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Special issue article

A cross-ecosystem assessment of the effects of land cover and land use on soil emission of selected greenhouse gases and related soil properties in Zimbabwe

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Summary

Land used for agricultural production can contribute significantly to greenhouse gas (GHG) emissions; however, there is very little information on the role of management and land use change in influencing these emissions in Africa. Thus, exploring GHG emissions that occur at the soil-atmosphere interface is an essential part of the effort to integrate land management strategies with climate change mitigation and adaptation in southern Africa. We measured soil emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) from rain-fed perennial tropical grassland, wastewater-irrigated perennial tropical pastureland, recently cleared woodland, miombo woodland, a *Eucalyptus* plantation, regular cropland and recently cleared-and-cropped land, on two contrasting soils at five sites in one cropping season in Zimbabwe. Gas samples were collected using static chambers and analysed by gas chromatography. Considerably high GHG emissions were found on sewage effluent-irrigated pastureland (means, 190 mg CO_2-C m^{-2} hour^{-1}, 102 μg CH_4-C m^{-2} hour^{-1} and 6 μg N_2O-N m^{-2} hour^{-1} from sandy soil) and altered woodlands (mean ranges, 38–70 CO_2-C m^{-2} hour^{-1}, 12–43 μg CH_4-C m^{-2} hour^{-1} and 20–31 μg N_2O-N m^{-2} hour^{-1} from deforested and cultivated woodland on clay and sandy soils). Relatively low and less variable emissions were found among the rain-fed perennial tropical grasslands, regular croplands and *Eucalyptus* plantations (mean ranges, 19–39 mg CO_2-C m^{-2} hour^{-1}, −9.4–2.6 μg CH_4-C m^{-2} hour^{-1} and 1.0–4.7 μg N_2O-N m^{-2} hour^{-1}). Variability in CO_2, CH_4 and N_2O emissions from soils was to the greatest extent influenced by soil temperature, but soil moisture, mineral-N and pH were also important. The increased N_2O emissions from cleared woodland on clay soil were attributed to increased mineralization and N availability when no tree could take up that N, while the N mineralized on the sandy soil could have been largely leached due to the soil's poor nutrient holding capacity, resulting in a relatively lower N_2O emission response to clearing. We concluded that the alteration of woodlands by deforestation and cultivation increased soil temperature, resulting in increased soil respiration, while the establishment of *Eucalyptus* plantations may provide an option for reduction in soil emissions of CO_2 and N_2O and a sink for CH_4.

Introduction

Land utilization and land-use change concern human society worldwide, and these issues have been of particular interest to southern Africa's regional agendas over the past decade, partly because of developments in the Zimbabwean land reform programme and its subsequent environmental impacts (Zikhali, 2008). Land-use and land-cover are linked to climate and weather in complex ways, but the key links include exchange of greenhouse gases (GHGs) carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (Pielke, 2005). Conversion or overutilization of land by processes such as cultivation, excessive removal of vegetation and burning lead to nutrient and soil organic matter depletion in most ecosystems (Zingore *et al*., 2005; Mapfumo &

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Mtambanengwe, 2007) although responses may be less significant in some ecosystems in the short-term (e.g. Chidumayo & Kwibisa, 2003). There are relatively few studies of the effects of land cover on soil nutrient dynamics and GHG emission in southern Africa (e.g. Chidumayo & Kwibisa, 2003; Rees *et al*., 2006), and likewise comparative studies across major ecosystems are scarce. Consequently, the majority of practices and techniques for adaptation to climate change that are now being advocated (e.g. Borron, 2006; FAO, 2007) are largely based on knowledge generated in other parts of the world. Thus, there is an urgent need for more assessments of ecosystem responses to land management (and mismanagement) in order to improve decision making regarding climate change adaptation and mitigation.

Zimbabwe is a land-locked country (approximately 38 685 000 ha in extent, Figure 1) with an estimated 43% shrubland, savanna and grassland; 54% cropland and crop-natural vegetation mosaic; and 3% of wetlands, wet areas, forests, open space and built areas (EarthTrends, 2003). This ecosystem distribution has, however, been constantly changing as the same assessment estimated a national forest area change of −15% per decade due to deforestation, compared with −4% per decade for the rest of the world. The area change for local forest stands established by afforestation and reforestation for industrial and non-industrial usage (plantations) is estimated at +2% per decade (EarthTrends, 2003), with major forest plantation species being *Pinus patula*, *P. elliottii* and *P. taeda*, *Eucalyptus grandis*, *E. cloeziana* and *Acacia mearnsii* (Mabugu & Chitiga, 2002). Substantial areas of natural grasslands and wetlands have also been converted to pasturelands and croplands. These land-use and cover changes may have significant impacts on climate change through their relationships with soil nutrient dynamics and GHG exchange.

The use of sewage sludge and effluent to irrigate perennial tropical grasses such as *Panicum* and *Cynodon* species is one practice that has improved productivity of peri-urban pasturelands in Zimbabwe. Municipal farmlands in Zimbabwe receive heavy applications of treated sewage sludge and effluent yearly (24 000–36 000 m^3 ha^{-1} $year^{-1}$, Mapanda *et al*., 2005). The increased abundance of sludge generated by municipalities and the limited land accessible to the sewage works (about 10 000 ha in Harare and Bulawayo) means that farmlands may receive very heavy applications of sludge in future to keep up with disposal rates (Oloya & Tagwira, 1996). Such developments may have a significant impact on GHG emissions as they have an influence on soil nutrient dynamics and plant traits (Mapanda *et al*., 2007).

The assessment of soil fertility and soil nutrient balance under different land utilization scenarios may indirectly reflect plant traits and ecosystem performance. Plant traits such as biomass and yield response reflect physiological limitations caused by soil nutrient composition change, and according to Diaz *et al*. (2002) plant traits may be a better indicator of the impact of land use or disturbance than species, particularly for species-rich systems such as grasslands. The exchange of GHG under different land uses may vary considerably with variability in soil properties that have an impact directly on these plant traits. Thus,

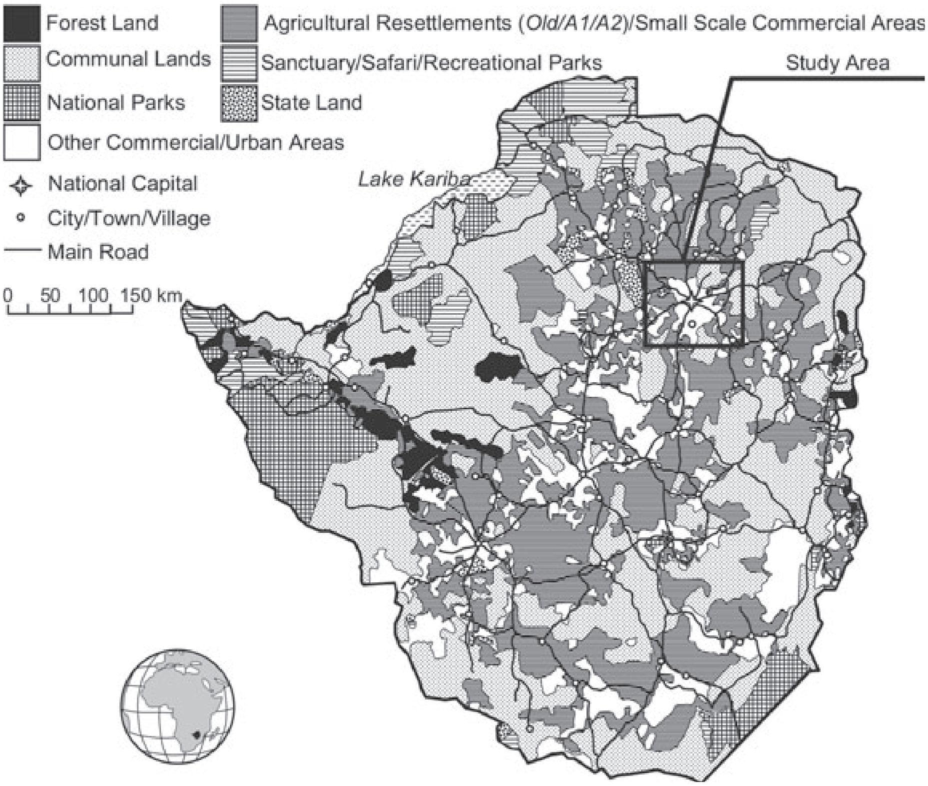

Figure 1 Zimbabwe's general land use map (April 2003) and the location of the study area (modified after VAC, 2004 and NOP, 2009).

