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LAND-USE AND LAND-USE CHANGE EFFECTS ON NITROUS OXIDE EMISSIONS IN THE SEASONALLY DRY ECOSYSTEMS OF ZIMBABWE: A REVIEW

G. NYAMADZAWO[1,2], N. CHIRINDA[3], F. MAPANDA[2], J. NYAMANGARA[4], M. WUTA[2], P. NYAMUGAFATA[2] and J.E. OLESEN[3]
[1]Department of Environmental Science, Bindura University of Science Education, Box 1020, Bindura, Zimbabwe
[2]Department of Soil Science and Agricultural Engineering, University of Zimbabwe, Box MP167, Mount Pleasant, Harare, Zimbabwe
[3]Department of Agroecology, Aarhus University, Blichers Allé 20, DK-8830, Tjele, Denmark
[4]International Centre for Research in Semi Arid Tropics (ICRISAT) Matopos, Box 776, Bulawayo, Zimbabwe
Corresponding author: gnyama@yahoo.com

ABSTRACT

Nitrous oxide (N_2O) is a greenhouse gas (GHG) with a considerable warming potential and involvement in the destruction of stratospheric ozone. The conversion of savannas to agricultural land has the potential of changing the characteristics and gas exchange of the ecosystems dramatically. The savanna woodlands cover over 95% of Zimbabwe's forest area, and are divided into five woodland types: *Acacia*, miombo, mopane, teak (*Baikiaea Plurijuga*) and *Terminalia-Combretaceae*. This review is aimed at exploring the effects of land-use changes and land management practices on N_2O emissions in Zimbabwe. Available data on N_2O emission were collected from standing and deforested miombo woodlands, grasslands and agricultural lands. Estimated mean annual N_2O emissions from savanna ecosystems in Zimbabwe were 17.1 Gg N_2O, while annual fluxes from arable land (cultivated and fallow) was 3.19 Gg N_2O. Biogenic N_2O emissions were mainly concentrated in the wet season as N_2O production is strongly enhanced by high soil moisture. During the dry season pyrogenic emissions were also important sources of N_2O, contributing, an estimated 6.7 Gg N_2O annually. Land use change in the form of biomass burning and conversion to grassland or arable land may be considerable source of N_2O, whereas current agricultural practices do not seem to provide a large source of N_2O in Zimbabwe. Seasonally dry savanna ecosystems, thus, constitute an important source of N_2O, which should not be ignored in national and regional estimates of emissions of N_2O. Land-use change from savanna to agricultural production results in an immediate increase in N_2O emissions. However, the emissions will decrease with time. The current estimates are associated with large uncertainties, thus, there is need for more detailed studies on the effects of land-use change on N_2O emissions and on spatial and temporal variations in N_2O emissions from the different savanna ecosystems.

Key Words: Greenhouse gases, miombo, mopane, savanna

RÉSUMÉ

L'oxyde nitreux (N_2O) est un gaz à effet de serre (GES) avec un potentiel de réchauffement et une implication dans la destruction de la couche stratosphérique d'ozone. La conversion des savanes en terres agricoles induit le changement radicales des caractéristiques et échanges gazeux des écosystèmes. Les savanes boisées couvrent plus de 95% de la couverture forestière au Zimbabwe et sont subdivisées en cinq types de boisements : *Acacia*, miombo, mopane, teak (*Baikiaea Plurijuga*) et *Terminalia-Combretaceae*. Cet article visait à examiner la contribution potentielle des écosystèmes à savanes non perturbées et les effets des changements dans l'utilisation des terres sur les émissions de N_2O. Les données disponibles sur les émissions de N_2O étaient collectées des régions boisées de Miombo, régions de boisées de miombo, les prairies et des terres agricoles. La moyenne des flux de N_2O des écosystèmes à savane estimée à 17.1Gg pendant que les flux annuels à partir des terres arables (cultivées

et en jachère) était de 13.9Gg. Les flux étaient principalement concentrés dans la saison humide du fait que les émissions de N_2O sont fortement influencées par l'humidité élevée du sol. Les émissions pyrogéniques de la saison sèche constituaient d'importantes sources de N_2O, avec un niveau annuel d'émission de 6.7Gg. Les écosystèmes de savane en saison sèche constituent ainsi une importante source de N_2O à ne pas négliger dans des estimations nationales et régionales des émissions de gaz. Les estimations actuelles sont associées à de grandes incertitudes, ainsi, la nécessité d'études plus détaillées sur les variations spatiales et temporelles des émissions produites dans différents écosystèmes à savane, et les effets du changement dans l'utilisation des terres sur les émissions de N_2O.

