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GREENHOUSE GAS EMISSIONS FROM SAVANNA (*MIOMBO*) WOODLANDS: RESPONSES TO CLEARING AND CROPPING

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ABSTRACT

Natural vegetation represents an important sink for greenhouse gases (GHGs); however, there is relatively little information available on emissions from southern African savannas. The effects of clearing savanna woodlands for crop production on soil fluxes of N_2O, CO_2 and CH_4 were studied on clay (Chromic luvisol) and loamy sand (Ferric acrisol) soils in Zimbabwe. Maize (*Zea mays* L.) was the test crop. Gas samples were measured from undisturbed, cleared and cultivated woodlands using the static chamber methodology involving gas chromatography for ample air analysis. Site and climatic variables were particularly important determinants of GHG emissions. Over an average of 154 days emissions of 0.8 – 2.5 kg N_2O-N ha^{-1}, 1146 – 2847 kg CO_2-C ha^{-1} and 7.4 – 38.5 kg CH_4-C ha^{-1} were estimated during a season that followed a relatively drier one. Fertiliser-N significantly increased GHG emissions on cropped plots (clay soil). The undisturbed woodland with a relatively higher tree density (loamy sand) was an important GHG source. The high CH_4 fluxes from woodlands provide ground based validation of satellite observations of CH_4 hotspots in sub-Saharan Africa, and have considerable implications on regional GHG balance.

Key Words: Carbon dioxide, methane, nitrous oxide, Zimbabwe

RÉSUMÉ

La végétation naturelle représente une source importante de gaz à effet de serre (GES) ; Par ailleurs, il existe relativement peu d’informations disponibles sur les émissions dans les savanes sud africaines. Les effets du déboisement de la savane pour la production agricole sur le flux du sol de N_2O, CO_2 et de CH_4 ont été étudiés sur les sols argileux (luvisol chromique) et sablo limoneux (acrisol ferrique) au Zimbabwe. La plante test considérée était maïs (*Zea mays* L.). Des échantillons de gaz étaient collectés des forêts non perturbées, défrichées et cultivées en utilisant la méthode de la Chambre statique impliquant le gaz chromatographie pour l’analyse de l’air. Le site et les variables climatiques étaient particulièrement des déterminants importants des émissions de gaz à effets de serre. Sur une moyenne de 154 jours des émissions de 0.8 – 2.5 kg N_2O-N ha^{-1}, 1146 – 2847 kg CO_2-C ha^{-1} et 7.4 – 38.5 kg CH_4-C ha^{-1} étaient estimées au cours d’une saison qui a suivi celle relativement la plus sèche. L’engrais N significativement augmenté les émissions de gaz à effets de serre sur les parcelles cultivées (sol argileux). Le sol (sablo-limoneux) sous forêts non perturbées avec relativement une plus grande densité d’arbres était une source importante de gaz à effets de serre. Les flux élevés de CH_4 en condition de végétation naturelle fournit une base de validation des observations satellitaires du CH_4 en Afrique subsaharienne, et ont une des implications sur la balance régionale des gaz à effets de serre.

Mots Clés: Dioxyde de carbone, méthane, oxyde nitreux, Zimbabwe

INTRODUCTION

Land use change has made a significant contribution to the increasing atmospheric concentrations of the greenhouse gases (GHGs), namely carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (Foley *et al.*, 2005; Solomon *et al.*, 2007). Changes that have taken place within forest and cropland ecosystems are particularly important and these have interacted with external drivers such as climate, giving rise to large scale regional changes in ecosystem functioning (Davidson *et al.*, 1993; MacDonald *et al.*, 1996; Compton and Boone, 2000). Forests are widely considered to act as net GHG sinks through carbon (C) uptake by photosynthesis (Milne *et al.*, 2000; Williams *et al.*, 2008). However, land deforestation followed by cultivation would generally increase soil respiration and reduce the soil organic C pool (Chidumayo and Kwibisa, 2003; Chen *et al.*, 2005), thereby making soil an additional source of GHGs to the atmosphere. There have been relatively few ground based studies of GHG emissions from Africa that can help us understand the importance of land use change in influencing C and N flows and balances. Such information is required in order to improve continental GHG inventories and inform policy developing on climate change adaptation and mitigation.

Savannas (ecosystems where trees and grasses co-exist) cover about 16 million km^2 or 11.5% of the global land surface, and are found in Africa, Australia, South America, India and Southeast Asia (Scholes and Hall, 1996). Savanna woodlands (*miombo*) occupy much of Zimbabwe (Fig. 1). *Miombo* is a vernacular word adopted to describe woodland ecosystems dominated by trees in the genera *Brachystegia*, *Julbernadia* and/or *Isoberlinia* (*Leguminosae*, sub-family *Caesalpinoieae*) (White, 1983). In Zimbabwe, *miombo* woodlands cover about 40% or approximately 156 000 km^2 of the country (SASRN, 2001), and an estimated area of 2.7 million km^2 in southern, central and east Africa (Frost, 1996), which is now 2.4 million km^2 (WWF, 2010a) because of land use change. The livelihoods of people and wildlife communities in these regions are dependant on resources (including, habitat) and products including wild foods and firewood drawn from *miombo* woodlands (Clarke *et al.*, 1996). According to Kundhlande *et al.* (2000), the estimated economic value of C sequestration in Zimbabwe's woodlands of both Communal and State Forests is substantial, but 25% lower on area basis, than the value of converting these lands to individually held croplands. Such an analysis using the shadow price of carbon (DEFRA, 2009) is not likely to place significant value on the conservation of woodlands.

The total natural forestland in Zimbabwe was estimated at 18.9 million ha (about 48% of total land area), against about 3.4 million ha cropland (FAO, 2002; Earth_Trends, 2003). However, these figures have not been constant as approximately 70,000-100,000 ha of the woodlands area were converted to cropland every year up to the early 1990s (Moyo *et al.*, 1991). Unpublished data from the Zimbabwe Forestry Commission (Research and Development Division) shows that natural woodland area changed from 20,790,000 ha in 1992 (ZFC, 1998) to 16,544,000 ha in 2008, representing a change of about 265,000 ha per year. In the same assessment, the area under cultivation increased from 10,739,000 ha to 16,114,000 ha for the same period. This implies that the carbon and nitrogen balances in southern Africa are likely to be shifting in favour of more GHG such as nitrous oxide, methane and carbon dioxide . It also relates to land degradation described by Henao and Baanante (2006) as the current focus of global climate change debates, and resource conservation and policy development in Africa. The magnitude of impact of this conversion on GHG fluxes in Zimbabwe, and southern Africa is poorly understood, but has the potential to be of major significance for global change.

The objectives of this study were to assess the impact of clearing of *miombo* woodlands and maize-cropping on the magnitude of soil emissions of N_2O, CO_2 and CH_4 in Zimbabwe.

MATERIALS AND METHODS

Study sites and weather conditions. The study was conducted in the 2006/2007, 2007/2008 and 2008/2009 cropping seasons at the University of Zimbabwe Farm (UZ-Farm) located about 15 km north of Harare (31° 00' 48'' E; 17° 42' 24'' S), and the Grasslands Research Station (GR-Station) located about 67 km east of Harare (31º 29' 00'' E; 18º 10' 14'' S) (Fig. 1). The UZ-Farm is 2000 ha, and is subdivided into 850 ha for arable land, 1050 ha for grazing land and 100 ha for woodland and farm buildings. Typical mixed *Brachystegia spiciformis* and *Julbernardia globiflora* woodland occupy most of the woodland area. The GR-Station covers about 2700 ha of land, subdivided into 300 ha for arable land, 2200 ha for grazing land and woodland; and 200 ha for roads, buildings and wasteland. Vegetation at GR-Station is wooded scrubland with *Terminalia sericea* and *Burkea Africana*, in association with *Combretum* and *Acacia* species. *Brachystegia spiciformis* and *Julbernardia globiflora* occur in some places (including the one selected for this study). The red clay soil at UZ-Farm is classified as Harare 5E.2 (Zimbabwean soil classification) or Chromic luvisol (FAO) derived from dolerite; while the brown loam-sand at GR-Station is Marondera 7G.2 (Zimbabwe) or Ferric acrisol (FAO) derived from granite (Nyamapfene, 1991). Other soil and site characteristics are given in Table 1.