the objectives of this study were to determine soil emissions of CO_2, CH_4 and N_2O, and to examine how they correlate with soil properties, land cover and utilization on (i) rain-fed perennial tropical grassland, (ii) wastewater-irrigated perennial tropical grassland, (iii) new grassland from recently tree-cleared woodland, (iv) undisturbed miombo woodland, (v) a *Eucalyptus* plantation, (vi) regular cropland, and (vii) new cropland from recently tree-cleared and cultivated land, on contrasting soils in Zimbabwe. This research will be used to guide current debates on the value of different strategies in contributing to climate change adaptation and mitigation because most of the proposed frameworks have been largely based on knowledge generated in other regions.

Materials and methods

Study site

The study was conducted in one cropping season (October 2006 to March 2007) at the University of Zimbabwe Farm, Pension Farm, Churu Farm, Grassland Research Station and Domboshawa Training Centre, in north-central Zimbabwe (Figure 1). The University of Zimbabwe Farm is located in Mazowe District some 15 km north of Harare (31°00′30″E; 17°42′03″S), and subdivided into 850 ha arable, 1050 ha grazing and 100 ha miombo woodland, a *Eucalyptus* plantation (>30 years old) and farm buildings (T. J. Chimbetete, personal communication). The farm is located on a dolerite terrain and was the only studied site with a heavy-textured soil (red clay; Chromic luvisol) and with all experimental treatments (except wastewater-irrigated pastureland). The remaining four sites were located on granitic terrains with light-textured soils (largely brown coarse-grained loamy sands and coarse-grained sandy loams; Haplic lixisols).

Pension Farm with wastewater-irrigated pastureland (30°55′36″E; 17°55′36″S) and the adjacent Churu Farm with rain-fed perennial tropical grassland (30°55′12″E; 17°55′41″S) are located in the southwest of the Harare District on largely loamy sands. The extensively cattle-grazed pastureland at Pension Farm was dominated by *Pennisetum clandestinum* and *Cynodon nlemfuensis* grass species (Mupini, 2007), and has been irrigated over the past 30 years with sewage effluent that is sometimes mixed with digested sludge. By contrast, the less extensively cattle-grazed natural pastureland at Churu Farm was dominated by *Hyparrhenia filipendula* and *Cynodon nlemfuensis* grass species and was rain-fed. The fourth site was the Grasslands Research Station located in Marondera District, 67 km east of Harare (31°28′56″E; 18°10′15″S), which was subdivided into 300 ha arable, 2200 ha grazing and 200 ha of woodland, roads and buildings (MOA, 2007). Domboshawa Training Centre is located in Goromonzi District, about 30 km northeast of Harare (31°00′30″E; 17°42′03″S). The croplands at the Domboshawa Training Centre and Grasslands Research Station were both on sandy loam soils. Typical mixed *Brachystegia spiciformis* and *Julbernardia globiflora* occupied miombo woodland areas at the Grasslands Research Station and University of Zimbabwe Farm, while grasslands at both sites were dominated by *Hyparrhenia* species. Other characteristics of the five study sites are given in Table 1, and the daily rainfall received at each site during the study period is shown in Figure 2.

Experimental treatments and management

The seven treatments presented in this study were selected from three experiments simultaneously conducted in one season using a similar gas and soil sampling protocol. The treatments (and sites) were:

1. rain-fed perennial tropical grassland (the University of Zimbabwe and Churu Farms);
2. wastewater-irrigated perennial tropical grassland (Pension Farm only);

Table 1 General characteristics and soil properties of the plantation (PLN), grassland (GLD), woodland (WLD) and cropland (CLD) ecosystems at the University of Zimbabwe Farm (UZF), Pension Farm (PEN), Churu Farm (CHU), Grasslands Research Station (GRS) and Domboshawa Training Centre (DTC) in Zimbabwe

	Study site							
Characteristic	UZF	UZF	UZF	UZF	PEN	CHU	GRS	DTC
Ecosystem	PLN	GLD	WLD	CLD	GLD	GLD	WLD	CLD
Altitude / m	1501	1500	1505	1499	1402	1410	1637	1540
Mean annual rainfall / mm year^{-1}	850	850	850	850	850	850	900	920
Mean maximum temperature / °C	25.0	25.0	25.0	25.0	25.2	25.2	31.1	25.0
Mean minimum temperature / °C	12.0	12.0	12.0	12.0	11.7	11.7	8.4	12.0
Slope / %	2–3	2–3	2–3	2–3	3–4	3–4	<2	2–3
Soil pH (in water)	7.0	6.3	5.9	6.4	6.0	6.4	5.1	5.5
Bulk density / g cm^{-3}	—	1.36	1.50	1.27	—	—	1.82	1.76
Soil organic C / %	1.80	2.1	1.46	1.63	2.10	1.01	0.98	1.05
Base saturation / %	63	71	53	39	63	90	51	71
CEC / cmol$^{(+)}$ kg^{-1}	13.9	16.2	8.4	10.5	19.5	4.7	4.3	4.2
Clay content / %	45	45	51	53	10	6	11	14

