

Greenhouse Gas Emissions from Intermittently Flooded (Dambo) Rice under Different Tillage Practices in Chiota Smallholder Farming Area of Zimbabwe

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ABSTRACT

Agriculture is one of the biggest sources of greenhouse gases. Rice production has been identified as one of the major sources of greenhouse gases, especially methane. However, data on the contributions of rice towards greenhouse gas emissions in tropical Africa are limited. In Zimbabwe, as in most of Sub-Saharan Africa, there are very few studies that have explored greenhouse gas emissions from agricultural lands. This study reports the first dataset on greenhouse gas emissions from intermittently flooded rice paddies in Zimbabwe. The objective of this study was to quantify greenhouse gas emissions from dambo rice under different tillage treatments, which were conventional tillage, no tillage, tied ridges, tied fallows, and mulching. Average soil nitrous oxide emissions were 5.9, 0.2, 5.4, 5.2 and 7.8 $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$ for tied fallows, conventional tillage, tied ridges, mulching and no tillage respectively. Average methane emission was 0.35 $\text{mg}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$ and maximum as 1.62 $\text{mg}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$. Average methane emissions for the different tillage systems were 0.20, 0.18, 0.45, 0.52 and 0.38 $\text{mg}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$ for tied fallows, conventional tillage, tied ridges, mulching and no tillage respectively. Carbon dioxide emissions were 98.1, 56.0, 69.9, 94.8 and 95.5 $\text{mg}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$ for tied fallows, conventional tillage, tied ridges, mulching and no tillage respectively. The estimated emissions per 150 day cropping season were 1.4, 3.6 and 0.6 $\text{kg}\cdot\text{ha}^{-1}$ for methane, carbon dioxide and nitrous oxide respectively. We concluded that intermittently saturated dambo rice Paddys are a potential source of greenhouse gases which is important to global greenhouse gas budgets, thus, they deserve more careful study.

Keywords: Greenhouse Gases; Smallholder Farming Sector; Rice; Seasonal Wetland (Dambo)

1. Introduction

Crop production is one of the biggest sources of greenhouse gases (GHGs). Globally, agriculture contributes approximately 58% to total anthropogenic emissions of nitrous oxide (N_2O) [1]. The magnitude of these emissions depends on several factors including nitrogen (N) fertilization [2], tillage and crop residue management [3] and soil moisture [4,5]. In Zimbabwe, most cropping systems are rainfall based as irrigation systems are poorly developed [6]. In many semi-arid to arid areas of Zimbabwe, dryland crop production has been decreasing because of perennial mid-season droughts which have been attributed to climate change. As a climate change adapta-

tion strategy, smallholder farmers in Zimbabwe and southern Africa have been cultivating seasonal wetlands (dambos) [7,8]. Therefore, presently, dambos are a valuable resource for crop production due to their widespread occurrence; saturation and inundation for months during rainy seasons; and high fertility when compared to uplands. Thus, in many developing countries, particularly in Africa, wetlands are now perceived as the “new frontier” for agriculture [9]. The use of seasonal dambos for crop production is potentially associated with increased emission of GHGs such as nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4). Nonetheless, the impact of dambo cultivation on GHG emissions is yet to be evaluated.

The production of rice, which is one of the major crops

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grown in dambos, has been associated with elevated GHG emissions, particularly CH₄ [2,10,11]. Specifically, soil disturbance during dambo cultivation and application of fertilisers that influence microbial processes, soil organic carbon (SOC) storage and turnover also affect GHG emissions from wetlands. Conservation tillage practices potentially reduce SOC degradation [12,13]. However, to date there are no studies that have evaluated the use of conservation tillage practices on SOC storage and GHG emissions from dambos in Zimbabwe.

In Zimbabwe, as in most of Sub-Saharan Africa, there are very few studies that have explored GHG emissions from cropped agricultural lands particularly dambos. There are a few reported studies the central and southern Africa regions e.g. Taylor *et al.* [14] The contributions of dambos of central and southern Africa to global CH₄, carbon dioxide (CO₂) and N₂O emissions are mainly estimates as there have been very few measurements and there is a risk that a very important source of GHGs is being overlooked. This has been the case because of several reasons, among them; high research costs, limited funding, limitation of analytical infrastructure and trained personnel. The objective of the study was to quantify GHG emissions from seasonal wetland (dambo) rice under different tillage systems, using static chambers.