The two sites experience a sub-tropical climate. The daily rainfall distribution and daily maximum and minimum temperatures at both sites are shown in Figure 2. January was the wettest of all rainy months, especially in season II (2007/2008) where close to 40 and 30% of the total rainfall was received in January for the UZ-Farm and GR-Station, respectively. Mean annual air temperatures were largely similar at the UZ-Farm and GR-Station: 18.8 and 18.3 °C, 18.4 and 18.1 °C, and 19.6 and 18.5 °C for the 2006/2007, 2007/2008 and 2008/2009 annual periods, respectively, and were consistent with the long term mean maximum and mean minimum temperatures in Table 1.

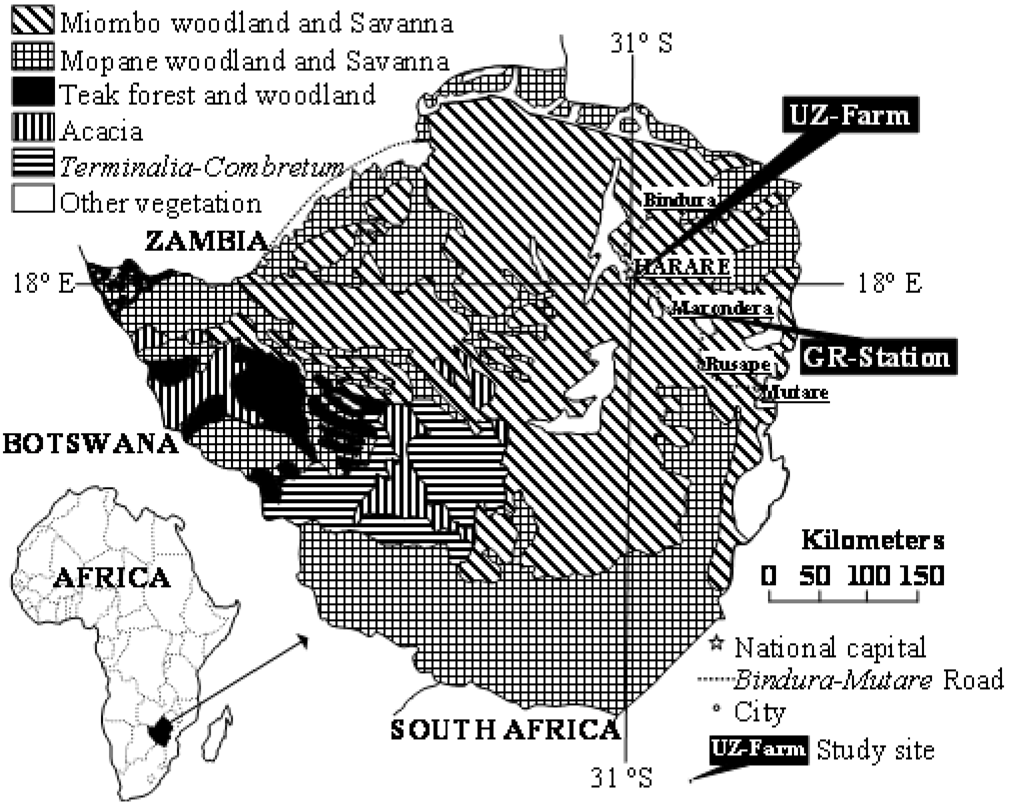

Figure 1. The Rattray and Wild (1961)'s vegetation distribution map for Zimbabwe, showing a generalised version of areas covered by the indigenous woodlands. Areas cleared after this distribution survey cannot be mapped at this scale.

TABLE 1. General characteristics of the study sites including climate data covering the period 2005 – 2010, soil properties (mean ± standard deviation) in the 0-0.1 m depth and vegetation status of woodlands in 2006

Characteristic	UZ-Farm	GR-Station
Altitude (m above sea level)	1505	1637
Mean annual rainfall (mm yr^{-1})	748 ± 176	829 ± 79
Mean maximum temperature (ºC)	26.1 ± 0.7	24.4 ± 0.3
Mean minimum temperature (ºC)	12.4 ± 0.4	10.5 ± 0.2
Soil type (FAO)	Chromic luvisol	Haplic lixisol
Soil parent material	Dolerite	Granite
Slope (%)	2-3	< 2
Soil pH (in water)	5.8 ± 0.6	5.2 ± 0.7
Bulk density (g cm^{-3})	1.49 ± 0.04	1.81 ± 0.06
Soil organic C (%)	1.66 ± 0.55	0.95 ± 0.06
Clay content (%)	51 ± 0	11 ± 0.7
Cation exchange capacity (cmol$^{(+)}$ kg^{-1})	9.5 ± 1.5	4.2 ± 0.1
Tree density (ha^{-1})	2604 ± 429	4896 ± 729
[a]Shrub density (ha^{-1})	2500 ± 977	3854 ± 1310
[b]DBH range (and median) (m)	0.05 – 0.27 (0.10)	0.04 – 0.15 (0.08)

[a] woody vegetation with height of <2 m; [b]tree diameter at breast height

Experimental treatment and management. Two identical experiments were conducted in the woodlands, one at the UZ-Farm and the other at the GR-Station. Four kinds of treatments were introduced, each on a plot measuring 4 m x 6 m in area arranged in a randomised complete block design with four replicates. The treatments were: undisturbed woodland; cleared woodland without cultivation; cleared woodland with cultivation, without N-fertilisation (maize-cropped), and cleared woodland with cultivation, with fertilisation (120 kg N ha^{-1}).

The clearing of tree stands from just above-ground was carried out once in October 2006 (about two weeks before the onset of the cropping season) by hand using axes, and cultivation was undertaken manually using hand picks to achieve a plough depth of about 0.15-0.20 m.

Sowing positions were marked at 0.9 m x 0.45 m spacing using hoes on cultivated plots, and a locally common maize variety (SC513, with 57 days to silk and 126 days to maturity (Seed-Co, 1998) was sown to target two plants per position. Mineral N fertiliser (NH_4NO_3, 34.5% N) was applied at a rate of 120 kg N ha^{-1}, 50% at sowing and the remainder in the following six weeks after sowing, (at a distance of about 5 cm from the crop stem). In addition, annual basal dressings of P (30 kg ha^{-1}, as single super phosphate) and K (30 kg ha^{-1}, as muriate of potash) were applied in holes of all cropped plots before sowing the seed. Basal dressings concurred with sowing to minimise mechanical operations, and the seed was placed at a distance of about 5 cm from fertilisers within each hole to reduce salt stress during crop emergence. The basal dressing was closely related to the local general recommendations of 300-400 kg ha^{-1} of N:P:K (8.0:7.0:6.3); while top dressing is locally recommended at 250-300 kg ha^{-1} NH_4NO_3 from six weeks after sowing. The crop was kept weed-free during cropping by hand-hoeing.