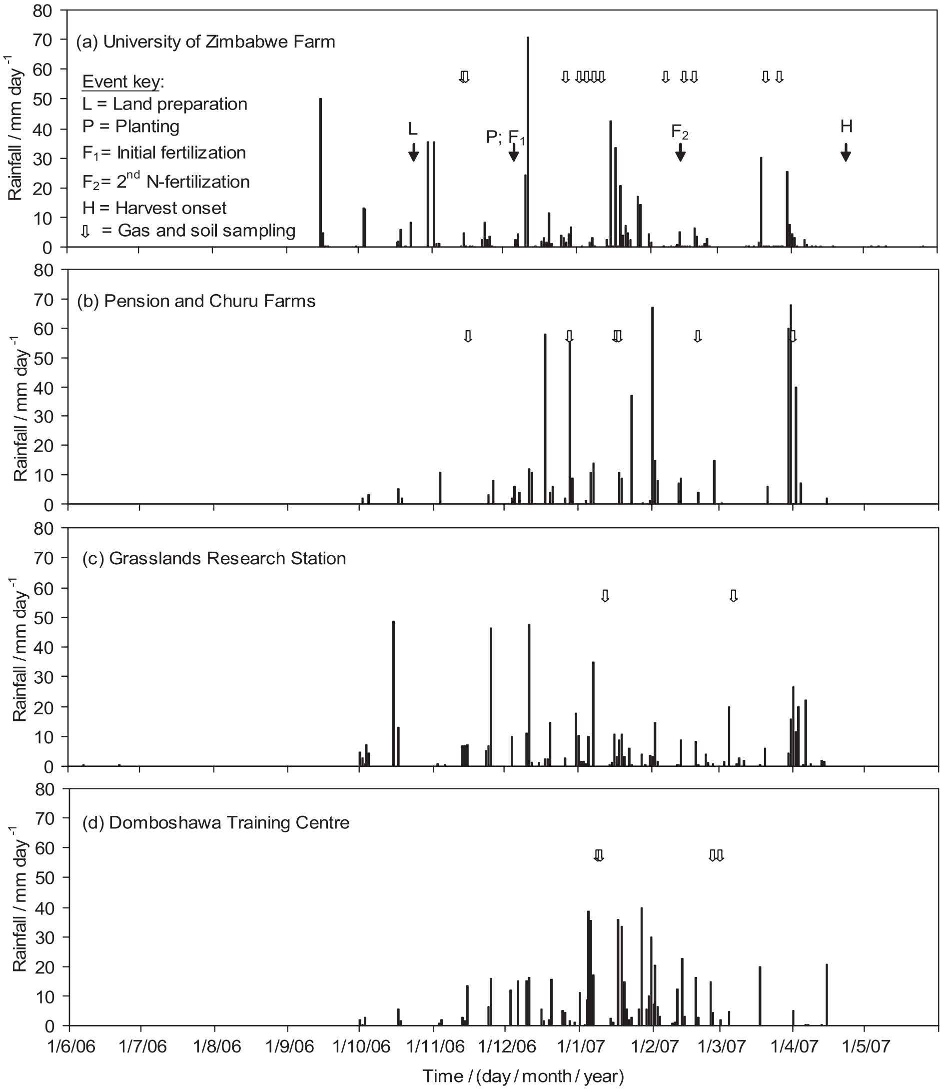

Figure 2 Daily rainfall distribution and some key events at the University of Zimbabwe Farm (a), Pension and Churu Farms (b), Grasslands Research Station (c), and Domboshawa Training Centre (d) during the 2006–2007 season.

3. new grassland from recently cleared woodland (the University of Zimbabwe Farm and Grassland Research Station);
4. undisturbed miombo woodlands (the University of Zimbabwe Farm and Grassland Research Station);
5. a *eucalyptus* plantation (the University of Zimbabwe Farm only);
6. regular cropland, maize-cropped, with 120 kg N ha^{-1} (as ammonium nitrate) (the University of Zimbabwe Farm and Domboshawa Training Centre); and
7. recently cleared woodland and cultivated land, with 120 kg N ha^{-1} (as ammonium nitrate) (the University of Zimbabwe Farm and Grassland Research Station).

Treatments 1, 2, 4 and 5 were included in an experiment that compared natural (rain-fed tropical grassland and miombo woodland) and managed (sewage effluent-irrigated pastures and a *Eucalyptus* plantation) vegetation systems in Harare. Twelve, 10 m × 10 m, plots were selected and pegged, four replicates in the woodland, four in *Eucalyptus* plantation and the remaining four in the open-grassland area, all on a clay soil (the University of Zimbabwe Farm). The plots were located at about 50 m from each other and along zigzag paths to ensure that variability across the transect was characterized. Similarly, for grassland on a loamy sand soil, six 10 m × 10 m plots were selected and marked, three on pastures irrigated with wastewater (Pension Farm) and the remaining three on rain-fed grassland (Churu Farm). These plots were, however, laid down at selected positions on the catena (upper, middle and lower slopes) at almost equal distances from each other, and on an approximately 500-m long transect for each site. The upper catena level had about 2–5% slope, while the middle and lower catena levels had about 2%, at both Pension and Churu Farms.

Treatments 3, 7 and 4 were part of an experiment that assessed the impact of clearing miombo woodlands and maize-cropping on soil emission of GHG at the University of Zimbabwe Farm and Grasslands Research Station. Sites were selected in the woodlands and a 4 m × 6 m plot was marked out for each treatment. The treatments were: undisturbed woodland, cleared uncultivated woodland and cleared cultivated land (planted with maize), laid out in a randomized complete block design with four replicates at each site. There was a 0.5-m gap between plots and 2 m between blocks. Clearing of tree stands was carried out in October 2006 (about 2 weeks before the onset of the cropping season) by hand using an axe, and cultivation was undertaken manually using hand picks to achieve a plough depth of about 15–20 cm. Maize was planted on cultivated plots at 0.90 m × 0.45 m spacing, with two seeds per planting position, and ammonium nitrate was applied at a rate of 120 kg N ha^{-1}, 50% at planting and the remainder approximately 6 weeks after planting. A basal application of P (30 kg ha^{-1}, as single superphosphate) and K (30 kg ha^{-1}, as muriate of potash, KCl) was applied at planting on cropped plots. The crop was kept weed-free by hand-hoeing.

Treatment 6 was part of an experiment that quantified emissions of GHG from maize amended with mineral fertilizer (among other treatments) at the University of Zimbabwe Farm and Domboshawa Training Centre. Crop management for this treatment was similar to the up-and-coming cropland, from recently cleared woodland and cultivated land (treatment 7), except that it was conducted on a regular cropland that had only been fallowed for about a decade. The key management events for each treatment are shown in Figure 2(a).

Meteorological data collection

Rainfall data were collected daily at 09.00 hours from a rain gauge at each site. The data for daily maximum and minimum temperatures at the study sites were gap-filled using meteorological data from: Grasslands Meteorological Station, located within the Grasslands Research Station about 1.8 km from our experimental site in a southwest direction; Henderson Meteorological Station, located some 18.6 km from Domboshawa Training Centre in a northwest direction; Belvedere Meteorological Station, located some 15.1 km from Churu and Pension Farms in a western direction; and the Automatic Weather Station, located within the University of Zimbabwe Farm, 0.5 km from our experimental site ina northwestern direction. All stations record daily data and are run by the Department of Meteorological Services, except the Automatic Weather Station, which records data every 30 minutes and is run by the University of Zimbabwe.

Soil sampling

Soil samples were collected, initially and following each gas sampling, using a bucket auger at 0–15 cm depth, and at two places at the location where a gas chamber was placed in each plot. The samples were stored in a freezer upon arrival at the laboratory, and later analysed for moisture, mineral N (NH_4^+-N and NO_3^--N) concentration, pH and organic carbon (using methods described below). Soil temperature was measured *in situ* at three randomly selected positions within each plot using digital thermometers with 10 cm long stainless steel probes. The soil temperature and air temperature were measured at the first and second gas collection (time zero and time 1 hour) from each plot.

Gas sampling

Gaseous emissions from soil were trapped using open-bottomed and transparent polythene chambers with a trapping area of 0.40 m × 0.28 m, perpendicular height of 0.2 m and a net volume of 19 dm^3. The chambers had rubber septa on the top centre to facilitate sampling using a syringe. Each chamber was placed above the sampling area (located randomly) within a plot. To avoid, as much as possible, gas escaping through any poor contact between soil surface and chamber edges, a small chisel was used to fasten this seal with surrounding soil. This was particularly important on non-cropped plots and when the surface soil was dry. The emitted gas was collected into pre-evacuated 10-cm^3 glass vials using a 50-ml syringe, immediately after securing the chamber on the sampling area and after 1 hour of trapping the gas. Gas sampling was carried out from 16 November 2006 to 27 March 2007 at the frequencies shown in Figure 2 and the samples were stored in glass vials in the dark at room temperature before being analysed for N_2O, CH_4 and CO_2.

The gas sampling method used in this study is widely used in comparable studies in Europe, Asia and Australia, in environments where the temperatures are as high as, or higher than, those in this study (e.g. Hui *et al*., 1999; Azam *et al*., 2002). Sampling days were generally characterized by abundant cloud cover with minimum direct sunlight reaching our transparent polythene chambers, especially later during the season when the crops and trees could provide some canopy cover to protect the chambers from direct sunlight to some extent.