2. Materials and Methods

2.1. Study Site

Chiota is a smallholder farming area with average land-holding size of 5 hectares and is located 70 km south of Harare (31°05'E; 18°11'S), with average rainfall of 700 - 800 mm and mean annual temperature of 18.6°C. Soil at Chiota is a sandy loam, classified as Haplic Lixisol, [15].

Seasonal wetlands, locally known as dambos, constitute 30% of the land area of Chiota (19,500 ha) and are used intensively for crop cultivation. A summary of the soil properties from the study site are shown in **Table 1**.

2.2. Experimental Design

At Chiota in Zimbabwe, greenhouse gas (GHG) (CH₄,

CO₂ and N₂O) emissions were measured from rice (*Oryza sativa* L.). The study at Chiota was conducted on-farm and was aimed at evaluating the effect of different tillage practices on GHG emissions in seasonal wetland (dambo) rice (*Oryza sativa* L.), during the 2010/2011 cropping season. Dambo rice was planted on 28 December 2010 and grown on residual moisture during the dry season and was only partially flooded, when the watertable rose to the surface during the rainy season. The rice germinated between 10 and 15 January 2011 and GHG emission measurements were carried out at 2 week interval from 5 March to April 30 2011. The five tillage treatments tested were conventional tillage (CT) with ploughing to 20 cm depth using an ox-drawn plough, no tillage (NT), tied-ridges (TR), tied-fallows (TF), and mulching (Mulch). The NT treatment involved manually opening planting stations using a hand-hoe with minimum soil disturbances.

Tied-ridging involved ploughing to 20 cm using an ox-drawn plough after which semi-permanent ridges (about 25 cm in height) were laid in the field at a grade of 0.4% - 1% across the slope at a interval of 50 cm. Cross-ties were constructed at 1 m intervals and were about two-thirds the height of the ridge. In tied-ridges, planting was done on top of the ridge. Tied-fallows are similar to tied-ridges except that, in the latter, planting was done in the furrows or in the flanks of 0.5 m wide rows. Mulching involved covering the soil surface with plant stover and litter (**Table 2**) after tillage. The plot sizes were 3 m × 1 m. Basal fertilisers, compound D (7, 14, 7 for N, P₂O₅, K respectively) was applied at planting at rates of 300 kg·ha⁻¹. Ammonium nitrate (AN) with 35% N, was used as a top dressing applied at a rate of 120 kg·N·ha⁻¹ six weeks after germination (**Table 1**).

2.3. GHG Emission Measurements

GHG flux measurements were taken from rice plots using opaque static polythene chambers with a base area of 0.40 m × 0.28 m and height of 0.5 m [4,16,17]. Each chamber had an air tight septum at the top through which samples were collected. Samples were collected with polypropylene syringe at time 0, 30 and 60 minute intervals. One chamber was randomly deployed in each rice plot and some rice was placed inside the chamber. To reduce gas leakages from the chamber, the chamber edges fastened using a small chisel and covered with surrounding soil, taking precaution not to disturb the chamber. Samples were collected from rice plots, starting at 7 am in the morning and completed by mid-morning. Samples were collected five times during the growing season, starting at week 6 after germination germination on the 3rd, 18th, 31st March, 16th April and 30 April 2011.

Table 1. Selected soil properties at the Chiota study site.

Coordinates	31°05'E; 18°11'S
Soil classification	<i>Haplic Lixisols</i>
Clay g·kg ⁻¹	150
Silt g·kg ⁻¹	110
Sand g·kg ⁻¹	740
SOC g·kg ⁻¹	33.3
Total N·g·kg ⁻¹	2.9
pH	5.4
Bulk density·g·cm ⁻³	1.4

Table 2. Tillage treatments in rice plots at the Chiota site, Zimbabwe.