Sampling. Gaseous emissions from soil were trapped using open-bottom and transparent polythene chambers with an area of 0.40 m x 0.28 m, (0.2 m high) and a net volume of 0.019 m^3, using a method similar to that reported by Rees *et al.* (2006) and Mapanda *et al.* (2011). Each chamber was placed above the sampling area located randomly within a plot. For the cropped plots, the chamber was positioned such that it protruded into the intra-row spacing with its width covering more than half of this spacing. This was partly to get as close as possible to where the fertiliser was applied, without disturbing crop roots, and also to use crop

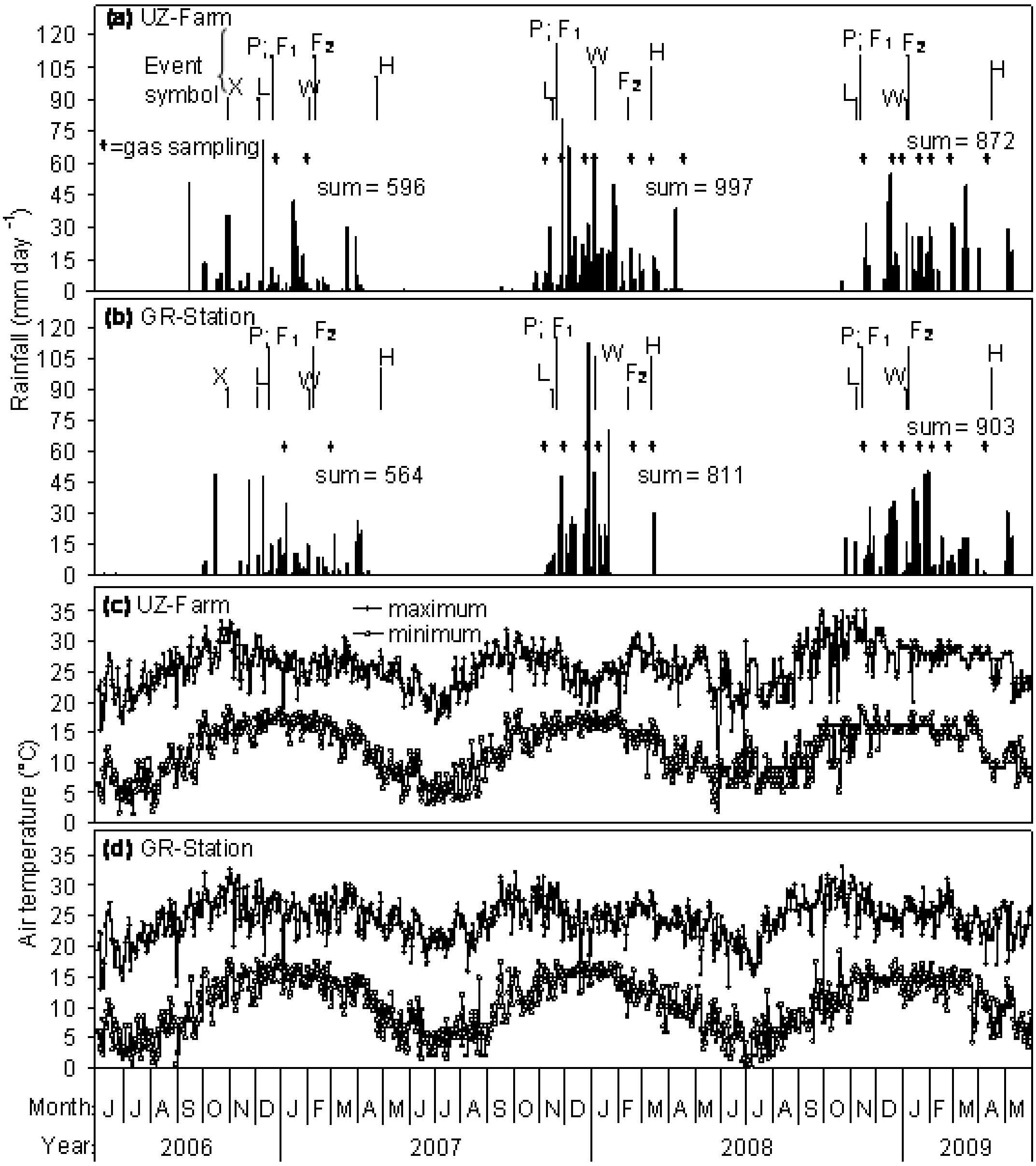

Figure 2. Rainfall distribution and events sequence (X, trees clearing; L, land preparation; F$_1$, initial fertiliser application; F$_2$, second N-application; W, major weeding; and H, harvesting) (a, b), and daily maximum and minimum air temperatures (c, d) during 2006-2009.

canopy to reduce excessive heating of chambers from direct sunlight. To avoid gas loss between the soil and chamber edges, a small chisel was used to fasten the contact between the chamber base and the surrounding soil. This was particularly important on non-cropped plots and when the surface soil was relatively dry. The emitted gas in each chamber was collected into pre-evacuated 20 cm^3 glass vials using a 50 ml-graduated syringe, once immediately after securing the chamber on the sampling area and once after one-hour of trapping the gas. In addition, a separate linearity test was carried out once in season III by similarly collecting the gas from three chambers at 10 minutes intervals for 60 minutes and plotting the fluxes against time.

Gas sampling was carried out at intervals shown in Figs 2a and b, in order to compare the relative treatment effects on GHG fluxes during the rainy season only since high moisture content during this period would be expected to trigger off more considerable GHG fluxes than during the dry period (Rees *et al.*, 2006; Dick *et al.*, 2008).

Soil samples were collected, initially and following each gas sampling, using a bucket auger at 0-0.15 m depth, and at two places within an area where a gas chamber was placed in each plot. Soil temperature was measured *in-situ* at three randomly selected positions within each plot, using digital soil thermometers with 0.1 m long stainless steel probes. Air temperature was measured at a height of approximately 1 m above ground. Both soil and air temperatures were measured at the first and second gas collection time from each plot. Soils were analysed for water content, mineral-N (NH_4^+-N and NO_3^--N), pH and organic C.

The maize crop was harvested at about 18 weeks after sowing in seasons I and II. These harvests were about a month earlier than the normal harvest time for dry maize, in order to recover all above-ground biomass, because much of the crop had prematurely dried out due to severe moisture stress at the UZ-Farm for season I and at GR-Station for season II. The harvesting for seasons I and II was conducted by cutting all above ground crop material within a net plot area of 3 m x 3 m. However, in season III the crop was harvested after reaching physiological maturity using the same procedure, but the materials were subdivided into grain, shelled-cob and maize residue, and weighed for above-ground biomass. Harvested crop materials were weighed, and for season I and II sub-samples of 3-4 whole-plants were collected from each plot for moisture correction and determination of total plant N. For season III the analysis of plant samples were done separately for grain, shelled-cob and maize residue. Moisture correction and determination of total plant N were done using the methods described by Okalebo *et al*. (2002).

Analysis of samples. Nitrous oxide, CO_2 and CH_4 were quantified by Gas Chromatography (GC model: Hewlett Packard 5890, Series II, Avondale, PA, USA) at Scottish Agricultural College (SAC) in the UK. Nitrous oxide was determined using an Electron Capture Detector maintained at 380 °C; CO_2 was analysed using a Thermal Conductivity Detector, and CH_4 using a Flame Ionisation Detector. The emissions of N_2O, CH_4 and CO_2 were calculated as the differences in concentration between sampling time zero and sampling after one hour. Atmospheric pressure and temperature during the time of sampling were considered in the calculations (Mapanda *et al.*, 2011). In order to detect gas leakage from sample containers during transportation, samples with known gas concentrations were sent from the UK to Zimbabwe. These standard samples were then returned within 10 weeks to the UK, together with samples in similar containers but collected from the field for analysis. The concentrations of 16 vials containing CO_2, CH_4 and N_2O mixed in each vial were consistently between 92-100% of the original value, with a mean of 98%.

Soil water content (SWC), NH_4^+-N and NO_3^--N analyses were carried out immediately from fresh samples, while pH and organic C analyses were done after air drying of samples and sieving through a 2 mm and a 0.5 mm sieve, respectively. Soil analyses were done using the methods described by Okalebo *et al.* (2002). Mineral-N was extracted mechanically by shaking 5 g of a soil with 50 ml of 2M KCl for one hour, and filtering. Ammonium-N was determined after steam distillation of the extract in MgO that is, trapping the NH_4^+-N in boric acid plus indicator (bromocresol-methyl red) solution. The distillate (50 ml) was titrated with 0.005 M H_2SO_4 in a micro-burette. Nitrate-N was determined in the same sample by adding Devarda's alloy to reduce NO_3^--N to NH_4^+-N and distilling again into fresh boric acid, followed by titration with 0.005 M H_2SO_4.

The SWC was determined gravimetrically as soil weight loss on oven drying at 105 ºC till constant weight. Soil pH was measured in a 15 g to 75 ml soil-distilled water suspension with a pH meter (model: Corning 215) after shaking the suspension on a mechanical shaker for 1 hour.