Analysis of soil samples

Soil moisture, NH_4^+-N and NO_3^--N analyses were carried out simultaneously from fresh samples (kept frozen prior to analysis), while pH and organic C analyses were carried out after air drying the soil sample and sieving it to pass through a 2- and 0.5-mm sieve, respectively. Soil analyses were performed in the Soil Testing Laboratory of the Chemistry and Soil Research Institute, Zimbabwe, using the methods described by Okalebo *et al*. (1993). Mineral-N was extracted by mechanically shaking 5 g of a soil sample with 50 ml of 2 M KCl for 1 hour, and filtering. Ammonium-N was determined after steam distillation of the extract in MgO, trapping the ammonium-N in boric acid plus indicator (bromocresol-methyl red) solution. The distillate (50 ml) was titrated with 0.005 M H_2SO_4. Nitrate-N was determined in the same sample by adding Devarda's alloy to reduce nitrate-N to ammonium-N and distilling again into fresh boric acid, followed by titration with 0.005 M H_2SO_4. Soil moisture was determined gravimetrically as weight loss on oven drying at 105°C to constant weight. Soil pH was measured in distilled water suspension with a pH meter, while total organic C was extracted by wet oxidation using concentrated sulphuric acid and potassium dichromate, and determined by titrating with ferrous ammonium sulphate solution.

Analysis of gas samples

Nitrous oxide (N_2O), CH_4 and CO_2 in gas samples were quantified by gas chromatography (GC model: Hewlett Packard 5890, Series II, Avondale, PA, USA) at the Scottish Agricultural College (SAC) in the UK. Sample vials were attached to the GC's autosampler, which then split a 22-ml sample into three parts for simultaneous analysis. The first part of the gas sample was used to flush the sampling system prior to introducing a 1-ml sample to each column for analysis. 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 was analysed using a flame ionisation detector. The fluxes of N_2O, CH_4 and CO_2 were calculated as the differences in concentration between sampling time zero and time 1 hour.

Data analysis

Bivariate correlation analysis (two-tailed) was performed among the variables using the Pearson correlation coefficients. The Kruskal–Wallis one-way analysis of variance by ranks (Genstat, 2003) was used to establish any significant treatment response ($P < 0.05$). This analysis was, however, done for only one sampling campaign for each treatment and covered a short period (2–18 January 2007) during which environmental conditions were relatively comparable across sites, and this was an attempt mainly to capture within-site variability in chamber measurements. This time interval was within the middle of the rainy season and largely marked the wettest part of the cropping season, making it most suitable for a cross-ecosystem comparison of GHG emissions. A pair-wise separation of significantly different treatment means was carried out using the Mann–Whitney test. Regression analysis was conducted to measure the relative importance of each soil factor and combination of factors on GHG emission, and the Durban–Watson test was preconducted to check validity of randomness assumption, which confirmed that the model errors were randomly distributed.

Results

Weather conditions

The annual average air temperatures for the 2006–2007 season were 18.6°C at the University of Zimbabwe Farm, 19.2°C at the Pension and Churu Farms, 17.6°C at the Grasslands Research Station and 18.5°C at the Domboshawa Training Centre. The temperatures were within their long-term annual average ranges (Table 1) at all sites. However, the cropping season (October to April) was officially declared a national drought with a low total rainfall of 596 mm for the University of Zimbabwe Farm, 597 mm for the Pension and Churu Farms, 562 mm for the Grasslands Research Station and 619 mm for the Domboshawa Training Centre (Figure 2). Compared with the long-term annual rainfall averages (Table 1), total rainfall deviations were −30% at the University, Pension and Churu Farms, −38% at the Grasslands Research Station and −33% at the Domboshawa Training Centre. Rainfall distribution was uneven at the University of Zimbabwe Farm, resulting in severe drought stress, which negatively affected crop performance at the tasseling stage (February), soon after the second fertiliser application.

Soil physical and chemical characteristics

The means and ranges of moisture content, temperature, $NH_4{}^+$-N, $NO_3{}^-$-N, pH and organic carbon of soils at the time of gas sampling for the period between 14 November 2006 and 27 April 2007 are given in Table 2. In addition to rainwater, pastures at the Pension Farm received sewage effluent and as a result they had the highest soil moisture content of the light-textured soils. The higher soil moisture content found on clay soils at the UZ-Farm than on sandy and sandy loam soils at the other sites was largely reflecting differences in the water holding capacities of the soils, rather than the amount of rainfall received at each site during the period under study. Organic carbon was also considerably higher in soils irrigated with wastewater at the Pension Farm, a factor that also improved their water holding capacity relative to other sandy soils. The average soil temperatures were generally within a narrow range across the treatments, but were considerably higher (≥31°C) on all maize-cropped plots and recently cleared woodland plots irrespective of soil texture. Mineral-N concentrations, particularly soil NO_3^--N, were also relatively high on the maize-cropped and recently cleared woodland plots, except the regular cropland at the Domboshawa Training Centre and cleared-and-cropped land at the University of Zimbabwe Farm. The average soil pH was considerably higher on all tropical grasslands, wastewater-treated pastures and the *Eucalyptus* plantation, and on the cleared-and-cropped land at the University of Zimbabwe Farm, than on other treatments.

Soil emissions of carbon dioxide

The sites included in this study generally showed a wide range of CO_2 emissions (medians, 10–147 mg CO_2-C m^{-2} $hour^{-1}$) for the period from 16 November 2006 to 27 March 2007, mainly as a result of the exceptionally high CO_2 emissions on the wastewater-irrigated pastures at the Pension Farm, when compared with the lowest emissions on recently cleared woodland and land cropped with maize at the Grassland Research Station (Figure 3). The remaining treatments were within a narrower CO_2 emission range (medians, 19–49 mg CO_2-C m^{-2} $hour^{-1}$). Observations from the sampling period 2–18 January 2007, during which environmental conditions were relatively comparable across sites, revealed

Table 2 Means ± standard errors (and rounded ranges) of moisture content, temperature, NH_4^+-N, NO_3^--N, pH and organic carbon (OC) of soils at the University of Zimbabwe Farm (UZF), Grasslands Research Station (GRS), Churu Farm (CHU), Pension Farm (PEN) and Domboshawa Training Centre (DTC) between 14 November 2006 and 27 April 2007