	Conventional tillage (CT)	No tillage (NT)	Tied-ridges (TR)	Tied-fallows (TF)	Mulch
Tillage	Yes	None	Yes	Yes	Yes
Ridges	None	None	Semi-permanent, 25 cm in height, 1 m apart 0.4% - 1% grade across slope at 0.5 m intervals	Semi-permanent, 25 cm in height, 1 m apart 0.4% - 1% grade across slope	None
Mulching	Yes		None	None	Yes
Fertilizer Basal (7, 14, 7 NPK)	300 kg·ha ⁻¹	300 kg·ha ⁻¹	300 kg·ha ⁻¹	300 kg·ha ⁻¹	300 kg·ha ⁻¹
Ammonium Nitrate, (34.5% N)	120 kg·ha ⁻¹	120 kg·ha ⁻¹	120 kg·ha ⁻¹	120 kg·ha ⁻¹	120 kg·ha ⁻¹

2.4. Sample Analysis

Samples were analysed for GHGs using gas chromatography (GC) (Shimadzu GC 2014 model) at Washington State University, USDA Research Laboratory, USA. The GC was equipped with an electron capture detector (ECD) for N₂O, a Thermal Conductivity Detector for CO₂ and a flame ionizing detect (FID) for CH₄. The shipment process was assumed to result in negligible changes in the GHG concentration of the samples, as standards that were shipped to and from the USA in an earlier study remained unchanged [18].

2.5. Flux Calculations

Fluxes for GHGs' were calculated as described by Khalil *et al.* [16] as shown in Equation (1).

$$F = \gamma \left[\frac{M}{No} \rho \frac{V}{A} \right] \frac{dC}{dt} \quad (1)$$

Where F = is the measured fluxes, C is the measured concentration in the chamber and dC/dt is the rate of accumulation in ppbv/min. A is the area from which methane is emitted into the chamber (m²), V is the volume of the chamber (m³), No is Avogadro's number, ρ is the density of air (molecule m⁻³), γ is a unit conversion factor equal to 6.0×10^{-5} , mg·min⁻¹·g·hr⁻¹·ppbv⁻¹, and M is the molecular weight of the greenhouse gas. Data was validated using a test of linearity of the accumulation of gases at different time as described in Khalil *et al.* [19].

2.6. Data Analysis

Data was analyzed for variance (ANOVA) of CH₄, CO₂ and N₂O fluxes using the Genstat Statistical package. The least significant differences (LSD) were used to separate means that were significantly different.

3. Results

At the study site in Chiota, the SOC content was 33.4 g·kg⁻¹ for the 0 - 20 cm depth and this can be considered to be high compared to most cropping lands in tropical

Zimbabwe where the average SOC is ~1% [15]. The average soil pH was 5.4 and bulk density of 1.4 g·cm⁻³ (Table 1). The total N content was 1.91 g·kg⁻¹ and the C:N ratio for this site was 11.5.

3.1. N₂O Emissions

Soil N₂O emissions from rice plots, which had N applied at 126 kg·N·ha⁻¹, were not significantly different among treatments (Table 3). The mean N₂O emission across all treatments was 4.9 μg·m⁻²·hr⁻¹ (132 μg·m⁻²·day⁻¹). N₂O emissions for the different treatments were 5.9, 0.2, 5.4, 5.2 and 7.8 μg·m⁻²·hr⁻¹ for TF, CT, TR, mulching and NT respectively. N₂O emissions varied with time of sampling and averages across treatments for week 6, 8, 10, 12 and 14 after germination. N₂O emission increased from first sampling (6 weeks after germination) to the last sampling (14 weeks after germinations) and were -6.4, -0.3, -0.9, 11.5 and 20.7 μg·m⁻²·hr⁻¹ for week 6, 8, 10, 12 and 14 after germination respectively, (Figure 1). Total seasonal N₂O emission per crop (150 days) was also estimated and the average was 0.12 kg·N₂O·ha⁻¹ per cropping season (Table 3). In this study, there was no yield data for rice as the crop was destroyed by rodents before harvest. We therefore used national average rice yields (0.87 t·ha⁻¹) to estimate yield scale emissions. The average yield scale emission was 0.26 g·N₂O·kg⁻¹ yield (Table 3).