The pH meter was calibrated using pH 4 and 7 buffer solutions. Total organic C was extracted by wet oxidation using concentrated H_2SO_4 and $K_2Cr_2O_7$, and determined by titrating with $Fe(NH_4)_2(SO_4)_2{\cdot}6H_2O$ solution.

Dry matter of harvested plant material was determined by weight difference upon oven drying at 70 ºC for about 3 to 5 hours till constant weight, depending on plant part and its moisture content, The plant materials were ground to pass through a 2-mm sieve. Total N content was determined using the semi-micro Kjeldahl method (Bremmer and Mulvaney, 1982). Three replicates were made for each sample in the laboratory.

Data analysis. Homogeneity of variances and normality tests were carried out on the data using the Levene's and Kolmogorov-Smirnov's Tests, respectively, at 5% level. The data did not meet all assumptions of the Fisher-founded Analysis of Variance (ANOVA) even after transformation, and hence the Kruskal-Wallis one-way ANOVA by ranks was used to establish significant treatment responses ($P<0.05$) using GenStat 7.2 (Discovery Edition, Lawes Agriculture Trust UK). A pair-wise separation of significantly different treatment means was done using the Mann-Witney test. Bivariate correlation analysis (two-tailed) was performed using the Spearman's Rank Correlation Coefficient (r_s); while regression analysis was conducted to measure the relative importance of each soil factor on GHG fluxes. The Statistical Package for the Social Sciences, SPSS 8.0 (SPSS Inc., USA) was used in testing data distribution, correlation analysis and calculating standard errors of means, as it was more convenient with tabulated output than GenStat. The total emissions or consumption of GHGs in seasons II and III were estimated from area under the fluxes-time graphs using the trapezoidal rule of integration (Whittaker and Robinson, 1967), for overall contrasting of the relative treatment effects.

RESULTS

Greenhouse gas fluxes and soil properties. The fluxes of N_2O, CO_2 and CH_4 responded significantly ($P<0.05$) to land use type, N fertiliser application and to season, particularly at the UZ-Farm (Figs 3a - f). Spatial variability in the fluxes of the GHGs, especially CH_4 was high. During the high rainfall period of season II, December-January, GHG emissions from the cleared woodland and the cleared and cropped land that was N-fertilised at the UZ-Farm, were between about 2 to 4 times greater than those from undisturbed woodland and cropped land without fertilisation. By contrast, the highest emissions from the GR-Station were observed on the undisturbed woodland in December of season II (120 µg N_2O-N m^{-2} hr^{-1}; 119 mg CO_2-C m^{-2} hr^{-1}; and 3.2 mg CH_4-C m^{-2} hr^{-1}). Cleared woodland had the lowest emissions of all GHGs during season II.

Season III, with evenly distributed rainfall, was characterised by low N_2O and CH_4 fluxes at both sites. Methane consumption in season III was observed in all treatments but the highest consumption, -44.4 µg CH_4-C m^{-2} hr^{-1} on cleared woodland at the UZ-Farm; -27.7 µg CH_4-C m^{-2} hr^{-1} on cropped plots without fertiliser-N at the GR-Station were in March after the rainfall peak period. In cropped plots with fertiliser, emissions of 31 µg N_2O-N m^{-2} hr^{-1} and 47.4 mg CO_2-C m^{-2} hr^{-1} were found during the peak of the rainy period, December in season III, compared with 222 µg N_2O-N m^{-2} hr^{-1} and 209 mg CO_2-C m^{-2} hr^{-1} from the same treatment in season II at the UZ-Farm. Nitrous oxide and CH_4 were positively correlated with CO_2 at both sites ($P<0.01$), but the relationships were more pronounced at UZ-Farm ($r_s = 0.71$ and 0.64, respectively) than at GR-Station ($r_s<0.10$ and 0.29, respectively).

SWC and soil temperature showed that season III was both wetter and cooler during the time of gas sampling at both sites, than seasons I and II (Figs. 4a–d). Temperatures of soil under tree canopies of the undisturbed woodlands were distinctly cooler than under the other land covers ($P<0.05$). There were no significant differences in SWC among different land covers at both sites. There was a positive correlation ($P<0.01$) between N_2O, CO_2 or CH_4 emission with SWC, but the relationships were more pronounced for the cropped treatment with fertiliser at the UZ-Farm (r_s, 0.38–0.59), and the undisturbed woodland at the GR-Station (r_s, 0.42–0.79). For the same treatments similar relationships were also apparent between GHG emissions and soil NH_4^+-N (Table 2) at the UZ-Farm ($P<0.01$; r_s, 0.25–0.56) and GR-

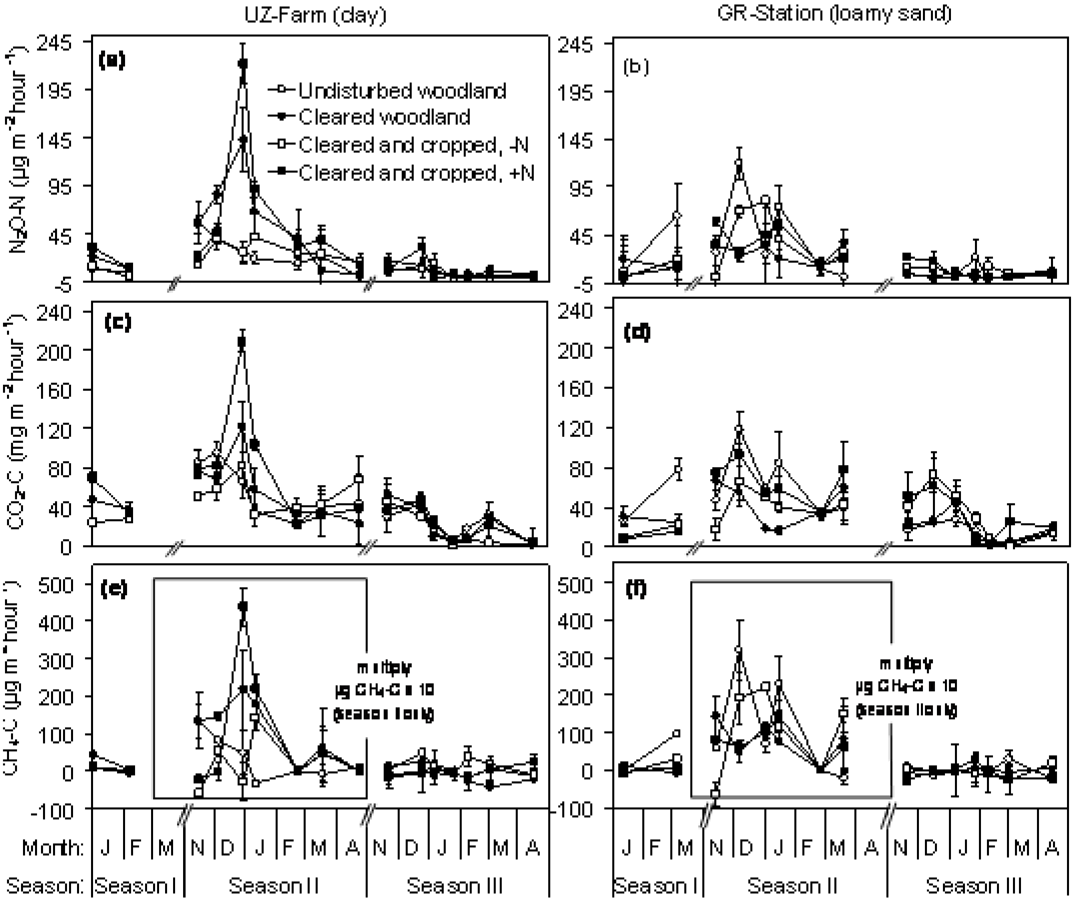

Figure 3. Soil N_2O, CO_2 and CH_4 fluxes from the experimental plots of different treatments at the UZ-Farm and GR-Station during 2006-2009. Error bars denote standard errors of means.

Station (P<0.01; r_s<0.10). There was a significant correlation between pH and GHG emissions (P<0.01; r_s, up to 0.38), while the remaining parameters (soil NO_3^--N, and organic C) were not significantly correlated with measured GHGs.