Treatment (site, and *n*)	Soil H_2O / %	Soil temp. / °C	NH_4^+-N / mg kg^{-1}	NO_3^--N / mg kg^{-1}	pH	OC / %
Eucalyptus plantation (UZF, 20)	9.3 ± 0.6 (6–14)	27.2 ± 0.7 (21–31)	4.9 ± 1.1 (0–19.2)	0.07 ± 0.02 (0–0.3)	6.6 ± 0.2 (4.8–7.9)	1.15 ± 0.15 (0.06–2.25)
Miombo woodland (UZF, 28)	9.3 ± 0.8 (4–20)	28.3 ± 0.7 (23–37)	3.84 ± 0.92 (0–21)	1.32 ± 0.54 (0.0–9.9)	5.9 ± 0.1 (4.6–6.9)	1.46 ± 0.15 (0.27–3.2)
Tropical grassland (UZF, 24)	7.0 ± 0.5 (4–12)	27.3 ± 0.6 (23–34)	4.64 ± 1.17 (0–21)	0.06 ± 0.01 (0.0–0.3)	6.3 ± 0.1 (4.8–7.1)	2.09 ± 0.05 (1.6–2.55)
Recently tree-cut land (UZF, 8)	14.0 ± 1.0 (10–19)	30.9 ± 2.3 (25–41)	8.43 ± 2.29 (3–20)	9.88 ± 2.81 (3–24)	5.2 ± 0.1 (4.8–5.7)	2.34 ± 0.15 (1.79–3.23)
Regular-cropland (UZF, 8)	15.0 ± 1.4 (9–21)	31.9 ± 2.7 (24–43)	10.6 ± 2.58 (3–21)	10.84 ± 3.6 (0.1–21)	5.2 ± 0.1 (4.9–5.6)	2.31 ± 0.14 (1.87–2.89)
Cleared-&-cropped land (UZF, 26)	15.5 ± 0.4 (10–20)	32.6 ± 0.9 (29–40)	3.38 ± 0.64 (0–13)	3.47 ± 0.71 (0–18)	6.4 ± 0.1 (4.9–6.9)	1.64 ± 0.08 (0.94–2.24)
Miombo woodland (GRS, 8)	7.4 ± 0.5 (6–10)	26.8 ± 1.4 (23–35)	7.66 ± 1.13 (3–12)	7.58 ± 1.91 (0–16)	5.8 ± 0.2 (4.8–6.3)	0.83 ± 0.11 (0.35–1.2)
Recently tree-cut land (GRS, 8)	7.2 ± 1.1 (5–13)	31.3 ± 2.2 (24–41)	7.96 ± 1.43 (6–18)	10.56 ± 1.34 (3–15)	5.7 ± 0.1 (5.2–6)	0.79 ± 0.08 (0.51–1.17)
Cleared-&-cropped land (GRS, 8)	5.8 ± 0.5 (5–9)	32.2 ± 1.6 (27–39)	8.18 ± 1.4 (3–15)	9.3 ± 0.89 (6–12)	5.7 ± 0.2 (4.8–6.1)	0.75 ± 0.13 (0.27–1.34)
Sewage-irrigated pasture (PEN, 60)	15.5 ± 1.1 (4–36)	23.6 ± 0.3 (21–31)	5.79 ± 0.8 (0–26)	0.9 ± 0.1 (0.0–2.6)	6.2 ± 0.1 (4.9–7.2)	1.77 ± 0.07 (0.07–2.56)
Tropical grassland (CHU, 60)	6.0 ± 0.6 (1–26)	27.3 ± 0.3 (22–32)	4.68 ± 0.65 (1–23)	0.07 ± 0.01 (0.0–0.3)	6.4 ± 0.1 (4.8–7.3)	1.01 ± 0.06 (0.04–2.1)
Regular cropland (DTC, 28)	9.9 ± 0.4 (7–16)	32.4 ± 0.6 (25–38)	4.34 ± 0.68 (0–13)	4.92 ± 0.7 (0–13)	6.0 ± 0.1 (5.5–6.6)	0.59 ± 0.08 (0.09–1.2)

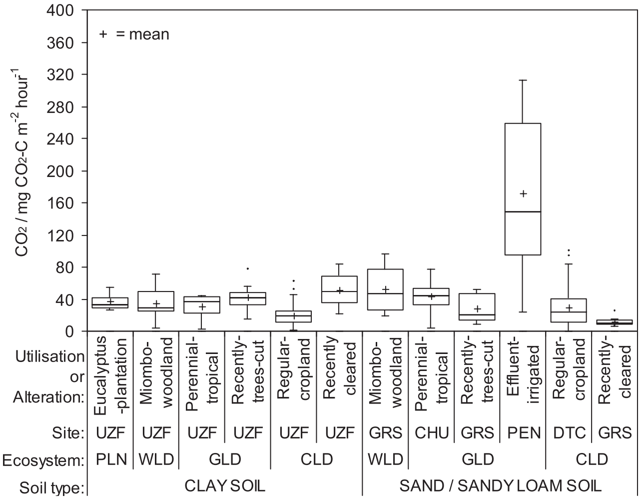

Figure 3 Soil emissions of carbon dioxide (CO_2) from plantation (PLN), woodland (WLD), grassland (GLD) and cropland (CLD) ecosystems for the period between 16 November 2006 and 27 March 2007 at the University of Zimbabwe Farm (UZF), Grasslands Research Station (GRS), Churu Farm (CHU), Pension Farms (PEN) and Domboshawa Training Centre (DTC).

that at the University of Zimbabwe Farm (clay) the highest CO_2 emissions ($P < 0.05$) occurred on the recently deforested land, recently cleared-and-cropped land, and on the undisturbed woodland (means range, 57–70 mg CO_2-C m^{-2} hour^{-1}), followed by the land under a *Eucalyptus* plantation and open natural grassland, and lastly the regular cropland (Table 3).

Soil emissions of CO_2 from the light-textured soil were highest on wastewater-irrigated pastureland at Pension Farm and least on recently cleared-and-cropped land at the Grasslands Research Station (Table 3). However, emissions from recently deforested land at the Grasslands Research Station and from open grassland at Churu Farm were comparable (38–47 mg CO_2-C m^{-2} hour^{-1}) but higher than those from cropland at the Domboshawa Training Centre and woodland at the Grassland Research Station (22–27 mg CO_2-C m^{-2} hour^{-1}).

Soil emissions and consumptions of methane

The variability in CH_4 emissions from soil (medians range, 0.4–77.1 μg CH_4-C m^{-2} hour^{-1}), like that of CO_2, was generally large across the study sites over the whole sampling period (Figure 4). Highest CH_4 emissions were observed from the pastureland irrigated with wastewater at Pension Farm, while natural grasslands at the Churu and the University of Zimbabwe Farms and regular cropland at the University of Zimbabwe Farm had the lowest CH_4 emissions (medians, 0.4–3.7 μg CH_4-C m^{-2} hour^{-1}). The *Eucalyptus* plantation at the University of Zimbabwe Farm, recently deforested land at the Grasslands Research Station, regular cropland at the Domboshawa Training Centre and land that was cropped soon after clearing at the Grasslands Research Station were largely sinks for CH_4 (medians,

Table 3 Means ± standard errors of CO_2, CH_4 and N_2O emissions from soil under different land utilizations and land covers ($n = 4$) at the University of Zimbabwe Farm (UZF), Grasslands Research Station (GRS), Churu Farm (CHU), Pension Farm (PEN) and Domboshawa Training Centre (DTC)

Treatment (site)	Date	CO_2-C / mg m^{-2} hour^{-1}	CH_4-C / µg m^{-2} hour^{-1}	N_2O-N / µg m^{-2} hour^{-1}
Eucalyptus plantation (UZF)	17 January 2007	37.1 ± 6.8	−10.1 ± 4.1	1.8 ± 0.3
Miombo woodland (UZF)	17 January 2007	58.6 ± 6.9	7.8 ± 1.4	10.0 ± 1.9
Tropical grassland (UZF)	17 January 2007	39.2 ± 4.6	6.9 ± 3.4	4.7 ± 0.7
Recently tree-cut land (UZF)	02 January 2007	56.5 ± 10.2	43.1 ± 1.3	21.7 ± 2.5
Regular-cropland (UZF)	08 January 2007	18.8 ± 2.7	−9.4 ± 2.2	3.3 ± 1.5
Cleared-and-cropped land (UZF)	02 January 2007	69.8 ± 5.5	11.9 ± 5.8	30.5 ± 1.2
Miombo woodland (GRS)	12 January 2007	26.5 ± 3.2	1.9 ± 1.9	7.7 ± 0.9
Recently tree-cut land (GRS)	12 January 2007	38.0 ± 11.5	17.0 ± 9.7	19.6 ± 7.3
Cleared-and-cropped land (GRS)	12 January 2007	8.4 ± 0.6	−6.1 ± 0.4	2.3 ± 0.2
Sewage-irrigated pasture (PEN)	18 January 2007	190.4 ± 32	102.1 ± 38.3	6.1 ± 1.5
Tropical grassland (CHU)	18 January 2007	46.8 ± 4.5	2.2 ± 2.5	1.0 ± 0.3
Regular cropland (DTC)	10 January 2007	22.5 ± 2.5	2.6 ± 2.4	3.4 ± 0.5
Significance	—	**	**	**
CV	—	62.7	159.8	60.2