3.2. CH₄ Emissions

Methane emission from rice did not show any significant differences among tillage treatments. The average CH₄ emission for all treatments was 0.35 mg·m⁻²·hr⁻¹ (8.4 mg·m⁻²·day⁻¹) and maximum fluxes were 1.62 mg·m⁻²·hr⁻¹ (38.9 mg·m⁻²·day⁻¹). Average CH₄ fluxes for the different tillage systems were 0.20, 0.18, 0.45, 0.52 and 0.38 mg·m⁻²·hr⁻¹ for TF, CT, TR, mulching and NT respectively. CH₄ emissions varied significantly with sampling time and emissions decreased from the first sampling (6 weeks after germination) to the last sampling (14 weeks after germinations) (Figure 2). Emissions were 0.54,

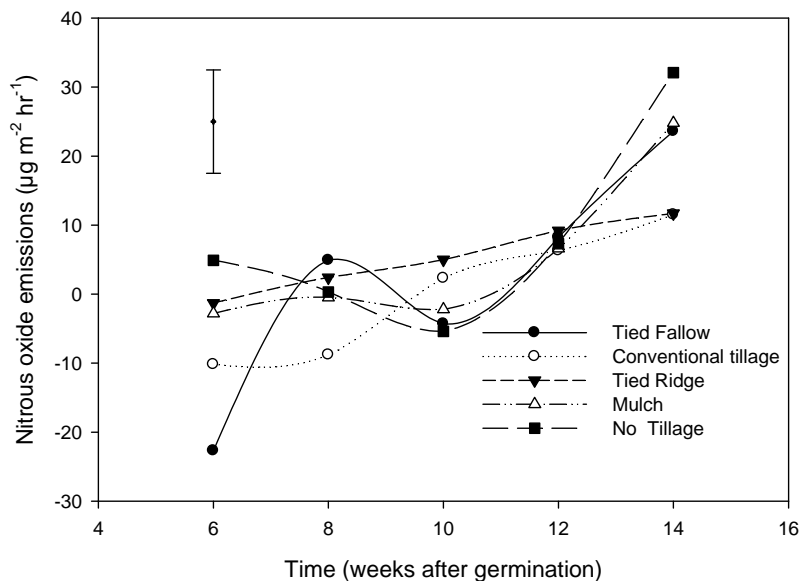


Figure 1. N₂O emissions in the different tillage practices from week 6 - 14 after germination. Vertical bar is the least significant difference (LSD). LSD = 14.98.

Table 3. Seasonal CH₄, CO₂ and N₂O emissions and yields based N losses.

Treatment	Inorganic N kg·N·ha ⁻¹	CH ₄ emissions kg·ha ⁻¹ ·season ⁻¹	CO ₂ Emissions kg·ha ⁻¹ ·season ⁻¹	N ₂ O Emissions kg·ha ⁻¹ ·season ⁻¹	Grain yield Mg·ha ⁻¹	Yield based emissions g·N ₂ O·kg ⁻¹ ·yield
Static Chamber Measurements						
CT	126	6.5a	2016a	0.01a	0.87	0.14
TF	126	7.5a	2016a	0.21a	0.87	0.28
TR	126	16.2a	2516a	0.19a	0.87	0.25
Mulch	126	18.7a	3412a	0.19a	0.87	0.24
NT	126	13.8a	3438a	0.28a	0.87	0.37
Average		12.54	2680	0.12	0.87	0.26

CT = conventional tillage, NT = no tillage, TR = tied-ridges, TF = tied-fallows and mulch = application of mulching. Seasona = 150 day growing season.

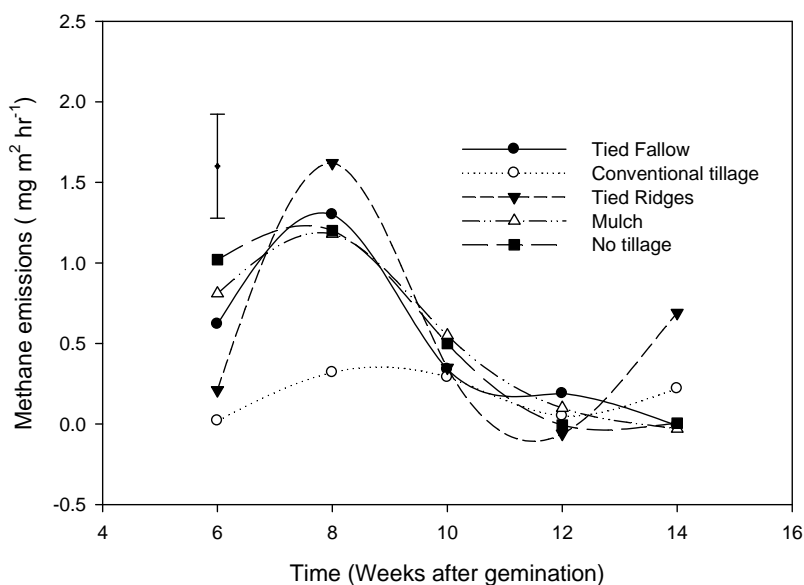


Figure 2. CH₄ emissions in the different tillage practices from week 6 - 14 after germination. Vertical bar is the least significant difference (LSD). LSD = 0.646.