Total N_2O, CO_2 and CH_4 emissions per season from the four treatments (Table 3) showed that on the clay soil, N_2O emissions increased by 1.2, 0.2 and 1.6 kg N_2O-N ha^{-1} on cleared woodland, cropped plots without fertiliser and cropped plots with 120 kg N ha^{-1}, respectively, relative to undisturbed woodland in season II. These increases were also observed in season III, but at magnitudes of about 10-fold less than those of season II. The highest N_2O emissions for the loamy sand soil was found in the undisturbed woodland in season II, while the cleared woodland has the least total N_2O emissions on the same soil. A similar trend was noted for CO_2 emissions, while for CH_4 all treatments changed from sources in season II to CH_4 sinks in season III at the GR-Station. At this site, the highest CH_4 sink in season III was on cropped plots with N fertiliser; CH_4 consumption was observed on cropped plots between February and April, after the rainfall peak period (Fig. 3f). For cropping season II this consumption peak was altered by the 50 mm of rainfall received in March 2008 following a drought of nearly two months at the GR-Station (Fig. 2b).

Crop productivity *versus* GHG fluxes relationships. The productivity of maize grown on recently cleared and cultivated woodlands at

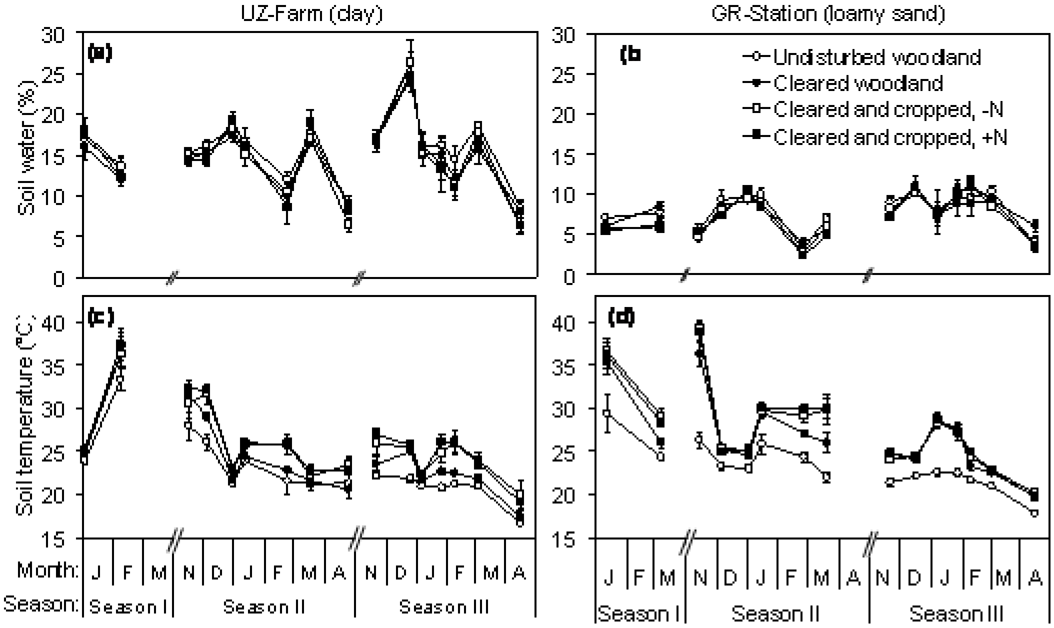

Figure 4. Water content and temperature of soils from experimental plots of four treatments at the UZ-Farm and GR-Station during 2006-2009. Error bars denote standard errors of means.

the UZ-Farm and GR-Station (Table 4) was poor during seasons I and II, and no grain could be harvested. Season III had the highest crop biomass and N uptake, and was the only season in which grain yield was attainable. Maize aboveground biomass and N uptake showed positive response ($P<0.05$) to N-fertiliser application at both sites and in all seasons. Expressing the total quantity of each greenhouse gas emitted in season III, given in Table 3, per unit amount of grain yield from each treatment, given in Table 4, established that 0.08 kg N_2O-Nt^{-1} grain was emitted when N-fertiliser was applied on the loamy sand soil, compared with 0.3 kg N_2O-Nt^{-1} grain when no N-fertiliser was applied. In contrast, the application of N-fertiliser on the clay soil gave 0.10 kg N_2O-Nt^{-1} grain which was almost similar to 0.08 kg N_2O-Nt^{-1} grain from non-application of fertiliser on the same soil. This trend was also similar for CO_2 and CH_4, and showed that there was a relatively higher GHG emission concern in cropped plots that did not receive fertiliser on the loamy sandy soils when the yield component was considered.

DISCUSSION

Results from the three cropping seasons provided some evidence that the clearing and conversion of *miombo* woodlands to croplands has considerable effects on the GHG balance, and that these are also site-specific. It is widely accepted (Melillo *et al.*, 2001; Lindo and Visser, 2003; Wick *et al.*, 2005) that after deforestation and creation of either new pastures or croplands, the mineralised nutrients in the soil will become rapidly available for microbial transformations that may generate GHGs since there are no trees to take them up, unless they are rapidly lost through leaching (e.g. Fukuzawa *et al.*, 2006). It is, however, not clear how long nutrient availability and emission pulses would last before the system is self-stabilised. According to Davidson *et al.* (2001) the magnitude and duration of the pulses of N availability and N oxides emission following site disturbance vary widely in tropical forests and probably depend upon the prior site soil fertility and rate of vegetation re-growth after the disturbance event. The contrasting findings on

TABLE 2. Means and ranges of NH_4^+-N, NO_3^--N, pH and organic carbon (OC) of soils from experimental plots of different treatments measured during the time of gas sampling in three cropping seasons at the UZ-Farm and GR-Station

Treatment	University of Zimbabwe Farm (UZ-Farm)				Grasslands Research Station (GR-Station)			
	NH_4^+-N	NO_3^--N	pH (H_20)	OC	NH_4^+-N	NO_3^--N	pH (H_20)	OC
Season I (2006/2007)	mg kg^{-1}			%	mg kg^{-1}			%
Undisturbed woodland	8.6 (3.6-14)	4.4 (1.2-7.5)	5.4 (5.3-5.5)	2.3 (2.2-2.4)	7.7 (6.3-9.1)	7.6 (4.5-11)	5.8 (5.6-5.9)	0.8 (0.7-1.0)
Cleared woodland	8.4 (3.5-14)	9.9 (3.1-17)	5.2 (5.0-5.5)	2.3 (2.1-2.6)	8.0 (6.3-9.7)	11 (8.4-13)	5.7 (5.6-5.8)	0.8 (0.7-0.8)
Cleared and cropped, -N	6.7 (3.3-10)	6.3 (1.5-11)	5.0 (4.8-5.3)	2.0 (1.9-2.0)	7.6 (6.2-8.9)	10 (8.5-12)	5.9 (5.8-6.0)	0.7 (0.5-1.0)
Cleared and cropped, -N	11 (4.0-17)	11 (1.2-21)	5.2 (5.2-5.2)	2.3 (2.0-2.6)	8.2 (7.4-8.9)	9.3 (4.8-7.9)	5.7 (5.6-5.7)	0.8 (0.7-0.8)
LSD	6.6	7.3	0.2	0.4	3.9	4.1	0.4	0.3
Season II (2007/2008)								
Undisturbed woodland	16 (1.8-20)	0.9 (0-1.9)	4.8 (4.4-5.2)	1.7 (1.1-2.2)	16 (13-18)	1.0 (0.5-1.4)	5.1 (4.8-5.4)	1.1 (0.9-1.3)
Cleared woodland	15 (1.3-18)	0.9 (0-1.5)	4.7 (4.4-5.1)	1.7 (1.1-2.1)	17 (16-18)	1.2 (0.7-1.9)	5.0 (4.8-5.2)	1.0 (0.9-1.2)
Cleared and cropped, -N	16 (1.3-22)	1.3 (0.1-3.0)	4.6 (4.3-5.0)	1.6 (1.0-1.9)	17 (16-20)	1.7 (0.7-4.7)	4.8 (4.7-5.0)	1.0 (0.9-1.2)
Cleared and cropped, -N	15 (2.0-20)	1.2 (0.2-1.8)	4.6 (4.3-4.9)	1.6 (1.1-2.5)	16 (15-17)	1.1 (0.6-1.4)	4.9 (4.7-5.1)	1.1 (0.9-1.3)
LSD	3.4	0.5	0.2	0.3	1.5	0.9	0.2	0.2
Season III (2008/2009)								
Undisturbed woodland	6.3 (0-12)	2.7 (0-5.0)	5.0 (4.7-5.2)	2.0 (1.6-2.4)	6.3 (1.5-16)	2.0 (0-6.3)	5.1 (4.8-5.6)	0.9 (0.7-1.3)
Cleared woodland	5.7 (0-12)	1.4 (0-4.1)	4.9 (4.5-5.5)	1.6 (1.3-2.0)	3.6 (0-9.1)	2.1 (0-4.1)	4.8 (4.5-5.4)	0.7 (0.5-0.9)
Cleared and cropped, -N	5.5 (2.9-9.3)	1.9 (0-4.8)	4.7 (4.4-5.1)	1.5 (1.2-1.8)	3.7 (1.3-6.8)	2.4 (0-5.4)	4.7 (4.4-5.1)	0.6 (0.4-0.7)
Cleared and cropped, -N	11 (2.3-27)	2.0 (0-4.1)	4.8 (4.3-5.2)	1.6 (0-7.2)	3.3 (4.8-7.9)	2.3 (1.2-3.9)	4.7 (4.2-4.9)	0.7 (0.4-1.0)
LSD	4.6	1.6	0.2	0.2	3.2	1.8	0.2	0.2