**significant at the 0.01 probability level.

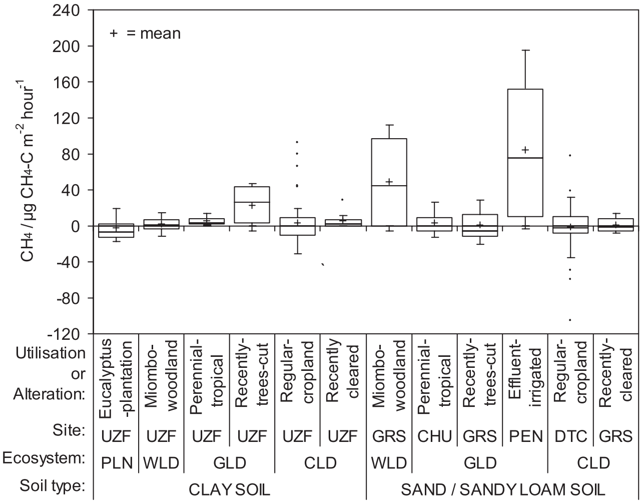

Figure 4 Soil emissions of methane (CH_4) from plantation (PLN), woodland (WLD), grassland (GLD) and cropland (CLD) ecosystems for the period between 16 November 2006 and 27 March 2007 at the University of Zimbabwe Farm (UZF), Grasslands Research Station (GRS), Churu Farm (CHU), Pension Farms (PEN) and Domboshawa Training Centre (DTC).

−6.7 to −1.6 µg CH_4-C m^{-2} hour^{-1}). There were considerable differences in CH_4 fluxes between the Grassland Research Station's and the University of Zimbabwe Farm's cleared and undisturbed woodlands. Cleared woodland at the Grasslands Research Station largely became a CH_4 sink whereas the uncleared woodland at the same site was a source (medians, −5.5 and 44.5 µg CH_4-C m^{-2} hour^{-1}, respectively), but the pattern was reversed at the University of Zimbabwe Farm (medians, 25.7 and 1.7 µg CH_4-C m^{-2} hour^{-1}, respectively).

The mean CH_4 fluxes across the study sites for the sampling period 2–18 January 2007, during which environmental conditions were relatively similar across sites, ranged from −10.2 to 102.1 µg CH_4-C m^{-2} hour^{-1} (Table 3). At the University of Zimbabwe Farm the highest emissions (43.1 µg CH_4-C m^{-2} hour^{-1}) were from recently deforested land, followed by recently cleared and cropped land, undisturbed woodland and open grassland (6.9–11.9 µg CH_4-C m^{-2} hour^{-1}), and lastly regular cropland and plantations, which were CH_4 sinks (−9.3 and −10.1 µg CH_4-C m^{-2} hour^{-1}, respectively). For light-textured soils the pastureland irrigated with wastewater at Pension Farm was found to have the highest CH_4 emissions (102.1 µg CH_4-C m^{-2} hour^{-1}), but the remaining treatments showed small net emissions (1.9–17.0 µg CH_4-C m^{-2} hour^{-1}), except the recently cleared-and-cropped land at the Grasslands Research Station, which became a CH_4 sink (−6.1 µg CH_4-C m^{-2} hour^{-1}).

Soil emissions of nitrous oxide

Soil emissions of N_2O across the different treatments had medians ranging from 0.5 to 35.7 µg N_2O-N m^{-2} hour^{-1}, and like CO_2 and CH_4 varied considerably with ecosystem type (Figure 5). However, irrigation of pastureland using wastewater at Pension Farm did not result in higher N_2O emissions as observed with CO_2 and CH_4. Instead, the highest median N_2O emission was from the undisturbed woodland at the Grasslands Research Stations, followed by the recently cut woodland at the University of Zimbabwe Farm. The *Eucalyptus* plantation at the University of Zimbabwe Farm and natural grasslands at all sites had low soil emissions of N_2O (0.5–4.1 µg N_2O-N m^{-2} hour^{-1}).

The mean N_2O emissions during the period in which environmental conditions were relatively similar across sites (2–18 January 2007) ranged from 1.0 to 30.5 µg N_2O-N m^{-2} hour^{-1} (Table 3). Unlike CO_2 and CH_4, the trend in N_2O emissions from clay soils at the University of Zimbabwe Farm during this selected period showed a picture similar to the trend observed in the overall sampling period. The highest emissions were found on the recently cleared-and-cropped land, followed by the recently

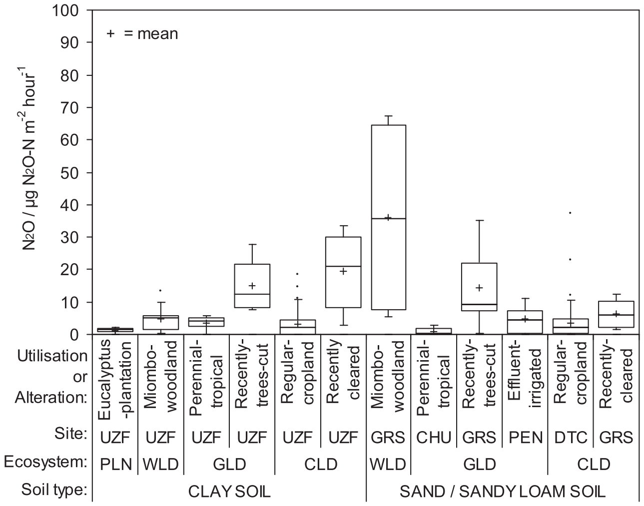

Figure 5 Soil emissions of nitrous oxide (N_2O) from plantation (PLN), woodland (WLD), grassland (GLD) and cropland (CLD) ecosystems for the period between 16 November 2006 and 27 March 2007 at the University of Zimbabwe Farm (UZF), Grasslands Research Station (GRS), Churu Farm (CHU), Pension Farms (PEN) and Domboshawa Training Centre (DTC).

deforested land, then the undisturbed woodland. Emissions from regular cropland and open grassland were comparable, while the lowest emissions were found on the *Eucalyptus* plantation. On the light-textured soils there were considerable differences in trend of N_2O emission among the treatments between this selected period and the overall sampling period. In the selected period, land at Grasslands Research Station where trees had been recently cut had the highest N_2O emissions, while the open grassland at Churu Farm had the lowest emissions.

Soil factors–GHG emission relationships

Results showed positive correlations ($P < 0.01$) between soil emissions of CO_2 and CH_4 and soil moisture content, but no correlations ($P > 0.05$) between N_2O emissions and soil moisture. The emissions of CO_2, CH_4 and N_2O were negatively correlated with soil temperature ($P < 0.05$), while N_2O emissions also had a positive correlation with soil mineral N ($NH_4{}^+$-N and $NO_3{}^-$-N) and a negative correlation with soil pH ($P < 0.01$). Regression analysis conducted using the soil factors and GHG emissions (Figure 6) provided evidence of some relationship between the emission of CO_2 and CH_4 and soil moisture (linear relationship), with the coefficients of determination (R^2) values ranging from 0.12 to 0.48 (Figure 6a, b, j, k). The CO_2 and CH_4 emissions from the clay soils at the University of Zimbabwe Farm were more strongly related to soil moisture than those from the light-textured soils at other sites. However, variability in all three GHGs on clay soil was strongly influenced by soil temperature (Figure 6d–f, $R^2 = 0.43 - 0.71$), but the differences in N_2O emissions were also dependent on soil $NO_3{}^-$-N and soil pH (Figure 6g, i). These relationships were largely polynomial (second order), with the highest emission responses occurring at a narrow temperature range of 25–28°C, and at pH 5. There was a decline in GHG emissions with temperature as it increased from 28 to 32°C. However, soil temperature–GHG emission relationships were weak on the light-textured soils (R^2 0.08–0.18, Figure 6m, n, p). There was no co-linearity among the effects of soil moisture, temperature, pH, $NO_3{}^-$-N and organic carbon (SOC) on GHG emissions ($P < 0.05$); hence the factors were not correlated to the extent that their individual influence was masked. However, cropland ecosystems were removed from this analysis because of an extremely poor response of GHG emission to these variables ($P > 0.05$).