0.53, 0.55, -0.07 and $0.18 \text{ mg}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$ for week 6, 8, 10, 12 and 14 after germination respectively. Estimated total emissions for the growing season are shown in **Table 3**, and the average CH_4 emission for all treatments from intermittently flooded dambo rice over 150 day growing season was $12.5 \text{ kg}\cdot\text{ha}^{-1}$.

3.3. CO_2 Emissions

Carbon dioxide did not show any significant differences between treatments. The mean CO_2 emission was $82.9 \text{ mg}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$ ($1990 \text{ mg}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$). CO_2 emission increased as it became drier, when saturation conditions decreased. There was net CO_2 consumption ($-4.0 \text{ mg}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$) during week 6, while emissions were 10.1, 33.4, 86.0 and $188.7 \text{ mg}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$ for week 8, 10, 12 and 14 after germination respectively. CO_2 emissions increased as the soil moisture content in the dambo decreased, as the soil became less saturated (**Figure 3**). Treatment averages were 98.1, 56.0, 69.9, 94.8 and $95.5 \text{ mg}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$ for TF, CT, TR, mulching and NT respectively. The estimated seasonal losses in CO_2 over a 150 day growing season translated to $2680 \text{ kg}\cdot\text{ha}^{-1}$ (**Table 3**).

There was a weak correlation between soil moisture and GHG emissions ($R^2 = 0.12 - 0.21$). The soil moisture was high throughout the period of measurement, $>30\%$ and moisture was not the limiting factor. Soil temperature was also poorly correlated to GHG emissions as the soil temperatures did not vary significantly among treatments.

4. Discussion

The manipulation of dambos through cultivation, application of fertilisers and growing of crops can affect GHG

emissions from dambos. Cultivating crops in dambos can potentially increase greenhouse gas emissions from dambos through the oxidation of large pools of soil organic matter stored in dambos that are exposed, and this increases CO_2 and N_2O emissions. In addition, the application of fertilizers may increase the production of GHGs especially N_2O , and plants e.g., rice are important in transporting CH_4 from the soil into the atmosphere [11, 20].

Agricultural soils are amended with organic and inorganic N fertilizers are generally sources of N_2O . In most tropical soils, particularly in Zimbabwe's smallholder farming areas, the soils are N deficient and this limits N_2O emission. In dambos, where there are high SOC contents, the addition of N based inorganic fertilizers, increases N_2O emissions. However, N_2O emissions are limited by the anoxic and saturated condition during the wet season. In addition, N_2O emissions are constrained by low N availability in the soil as low N inputs ($\sim 120 \text{ kg}\cdot\text{N}\cdot\text{ha}^{-1}$) were used and some of the N may be immobilised, making soils weak sources of N_2O [21,22]. In countries such as China, N application rates of up to $1000 \text{ kg}\cdot\text{N}\cdot\text{ha}^{-1}$ are used and this makes the soils major sources of N_2O [23]. The soil N_2O emissions recorded at Chiota site were generally low and consistent with other studies conducted on arable African soils, which are generally below $2.0 \text{ kg}\cdot\text{N}_2\text{O}\cdot\text{N}\cdot\text{ha}^{-1}$ [24,25].