TABLE 3. Total soil emissions or consumption of N_2O, CO_2 and CH_4 from four treatments at two sites, estimated as area under curve of mean fluxes from the seven measurements, in the wet seasons at two sites

Treatment	University of Zimbabwe Farm			Grasslands Research Station		
	N_2O-N	CO_2-C	CH_4-C	N_2O-N	CO_2-C	CH_4-C
	Kg ha^{-1}					
‡ Season II: (2007/2008)						
Undisturbed woodland	0.87^{a}	1931^{a}	7.44^{a}	1.48^{c}	2055^{b}	38.53^{b}
Cleared woodland	2.08^{b}	2115^{a}	37.35^{b}	0.78^{a}	1146^{a}	19.65^{a}
Cleared and cropped, -N	1.06^{a}	1961^{a}	12.50^{a}	1.23^{bc}	1327^{a}	32.11^{ab}
Cleared and cropped, +N	2.50^{b}	2847^{b}	36.84^{b}	1.01^{ab}	1890^{b}	21.84^{a}
Significance	*	*	*	*	*	*
LSD	0.57	380	8.92	0.27	415	11.40
Season III: (2008/2009)						
Undisturbed woodland	0.12	772	0.22	0.12	537^{a}	-0.01
Cleared woodland	0.20	759	-0.30	0.11	592^{a}	-0.03
Cleared and cropped, -N	0.11	515	0.22	0.23	1029^{b}	-0.22
Cleared and cropped, +N	0.27	745	-0.03	0.22	1095^{b}	-0.31
Significance	ns	ns	ns	ns	*	ns
LSD	0.16	379	0.54	0.17	327	0.59

* Significant at the 0.05 probability level; ns, not significant; ‡Data points for season I were too few to estimate total fluxes by interpolation and therefore it was not included. Different letters denote significant differences

clay and loamy sand soils in this study could therefore be explained by this phenomenon.

The results showed that both clearing and cultivating of woodland on clay soil at UZ-Farm consistently increased N_2O emissions until the end of season III, while for CO_2 and CH_4 a similar trend was observed but in season III; whereby the disturbed plots emitted relatively less amounts of CO_2 and CH_4 than undisturbed woodland plots (Table 3). The importance of fertiliser-N and cultivation in stimulating N_2O and CO_2 emissions from savanna soils has been recognised by a number of other studies (Martin *et al.*, 2003; Castaldi *et al.*, 2006; Rees *et al.*, 2006). In this study, the results on N_2O fluxes were in the range of values reported by the previous studies, particularly those on relatively fertile soils. Higher SWC at the start of the rainy season and addition of fertiliser-N led to GHG emissions pulses at the UZ-Farm, particularly in season II which followed a season that was characterised by drought stress. The WWF (2010b) indicated that in southern Africa alone, an estimated 200,000 ha of woodlands are cleared annually to support tobacco farming, representing 12% of deforestation in the region. It may be estimated that roughly 10% of the *miombo* woodland area in Africa is on clay topsoil (Frost, 1996). By linking this information and results of this study with the 200 000 ha of woodland area cleared annually, deforested land on heavier textured soils could be contributing up to about 0.02, 3.68 and 0.60 Gg season^{-1} of N_2O-N, CO_2-C and CH_4-C, respectively, as emissions towards the global GHG budget within the two years of clearing. Similarly, if this deforested land is immediately converted to cropland under maize with fertiliser-N input of 120 kg N ha^{-1}, the possible contributions could go up to 0.03, 18.3, 0.60 Gg season^{-1} of N_2O-N, CO_2-C and CH_4-C, respectively.

TABLE 4. The crop establishment (Estab.), above-ground biomass (AGB), grain yield, total-N uptake and grain-N from maize under two N rates, harvested at 18 weeks after sowing (seasons I and II) and at 22 weeks after sowing (season III) at two sites

Site and treatment	Estab.	AGB	Yield	Total-N	Grain-N
Season I	%	Kg ha^{-1}			
UZ-Farm: -N	81	305^{a}	-	3.5^{a}	-
UZ-Farm: +N	79	852^{b}	-	9.9^{b}	-
GR-Station: -N	69	604^{ab}	-	5.9^{ab}	-
GR-Station: +N	79	1598^{c}	-	17.5^{c}	-
Significance	ns	*	-	*	-
LSD	14	404	-	4.3	-
Season II					
UZ-Farm: -N	85	601^{ab}	-	4.6^{a}	-
UZ-Farm: +N	81	1028^{b}	-	11.2^{b}	-
GR-Station: -N	78	216^{a}	-	2.2^{a}	-
GR-Station: +N	71	911^{b}	-	11.3^{b}	-
Significance	ns	*	-	*	-
LSD	14	369	-	3.8	-
Season III					
UZ-Farm: -N	85	3857^{a}	1395^{a}	34.3^{a}	15.5^{a}
UZ-Farm: +N	78	9108^{b}	2823^{b}	78.7^{b}	34.6^{b}
GR-Station: -N	94	2386^{a}	775^{a}	19.3^{a}	8.8^{a}
GR-Station: +N	80	8723^{b}	2831^{b}	77.7^{b}	35.1^{b}
Significance	ns	*	*	*	*
LSD	11	1679	521	12.1	6.1

*significant at the 0.05 probability level; ns, not significant; Different letters denote significant differences

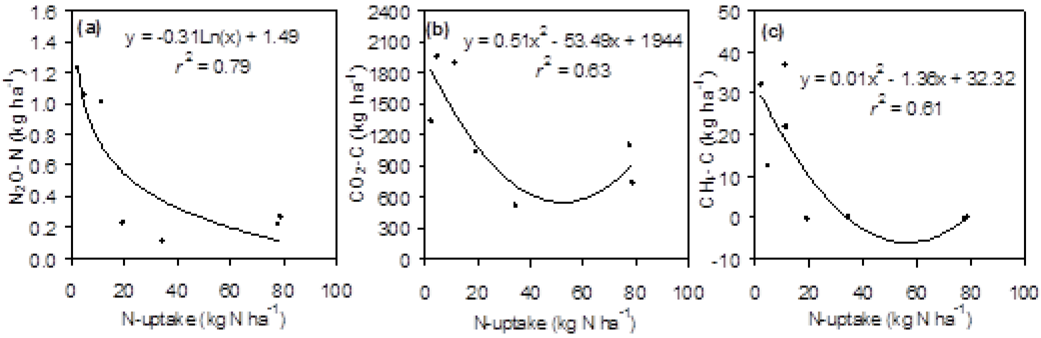

Figure 5. Relationships between total N uptake by maize and GHG emissions and consumption over an average period of 154 days from both sites in seasons II and III.