Discussion

Soil emission of GHGs resulting from the different land management treatments examined in this study varied considerably, despite the widespread prevalence of the dry spells that characterized the cropping season, which was officially declared a national drought. Results showed that the tropical perennial grasses irrigated with sewage effluent had the highest relative soil emissions of CO_2 and CH_4, although N_2O emissions from this treatment were lower compared with the undisturbed woodland at the Grasslands Research Station and the woodlands that were altered by deforestation and cultivation on both clay and sandy loam soils. Irrigating with sewage effluent has been shown to result in increased GHG emissions, for example Zou *et al.* (2009) found 27% increase in CH_4 and 68% increase in N_2O emissions from sewage-irrigated rice paddies compared with those that were irrigated with river water alone. In our study the relatively low N_2O emissions from sewage effluent-treated grassland were unlikely to have been due to low N availability. The concentrations of available N in this treatment were >6 mg N kg^{-1} (Table 2) and other research has indicated that N mineralization in grasslands may be greater than that in other systems (Ambus, 2005). Nitrous oxide is produced in soil by nitrification and denitrification, but under waterlogged or flooded conditions (as was frequently the case with flood-irrigated pastureland at Pension Farm) it is presumed that much of the N_2O produced during denitrification is completely reduced to N_2 (Smith *et al.*, 2003). It may also be possible that the relatively lower N_2O emissions from wastewater-irrigated pasturelands could have resulted from toxicity of heavy metals such as Pb, Cu and Zn (which are characteristic of this site, Nyamangara & Mzezewa, 1999). The concentrations of these metals have been shown to be negatively correlated with N_2O emissions (Vasquez-Murrieta *et al.*, 2006).

The treatments in which trees were recently cleared (where an open space allowed grass growth) showed contrasting N_2O emission responses on the clay and sandy loam soils during the period of observation. Compared with the rain-fed tropical perennial grassland and grassland irrigated with wastewater the recently cleared woodland gave the highest N_2O fluxes. This phenomenon may be possibly attributed to the increased mineralization and N availability, and simultaneously no trees to take up that N following the clearing (Lindo & Visser, 2003). The increased amount of

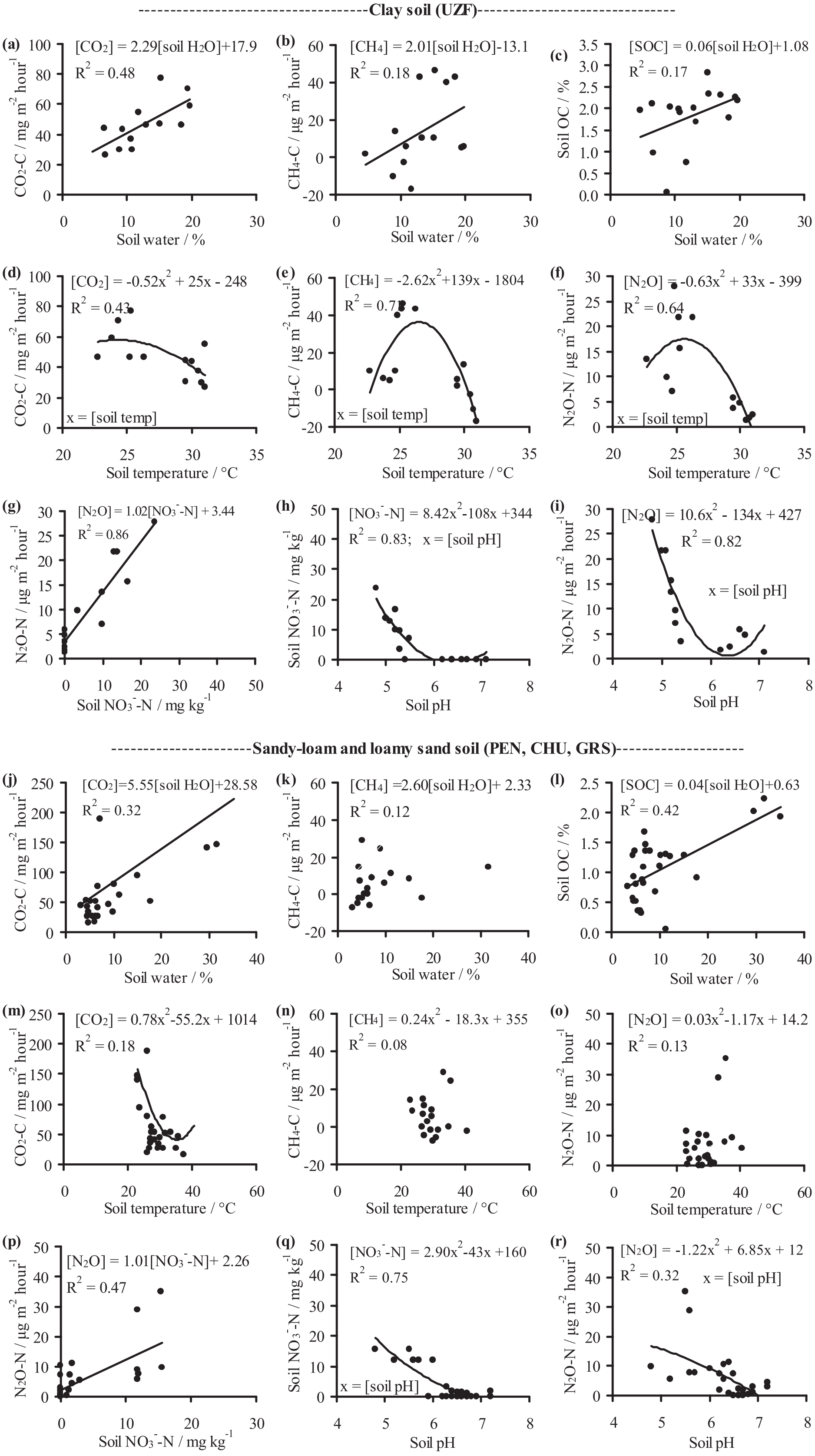

Figure 6 Regression analyses showing the direct and indirect effects of soil factors on greenhouse gas emissions from the sampled period.

leaf litter left in the plots after the trees were removed, and subsequent decomposition of litter and roots left in soil, may have considerably contributed to increased N availability, especially in clay soil at the University of Zimbabwe Farm, resulting in increased N_2O emissions. However, due to the low nutrient-holding capacity of sandy loam soil at the Grasslands Research Station, which also had one of the lowest soil organic carbon contents (Table 2), it may be possible that much of the N released from mineralization was lost largely through leaching (e.g. Fukuzawa *et al*., 2006), resulting in relatively lower N_2O emissions from tree clearing. The trees were removed in October 2006 (about 2 weeks before the onset of the cropping season) during the time of shoot growth, and according to Chidumayo (1994) it should also be about the time when substantial amounts of N and P were being translocated to the growing parts from the stem and roots. The stem and roots reserve these nutrients as an adaptive strategy where N and P are withdrawn from the senescing tree leaves before they fall off, a process called resorption (Eckstein *et al*., 1999). According to Jianjun & Boerner (2007), plant roots release stored nutrients to the regenerating parts, and it is therefore possible that when the trees were removed by clearing the N left in plant roots was released by mineralization and was subsequently able to contribute to N_2O emissions either by nitrification or denitrification processes.