N_2O emissions were lower during the first 3 weeks because of saturated conditions which reduced N_2O formation. Increase in N_2O emissions were observed in week 10 and 12, when rainfall decreased and the dambo became less saturated (**Figure 1**). In dambos N_2O fluxes varied with changes in saturation and fluxes are least when the dambos soils are saturated and increase when

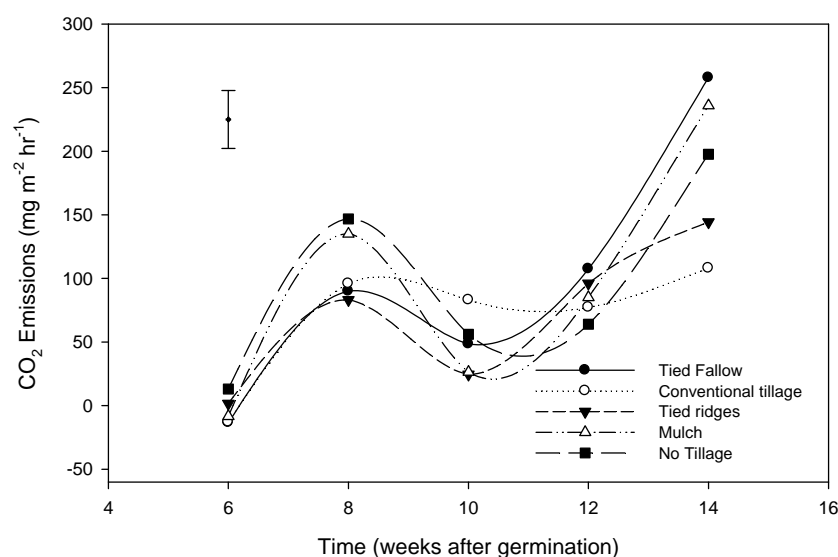


Figure 3. CO_2 emissions in the different tillage practices from week 6 - 14 after germination. Vertical bar is the least significant difference (LSD). $\text{LSD} = 44.15$.

saturation decreased. Nitrous oxide is an intermediate product of microbial processes such as nitrification and denitrification [26] and the microbial process are controlled by soil moisture and or saturation. This suggests that the concentrations of N_2O that are emitted from dambos vary depending on the soil conditions e.g., soil moisture is a major controlling factor of soil microbial processes [4,5].

There were no significant differences in N_2O emission among treatments and this was probably because the tillage treatments were only one year old. Although, conservation tillage practices have been reported to maintain soil moisture even during dry spells compared to CT [12,13], in this study the effects were not apparent. N_2O emission studies from intermittently flooded rice from India, [27] reported mean fluxes of $30 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$ and these values are by far greater than our average ($4.9 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$). However, our average was comparable to emission reported by Rees *et al.* [4] of $6.2 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$ in saturated bottom catena positions in Zimbabwe. Dambo cultivation and planting of rice resulted in increased N_2O emissions ($4.9 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$), than emission from natural dambos ($-6.5 - 0.02 \mu\text{g}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$). Though the increase was small, low concentration of N_2O may have a big impact as N_2O has a GWP of 298 times than CO_2 over 100 year period [28].

CH_4 emissions were higher during the week 6 and 8 and this could be attributed to increased rainfall and saturated conditions which were conducive to methanogenesis. As the water table receded, from week 10 - 14, the amount of CH_4 emitted decreased. As CH_4 diffuses through the oxidised layer to the soil surface some of it is oxidized to CO_2 [11]. Methanotrophy can oxidise between 40% - 90% of CH_4 produced [29]. Earlier studies by Khalil *et al.* [10] reported that draining fields of lack of water may result in cessation of CH_4 fluxes. As dambos became drier, methanogenesis could have been occurring deeper in the soil, however increased oxidation of CH_4 as it moves to the soil surface may reduce the amount of CH_4 that reached the surface. In dambos beds are usually raised to put the crop and the wetting and drying cycles creates aerobic surface layers. Castaldi and Fierro [30] reported that CH_4 consumption increased when water filled pore space (WFPS) decreased from 20% - 3%, while Otter And Scholes [20] reported CH_4 consumption in African savanna at WFPS between 20% and 5%, with a peak at 5%.