Greenhouse gases emissions from the loamy sand soil at the GR-Station, observed in season II and partially in season I (Figs. 3b,d,f) from the undisturbed woodland were, however, unusually high. This may be a result of the high leaf litter input from this woodland which had a denser tree and shrub population than the woodland at the UZ-Farm (Table 1). Measurements from this site were taken after a season with relatively low rainfall, but the observed N_2O emissions on the basis of observed physical or chemical changes in the soil could not be explained. In a related study of N_2O emissions from a tropical forest following a drought, van Haren *et al.* (2005) argued that N_2O was produced at the litter-soil interface with microbial biomass supplying the N source resulting in peaks in N_2O emissions. Similar patterns have been widely reported (e.g. Davidson *et al.*, 1993; Kiese *et al.*, 2003) and occur as a consequence of the rapid mineralisation of organic matter that accumulates during dry seasons (Werner *et al.*, 2007). These observations were particularly important since it is generally observed that over 50% of the *miombo* woodlands area in Africa is on sandy loam to sandy clay loam soil (Frost, 1996), the remainder representing those on Kalahari sands and other intermediate textural classes. It is most likely that a single year after clearing such woodlands the soils become highly nutrient depleted possibly due to leaching and increased soil acidity. The contributions of resultant land as a GHG source to the global budget would then drop considerably.

Methane fluxes observed in seasons I and III, and parts of season II, were consistent with studies under both tropical (e.g. 2.7 to -5.6 mg CH_4 m^{-2} day^{-1}, from Knief *et al.* (2005), which is 84 to -175 µg CH_4-C m^{-2} hr^{-1}) and temperate (e.g. 245 to -160 µg CH_4 m^{-2} hr^{-1}, from Peichl *et al.* (2009), which is 184 to -120 µg CH_4-C m^{-2} hr^{-1}) climate conditions. However, CH_4 emissions in season II were unusually high. A limited number of studies (Scholes and Andreae, 2000; Otter and Scholes, 2000) have reported CH_4 emissions or consumption that are as high as those found in season II from seasonally-wet or upland savanna. Recent satellite data have also identified hotspots of methane production in northern Zimbabwe towards the end of the rainy period in March that are greater than fluxes reported in this study (Bergamaschi *et al.*, 2009). It is likely that the combination of seasonal wetness and surface organic deposits from the woodland produce peaks in CH_4 emissions. A review by Scholes and Andreae (2000) highlighted emissions values of 9.0 mg CH_4-C m^{-2} hr^{-1} from periodically saturated valleys in moist savanna landscapes at the peak of a saturated period, and these high emissions lasted for 3 months. Otter and Scholes (2000) recorded an average of 69.4 mg CH_4 m^{-2} day^{-1} (2875 µg CH_4-C m^{-2} hr^{-1}) from saturated southern African savanna and up to 466.3 mg m^{-2} day^{-1} (38 858 µg CH_4-C m^{-2} hr^{-1}) from water surface of flooded soil under the same ecosystem.

There have been few studies on GHG emissions from natural and managed ecosystems that continue for more than a year or two (Otter and Scholes, 2000; Mapanda *et al.*, 2011). Results of this study have shown not only that there can be considerable intra and inter-annual differences but also that these interact with treatment and site in influencing the long term GHG balance.

CONCLUSION

Clearing and conversion of *miombo* woodlands to croplands have considerable implications on soil emissions of N_2O, CH_4 and CO_2, which are site and soil specific in Zimbabwe. Extremely high emissions of CH_4 are observed during the period when rainfall is relatively high and poorly distributed, particularly following a drought period generally characterised by deposition of leaf litter at the surface. These emissions could drop significantly by more than 10-fold in another wet season, making each season unique in terms of GHG emissions. Spatial variability in the fluxes of GHGs, especially CH_4 is considerably high for both disturbed and undisturbed woodland ecosystems making it necessary to increase the spatial representativeness of GHG measurements. The application of fertiliser-N increases GHG emissions in areas that have been cleared and cropped with maize on clay soil. However, undisturbed woodland with a relatively high tree density can be an important GHG source and this could be potentially attributed to mineralisation of organic matter that accumulates during the dry season. This study has improved the understanding of land-atmosphere exchange of GHGs emissions in savanna woodlands, highlighting the highly dynamic nature of sources and sinks in response to climate and management.

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REFERENCES

Bergamaschi, P., Frankenberg, C., Meirink, J.F., Krol. M., Villani, M.G., Houweling, S., Dentener, F., Dlugokencky, E.J., Miller, B.J., Gatti, L.V., Engel, A. and Levin, I. 2009. Inverse modeling of global and regional CH_4 emissions using SCIAMACHY satellite retrievals. *Journal of Geophysical Research-Atmospheres* 114: doi:10.1029/2009JD012287.

Castaldi, S., Ermice, A. and Strumia, S. 2006. Fluxes of N_2O and CH_4 from soils of savannas and seasonally-dry ecosystems. *Journal of Biogeography* 33:401- 415.

Chen, X., Hutley, L.B. and Eamus, D. 2005. Soil organic carbon content at a range of north Australian tropical savannas with contrasting site histories. *Plant and Soil* 268:161-171.

Chidumayo, E.N. and Kwibisa, L. 2003. Effects of deforestation on grass biomass and soil nutrient status in miombo woodland, Zambia. *Agriculture, Ecosystems and Environment* 96:97-105.

Clarke, J., Cavendish, W. and Coote, C. 1996. Rural households and miombo woodlands: use, value and management. pp.101–135. In: *The miombo in transition: woodlands and welfare in Africa.* Campbell, B. (Ed.). Centre for International Forestry Research, Bogor, Indonesia.

Compton, J.A. and Boone, R.D. 2000. Long-term impacts of agriculture on soil carbon and nitrogen in New England. *Microbiology Reviews* 60:609 - 640.

Davidson, E.A., Matson, P.A., Vitousek, P.M., Riley, R., Dunkin, K., Garciamendez, G. and Maass, J.M. 1993. Processes regulating soil emissions of NO and N_2O in a seasonally dry tropical forest. *Ecology* 74:130 -139.

Davidson, E.A., Bustamante, M.M.C. and Pinto, A.S. 2001. Emissions of nitrous oxide and nitric oxide from soils of native and exotic ecosystems of the Amazon and Cerrado Regions of Brazil. *The Scientific World* 1:312 - 319.

DEFRA. 2009. The social cost of carbon and the shadow price of carbon: What they are, and how to use them in economic appraisal in the UK. DEFRA, Economics Group.

Dick, J., Kaya, B., Soutoura, M., Skiba, U., Smith, R., Niang, A. and Tabo, R. 2008. The contribution of agricultural practices to nitrous oxide emissions in semi-arid Mali. *Soil Use and Management* 24:292 -301.

Earth_Trends 2003. Forests, Grasslands, and Drylands Zimbabwe. World Resources Institute, Washington, DC (At: http://earthtrends.wri.org/country_profiles/fetch_profile.php?theme =9&filename= for_cou_716.PDF. Accessed 6/4/2010.

FAO 2002. Agriculture and Food-Zimbabwe. FAOSTAT on-line statistical service. Food and Agriculture Organisation of the United Nations. At: http://earthtrends.wri.org/pdf_library/country_profiles/agr_cou_716.pdf. Accessed 5/4/2010.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N. and Snyder, P.K. 2005. Global consequences of land use. *Science* 309:570 - 574.

Frost, P. 1996. The ecology of miombo woodlands. pp. 11 - 57. In: The miombo in transition: woodlands and welfare in Africa. Campbell, B. (Ed.). Centre for International Forestry Research, Bogor. Indonesia.

Fukuzawa, K., Shibata, H., Takagi, K., Nomura, M., Kurima, N., Fukazawa, T., Satoh, F. and Sasa, K. 2006. Effects of clear-cutting on nitrogen leaching and fine root dynamics in a cool-temperate forested watershed in northern Japan. *Forest Ecology and Management* 225:257- 261.

