

RC: Ln 377, Sand proportion was lower than what? In comparative sentences, learn also to use “lowest” or “highest” see ln 417.

AC: *Sand proportion was lowest in the grazing land (64.3±0.4 %) than in the other study three sites. We will adjust the phrasing in the revised manuscript.*

RC: Ln. 456 present data/results according to the chronology of the figures and avoid this back and forth.

AC: *Done*

RC: Ln 481. Delete (in) before during.

AC: *Done*

Discussion

RC: SOC is only mentioned in the introduction but not in the methodology or results, yet it becomes very prominent in the discussions. Be consistent in the use of terms.

AC: *Noted with thanks.*

RC: Ln 525 is not correct. You cannot attribute the differences only to vegetation. It is definite that land use itself leads to the differences in soil C. Although this is argued correctly in the later sections, this section should be revised.

AC: *Corrected*

Ln 548. The argument with clays is a bit far-fetched anyway.

AC: *We removed this argument in the revised manuscript.*

RC: Ln 592. ---temperature was measured “down” to 5 cm. I would imagine that 5 cm depth is almost at the surface. What was the deciding factor for installing temp/moisture sensor at this depth? This depth, being close to the surface is associated with very strong temperature fluctuations. It may be one of the reasons why the authors found no temperature correlation with CO_2 efflux. Most grass roots, cereals included, have roots located within 10 cm, and may extend down to 30 cm. the woody vegetation in such dry places have their roots even deeper. Trying to establish relations with variables measured at 5 cm may not yield positive results.

AC: *According to a study by Pavelka et al. (2007), daily dynamic of soil CO_2 fluxes are affected by soil temperature near the soil surface and hence for correlation between soil CO_2 emissions and soil temperature, the measurement of soil temperature at the soil surface, is highly recommended to avoid the inaccuracies. Coupled with this, the ProCheck handheld GS3 sensor (Decagon Devices Inc) for soil moisture and temperature that we were using could only measure up to 5cm. Because, we were taking measurement within or close to the chamber collars, we did not want to cause any soil disturbance. This is also recommended by the GRACENet protocol we were using as our reference protocol.*

RC: Ln 593 check the sentence. How does root respiration tap moisture?

AC: *Noted. Here we mean roots can still tap moisture from deeper profile and thus root respiration can continue even after the surface moisture has dried up.*

RC: Ln 640. Consider soil erosion and volatilization also.

AC: *This is an important point and we thank the reviewer for pointing this out.*

RC: Ln 651. Use “dung” instead of faeces.

AC: *Corrected*

RC: Ln 665 what’s T? From nowhere, you introduce T.

AC: *T stands for soil temperature.*

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Authors Response:

Two reviewers have reviewed the manuscript and an additional comment was made in the open discussion. Before, responding to each reviewer and comment individually, we would like to thank for the constructive comments and informative feedback.

The document is structured as follows: each of the short comment (indicated by SC) is first repeated followed by our response (indicated as AC and in italic). Where relevant we either include a rephrased sentence already or explain on how we intent to implement suggested changes.

Short comments

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I want so suggest some changes for that publication:

SC: N2O fluxes are sometimes given in µg N2O-N m^{-2} h^{-1} (e.g. l. 295 or 420) and in some graphics they are given in N2O (µg m^{-2} h^{-1}) (e.g. figure 4 or figure 5). This is the same for CO_2. Units should be used consistent, so that you can compare the fluxes.

AC: *We thank Mr. Oertel for pointing this out and have made the necessary correction.* CO_2 *(mg* m^{-2} h^{-1}*)* N_2O *(µg* m^{-2} h^{-1}*) and* CH_4 *(mg* m^{-2} h^{-1}*).*

SC: l. 171: Height a.s.l. is only given for the cropland site and should be given as well for the other sites.

AC: *This will be done in the revised manuscript. Cropland is at 1070 m a.s.l, bushland at 1076 m a.s.l, grazing land at 970 m a.s.l, and conservation land at 928 m a.s.l.*