The observed increase in N_2O emissions following the removal of trees on clay soils confirms other research findings from tropical forests, for example Melillo *et al*. (2001) found N_2O emissions from a newly created pasture (after deforestation) to be about 250% higher than the uncut forest emissions during the first 2 years (5.0 vs. 1.9 kg N_2O-N ha^{-1} $year^{-1}$). However, in their study N_2O emissions from pastures older than 3 years were on average 33% lower than emissions from the uncut forest. In contrast, Wick *et al*. (2005) measured tropical forest emissions of up to 17 ng cm^{-2} N_2O $hour^{-1}$ (equivalent to 110 μg N_2O-N m^{-2} $hour^{-1}$) during the wet season on clay soil (and about 5 ng N_2O cm^{-2} $hour^{-1}$ during the dry season), and observed a 67% decrease in N_2O emissions 6 months after forest clearing. In their study N_2O emissions from uncut forest soils always exceeded emissions from pasture sites, irrespective of pasture age. The two contrasting responses, also observed in our study, may be explained by Davidson *et al*.'s (2001) indication that the magnitude and duration of pulses of N availability and N oxide emissions following site disturbance vary widely in tropical forests and probably depend upon the prior site fertility (i.e. the stocks of potentially mineralizable N) and the rate of vegetation regrowth after the disturbance event.

The correlation and regression analyses using soil variables indicated that the variability in CO_2, CH_4 and N_2O emissions from clay soils was to the greatest extent influenced by soil temperature, but soil mineral N and pH were also important. Land utilization practices that increase soil temperature include the alteration of woodlands by deforestation and cultivation (Table 2). These practices expose the soil to direct sunlight, and reduce the albedo associated with a vegetative cover. *Eucalyptus* plantations provide a canopy cover that is high enough to protect the soil from direct sunlight, which can result in lower soil respiration as a consequence of lower soil temperature and moisture contents. Livesley *et al*. (2009) suggested that afforestation using *Eucalyptus* species can also decrease N_2O emissions (to <2.0 μg N_2O-N m^{-2} $hour^{-1}$) and provide CH_4 sinks (up to −20 μg CH_4-C m^{-2} $hour^{-1}$). The drought stresses experienced during a cropping season are likely to contribute indirectly to changes in soil respiration and GHG emission because high temperatures can cause rapid loss of surface soil moisture. High soil temperatures in this study (above 28°C) were associated with significantly lower soil water contents ($P < 0.05$). The application of sewage effluent may temporarily cool the soil in the irrigated grassland, but savanna grasslands are generally less effective at cooling the underlying soil than forest plantations.

Soil mineral-N as NO_3^--N had greater influence on the variability found in N_2O emission (Figure 6g, p) than as NH_4^+-N (R^2, 0.86 vs. 0.45 on clay; and 0.47 vs. 0.22 on sandy loams). The increase in soil mineral-N concentrations (both NH_4^+-N and NO_3^--N) with decreasing soil pH on both clay and light-textured soils (Figure 6h, q) may suggest that losses from the mineral N pool (immobilisation, uptake, leaching and gaseous loss) were reduced. N_2O emissions were negatively correlated with pH ($P < 0.01$) (Figure 6i, r). Denitrifiers are thought to operate at an optimum pH of between 6.5 and 8.0 (Simek *et al*., 2002); therefore the low pH of the soils studied here may have reduced N_2O emissions by denitrification. The partitioning of N_2O and N_2 emissions is also influenced by pH, with a higher proportion of N_2O in more acid conditions (Simek *et al*., 2002). However, in our study, soil pH was also strongly negatively correlated with extractable NO_3^- ($r = -0.75$). In these circumstances, the lower N_2O emissions at higher pH values could also have occurred as an indirect response to low soil nitrogen availability.

The management of soil pH may be important in determining the net GHG emissions from a site through indirect changes in underlying processes. For example, it has been shown in a previous study (Mapanda *et al*., 2005) that land application of sewage effluent can have a liming effect on the soil. Curtin *et al*. (1998) found that soil liming may increase organic matter mineralization, resulting in up to 67% increase in CO_2 emissions compared with the non-limed soil. In our study the grassland that was irrigated with sewage effluent had the highest soil emissions of CO_2 and CH_4. This could be a result of high soil respiration producing CO_2 under aerobic conditions, and eventually under extreme reducing conditions, alternative electron acceptors such as CO_2 and other C compounds being used by methanogens to produce CH_4 (Dubey, 2005).

A decision regarding the long-term implication of sewage sludge application at the Pension Farm for the C balance to which CO_2 and CH_4 emissions are linked may be reserved until a clear link between the labile C returning to the atmosphere and plant-fixed C from sludge-receiving pastures has been established. Our results therefore only provide an important guide in relative terms. Mupini (2007) compared the total grass and herbaceous biomass from rain-fed tropical perennial grassland (Churu Farm) and grassland irrigated with sewage sludge and effluent (Pension Farm), the same sites and study period reported in our study. In contrast to the GHG emission trends, Mupini (2007) found that total plant biomass at the Pension Farm (45.2 and 13.4 g m^{-2} at the middle and lower catena levels, respectively) was lower than that at the Churu Farm (62.5 and 32.2 g m^{-2}, respectively). Both sites were not under grazing during the study period. This trend may imply a progressive decrease in plant-fixed C on the pastureland on which wastewater is applied, possibly due to heavy metal toxicity. Studies conducted on municipal farms have already shown that heavy metal pollution loads on some portions of the farms already exceed permissible limits (e.g. Nyamangara & Mzezewa, 1999; Mapanda *et al*., 2005). This is largely because sludge application on municipal farms is uncontrolled, with more emphasis on sewage sludge disposal than crop fertilization (Nyamangara & Mzezewa, 1999).

The static chamber technique used gives the relative values of CO_2 fluxes across the sites, but it is generally accepted that this technique underestimates CO_2 fluxes compared with infrared (IR) techniques, particularly at high CO_2 fluxes (Jensen *et al*., 1996). It is therefore possible that the absolute values might be higher if measured by IR. Chavez *et al*. (2009) found the linear relationship in soil CO_2 fluxes (in kg ha^{-1} day^{-1}) between the static chambers (SC) and the dynamic chambers or IR techniques to be: $[SC] = 4.36 + 0.63[IR]$ ($R^2 = 0.78$, for the fluxes range 8–22 kg CO_2-C ha^{-1} day^{-1}).

Conclusion

Managed ecosystems that received irrigation using sewage effluent and areas that were cleared of trees contributed considerably to additional GHG emissions, while relatively low and less variable emissions were found from the rain-fed perennial tropical grasslands, regular croplands and *Eucalyptus* plantations. Soil respiration was predominantly enhanced by the clearing of trees on clay soils, while wastewater application on pastures was the most important factor triggering CO_2 emissions from the sandy soils. Methane emissions were highest from the wastewater-irrigated pastures and from the miombo woodland on the sandy soils, while the clearing of trees also enhanced CH_4 emissions from the clay soils. The clearing of woodlands, allowing the development of grassland vegetation, increased emissions of N_2O from the clay soil but had an opposite effect on a sandy loam soil. This difference was attributed to the increased mineralization and N availability, and simultaneously no trees to take up that N, resulting in increased N_2O emissions on the clay soil. A similarly increased N availability may have occurred on cleared woodland on sandy loam soil, but due to the soil's lower nutrient-holding capacity, much of the N released from mineralization may have been lost largely through leaching, resulting in lower N_2O emissions relative to the undisturbed woodland. The variability in CO_2, CH_4 and N_2O emissions from clay soils was to the greatest extent influenced by soil temperature, but soil moisture, mineral N and pH were also important. Alteration of woodlands by deforestation and cultivation increased soil temperature, resulting in increased soil respiration. The establishment of *Eucalyptus* plantations may provide an option for reduction in soil emissions of CO_2 and N_2O and a sink for CH_4.

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