Henao, J. and Baanante, C. 2006. Agricultural production and soil nutrient mining in Africa: Implications for resource conservation and policy development. An International Centre for Soil Fertility and Agricultural Development, Alabama. At: http://ictsd.org/downloads/2008/04/soil_nutrient_mining_in_africa_report_final.pdf. Accessed 19/2/2010.

Kiese, R., Hewett, B., Graham, A. and Butterbach-Bahl, K. 2003. Seasonal variability of N_2O emissions and CH_4 uptake by tropical rainforest soils of Queensland, Australia. *Global Biogeochemical Cycles* 17:1043 - 1054.

Knief, C., Vanitchung, S., Harvey, N.W., Conrad, R., Dunfield, P.F. and Chidthaisong, A. 2005. Diversity of methanotrophic bacteria in tropical upland soils under different land uses. *Applied and Environmental Microbiology* 71:3826 - 831.

Kundhlande, G., Adamowicz, W.L. and Mapaure, I. 2000. Special section: Land use options in dry tropical woodland ecosystems in Zimbabwe. Valuing ecological services in a Savanna ecosystem: A case study from Zimbabwe. *Ecological Economics* 33:401-412.

Lindo, Z. and Visser, S. 2003. Microbial biomass, nitrogen and phosphorus mineralisation, and mesofauna in boreal conifer and deciduous forest floors following partial and clear-cut harvesting. *Canadian Journal of Forest Research* 33:1610 - 1620.

Mapanda, F., Wuta, M., Nyamangara, J. and Rees, R.M. 2011. Effects of organic and mineral fertiliser nitrogen on greenhouse gas emissions and plant-captured carbon under maize cropping in Zimbabwe. *Plant and Soil* 343:67- 81.

Martin, R.E., Asner, G.P., Ansley, R.J. and Mosier, A.R. 2003. Effects of woody vegetation encroachment on soil nitrogen oxide emissions in a temperate savanna. *Ecological Applications* 13:897 - 910.

Mcdonald, J.A., Skiba, U., Sheppard, L.J., Hargreaves, K.J., Smith, K.A. and Fowler, D. 1996. Soil environmental variables affecting the flux of methane from a range of forest, moorland and agricultural soils. *Biogeochemistry* 34:113 - 132.

Melillo, J.M., Steudler, P.A., Feigl, B.J., Neill, C., Garcia, D., Piccolo, M.C., Cerri, C.C. and Tian, H. 2001. Nitrous oxide emissions from forests and pastures of various ages in the Brazilian Amazon. *Journal of Geophysical Research* 106:34179 - 34188.

Milne, R., Hargreaves, K. and Murray, M. 2000. Carbon stocks and sinks in forestry for the United Kingdom greenhouse gas inventory. *Biotechnology, Agronomy, Society and Environment* 4:290 - 293.

Moyo, S., Robinson, P., Katerere, Y., Stevenson, S. and Gumbo, D. 1991. Zimbabwe's Environmental Dilemma: Balancing Resource Inequities. Zimbabwe Environmental Research Organisation. Harare, Zimbabwe.

Nelson, D.W. and Sommers, L.E. 1996. Total carbon, organic carbon, and organic matter. pp. 961-1010. In: Page, A.L., Miller, R.H. and Keeney, D.R. (Eds.). Methods of Soil Analysis, Part 2, 2nd Edition. Agronomy. 9. Am. Soc. of Agron., Inc. Madison, WI.

Nyamapfene, K. 1991. Soils of Zimbabwe. Nehanda Publications. Harare, Zimbabwe.

Okalebo, J.R., Gathua, K.W. and Woomer, P.L. 2002. Laboratory methods of soil and plant analysis: A working manual, 2nd Edition. Tropical Soil Biology and Fertility Programme. Soil Society of East Africa Technical Publication No. 1. Marvel EPZ (Kenya) Nairobi, Kenya.

Otter, L.B. and Scholes, M.C. 2000. Methane sources and sinks in a periodically flooded South African savanna. *Global Biogeochemical Cycles* 14:97 - 111.

Peichl, M., Arain, M.A., Ullah, S. and Moore, T.R. 2009. Carbon dioxide, methane, and nitrous oxide exchanges in an age-sequence of temperate pine forests. *Global Change Biology* 16:2198 - 2212.

Rattray, J.M. and Wild, H. 1961. Vegetation map of the Federation of Rhodesia and Nyasaland. *Kirkia* 2:94 - 104.

Rees, R.M., Wuta, M., Furley, P.A. and Li, C.S. 2006. Nitrous oxide fluxes from savanna (miombo) woodlands in Zimbabwe. *Journal of Biogeography* 33:424 - 437.

SASRN. 2001. The Status of Southern Africa's Savannas. Report to UNEP by the Southern Africa Savanna Research Network (SASRN). Annex 31. Coordinated by Kings College London-University of London, UK. 102pp.

Scholes, M. and Andreae, M.O. 2000. Biogenic and pyrogenic emissions from Africa and their impact on the global atmosphere. *AMBIO: A Journal of the Human Environment* 29:23 - 29.

Scholes, R.J. and Hall, D.O. 1996. The carbon budget of tropical savannas, woodlands and grasslands. pp. 69 - 100. In: Breymeyer, A.I., Hall, D.O., Melillo, J.M., Agren, G.I. (Eds.). Global change: Effects on coniferous forests and grassland. Wiley, NewYork.

Seed-Co. 1998. Productive farming seed manual 1998/99. Seed-Co Company, Harare, Zimbabwe.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment IPCC. At: http://ds.heavyoil.utah.edu/dspace/bitstream/123456789/9951/1/ClimateChange2007-1.pdf; Accessed 25/05/2010.

van Haren, J.L.M., Handley, L.L., Biel, K.Y., Kudeyarov, V.N.K., Mclain, J.E.T., Martens, D.A. and Colodner, D.C. 2005. Drought-induced nitrous oxide flux dynamics in an enclosed tropical forest. *Global Change Biology* 11:1247 - 1257.

Werner, C., Kiese, R. and Butterbach-Bahl, K. 2007. Soil-atmosphere exchange of N_2O, CH_4 and CO_2 and controlling environmental factors for tropical rain forest sites in western Kenya. *Journal of Geophysical Research-Atmospheres* 112: doi:10.1029/2006JD007388.

White, F. 1983. The vegetation of Africa, a descriptive memoir to accompany the UNESCO/AETFAT/UNSO Vegetation Map of Africa (3 Plates, Northwestern Africa, Northeastern Africa, and Southern Africa). 1:5,000,000. UNESCO. Paris.

Whittaker, E.T. and Robinson, G. 1967. The Trapezoidal and Parabolic Rules. pp. 156 - 158. In: The Calculus of Observations: A Treatise on Numerical Mathematics, 4th Edition. Dover, New York, USA.

Wick, B., Veldkamp, E., Mello, W.Z., Keller, M. and Crill, P. 2005. Nitrous oxide fluxes and nitrogen cycling along a pasture chronosequence in Central Amazonia, Brazil. *Biogeosciences* 2:499 - 535.

Williams, M., Ryan, C.M., Rees, R.M., Sarnbane, E., Femando, J. and Grace, J. 2008. Carbon sequestration and biodiversity of re-growing miombo woodlands in Mozambique. *Forest Ecology and Management* 254:145 - 155.

WWF. 2010a. Miombo woodlands, Africa. World Wide Fund For Nature, Switzerland. At: http://wwf.panda.org/what we do/where we work/miombo woodlands; Accessed 21/08/2010.

WWF. 2010b. Environmental impacts of production: deforestation. Agriculture and Environment. World Wide Fund For Nature, Switzerland. At: http://wwf.panda.org/about our earth/agriculture impacts/tobacco/environmental impacts/deforestion; accessed 21/08/2010.

ZFC. 1998. Vegetation mapping in Zimbabwe using satellite remote sensing and geographic information system. ForMat Newsletter, Research and Development Division, Zimbabwe Forestry Commission, Harare, Zimbabwe.