Our results suggest that intermittently flooded rice grown in sandy dambos was a weak source of CH_4 . CH_4 emissions from this study were lower than the only other reported rice CH_4 emission data of $14.7 \text{mg}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$ ($355 \text{mg}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$) were reported under flooded conditions in Kenya [14]. The results were also lower than CH_4 emission from undisturbed dambos that have been reported from earlier studies e.g., Scholes and Andrae [31] who

reported emission of $9 \text{mg}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$. Our results, mean (0.35) and $1.6 \text{mg}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$ (maximum), were in the same range with emissions of $0.45 \text{mg}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$ from cultivated dambo under rape (*Brassica napus*) at the same site [7]. Our results are also within range of emissions reported by Brown *et al.* [18], of $1.23 \text{mg}\cdot\text{CH}_4\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$ (mean) to $9.58 \text{mg}\cdot\text{CH}_4\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$ (maximum) from undisturbed dambos in Uganda and they also fall within range of reported fluxes from Ohio, by Altor and Mistch [32] who reported emission ranging from $-0.2 - 6 \text{mg}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$ in periodically saturated riparian marshes. The results are also comparable to fluxes that have been reported from other tropical regions e.g., Marani and Alvala [33] who reported diffusive fluxes 6 and $28 \text{mg}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ from Brazilian flood plains.

Dambos can also be a source of CO_2 which is formed as a by-product of cell respiration, oxidation of carbon stored in the dambos, methanogenic fermentation, acetate fermentation, or the oxidation of CH_4 as it diffuses through the aerobic zones. Carbon dioxide concentration in rice plots was lower when dambos were saturated because of reduced soil respiration. Similar observation showing low CO_2 concentrations from rice paddies were also reported by [14], who suggested that when samples are collected during day time, both respiration and photosynthesis are taking place. As plants photosynthesise, they will use up CO_2 originally under the chamber, after which they will begin to use up respired CO_2 for photosynthesis. The overall result is that the chamber will become depleted in CO_2 [14]. However, the increase in CO_2 emissions in week 8, a period when there we had the highest CH_4 emission probably suggest that, the source of CO_2 was CH_4 oxidation as it moved to the soil surface. The general qualitative relationship between N_2O and CH_4 is that when fields are saturated CH_4 increases, CO_2 and N_2O decreases. However, when fields become drier, CH_4 emissions decreased and CO_2 and N_2O emissions increased. This pattern is also seen in our data (**Figures 1-3**).

The poor correlation between soil moisture and GHG emissions ($R^2 = 0.12 - 0.21$) could be due to the fact that the study was conducted in summer (rain season) when dambos have high soil moisture to saturated conditions and also the fact that our dataset was small. The high soil moisture throughout the measurement period suggests that moisture was not the limiting factor. In tropical dambos which are saturated, substrate availability e.g., N source is rather more limiting than soil moisture. Soil temperature was also poorly correlated to GHG emissions as the soil temperatures did not vary significantly among treatments. Our temperatures ranged from $24^\circ\text{C} - 27^\circ\text{C}$ in the dambos. Though temperatures are important, they are likely not to be dominant in tropical environments [19].

Yield Scale N₂O Emissions

Our national average rice yields are lower compared to other regions e.g. China where yields for low land rain-fed rice can be 3.0 t·ha⁻¹ [34]. There is a huge yield gap which needs to be closed in the smallholder farming sector of Zimbabwe. Our yield-scaled N₂O emissions are higher than those reported from other studies e.g., Shi *et al.* [35], highlighting a need to improve N fertiliser use efficiency for smallholder farmers in Zimbabwe. To improve sustainability, there is need to minimize yield-scaled N₂O emissions rather than only focusing on absolute N₂O emissions [36].

5. General Overview and Conclusions

We concluded that intermittently saturated dambo rice paddies are a potential source of GHGs. When saturated, dambos are important sources of CH₄. However, when saturated condition decreases, CH₄ emission decreases, and N₂O and CO₂ emissions increase. The CH₄ emissions from cultivated dambos were lower than that from natural dambos. Yield scale N₂O emissions were higher and this suggests that there is a need to improve N fertiliser use efficiency for smallholder farmers to reduce yield based N₂O emission losses. Uncertainties in GHG emissions from dambo rice from the region are very large because there are few measurements that have been done. Although the sampling was not intense to obtain robust data on GHG emission from dambo rice fields, the results are still comparable to earlier studies and GHG emissions from other regions. This shows that GHG emissions from dambo rice are important to global GHG budgets and they deserve more studies. Because GHG emissions occur in pulses, for future studies we recommend high sampling frequencies. By not including emissions from seasonal wetlands such as dambos, there is a risk that a very important source of GHGs is being overlooked.

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