Mots Clés: Gaz à effet de serre, miombo, mopane, savane

INTRODUCTION

Nitrous oxide (N_2O) is a greenhouse gas (GHG) with a considerable atmospheric warming potential and involvement in the destruction of stratospheric ozone (Crutzen, 1981). The greenhouse effect occurs because N_2O molecules traps long wave radiations emitted from the earth's surface; hence affecting the heat balance of the earth surface and resulting in rising surface temperatures (IPCC, 2007). Most of the severe impacts of climate change have been felt in tropical regions such as southern Africa, where most people depend on rain-fed agriculture (Mertz *et al.*, 2009). Therefore, changes in climate have critical implications for economies of developing countries (Ahmed *et al*., 2011).

Seasonally dry savannas cover approximately 3.1 million km^2 of land in southern Africa (Woomer, 1993). Seasonally dry savanna ecosystems consist of woodlands, grasslands and some seasonal wetlands in areas with rainfall between 500-1000 mm (Celander, 1983; Chidumayo and Frost, 1996). In their natural states, these seasonally dry ecosystems are expected to be limited sources of N_2O (Wuta, 2003; Mapanda *et al*., 2010). Emissions from soils in the savannas are greater under wet than dry conditions (Wick *et al.*, 2005; Castaldi *et al.*, 2006), which is due to the effects of moisture on mineralisation of organic matter and on denitrification at high soil water contents (Dobbie and Smith, 2003). The link between rainfall and the emission of nitrous oxide in Zimbabwe was shown by Scholes *et al*. (1997) and Rees *et al*. (2006), who reported that N_2O fluxes varied with soil moisture content. Fluxes were lowest in October (before the rains) and peaked just after the onset of the rains, after which fluxes declined.

The conversion of savannas to agricultural land has the potential to change dramatically the characteristics and gas exchange of the ecosystems. Approximately 1741 000 ha (0.9%) of once forested woodlands in southern Africa (Africa South of the Equator) has been deforested (Kigomo, 2003). FAO (2010) reported that in southern Africa, 84% of deforestation of forests and savannas was for agricultural purposes. Current statistics show that between 1990 and 2010, Zimbabwe lost an average of 327 000 ha (1.48%) of woodlands per year towards agricultural activities and new settlements. During the same period, Zimbabwe lost 29.5% of its forest cover (6 540 000 ha) (FAO, 2010). Clearing of primary forests often leads to an acceleration of decomposition of the residual litter (Watson et *al.*, 2000), and this can potentially increase N_2O emissions after making nitrogen (N) available in mineral form. Mapanda *et al*. (2010) reported average emissions of 21.7 and 19.6 $\mu g\ m^{-2}\ hr^{-1}$ from recently cleared miombo woodlands on clay and loamy sandy soils respectively; relative to 10 and 7.7 $\mu g\ m^{-2}\ hr^{-1}$ for the undisturbed woodland.

However, in the long term, the cleared land will change to grasslands and N_2O emissions will likely decrease. Wuta (2003) reported smaller N_2O losses in stabilised grasslands that were formerly woodlands compared with miombo woodland; whereas Rees *et al*. (2006) reported N_2O fluxes of 5.7 to 3.2 $\mu g\ m^{-2}\ hr^{-1}$ for miombo woodlands and deforested woodland (grassland), respectively. Lower emissions, over time, under deforested lands could be attributed to a decrease in the amounts of soil organic matter due to low biomass additions; and lower soil moisture. Additionally, Rees *et al*. (2006) reported that soil moisture

explained up to 80% of the variations in N_2O emissions in miombo woodlands.

The conversion of deforested land or grasslands to agricultural use can increase N_2O emission when N fertilisers are used. In crop production, when the N application rates are high, e.g. 400 kg N ha^{-1} used in other areas like the Netherlands (Kuikman *et al.*, 2003), the soils become sources of N_2O (Smith *et al*., 2007). However, when N application rates are low, e.g. 15 kg N ha^{-1}, the soil may be a net sink of N_2O rather than a source (Glatzel and Stahr, 2001; Chapuis-Lardy *et al*., 2007). Unlike managed ecosystems such as cropped land in which increased N_2O emissions are stimulated by deliberate N input (Rees *et al*., 2012), N_2O fluxes from unmanaged ecosystems such as savanna woodlands result from interacting microbial and plant processes affecting soil mineral N concentrations and their turnover. In this review, we explore the potential contribution of undisturbed savanna ecosystems, land-use change and agriculture to N_2O emissions in Zimbabwe.

METHODOLOGY

Site description. Zimbabwe is located in southern Africa between 19° and 30° south of the Equator. The country has a total land area of 39 million ha. The annual rainfall ranges from 500-1500 mm, with a rainy season from November to March. The average annual temperature is 25 °C. Approximately, 15.6 million ha (40%) of Zimbabwe is under forests and woodlands (FAO, 2010). The savanna woodlands cover over 95% of the country's forest cover, comprising five woodland types: *Acacia*, miombo, mopane, teak (*Baikiaea Plurijuga*), and *Terminalia-Combretaceae*. The miombo woodlands, which are composed primarily of *Brachystegia* species with *Julbernadia globiflora*, cover ~60% of the forest areas in Zimbabwe. In these woodlands, both grasses and woody plants are characteristic components (Huntley and Walker, 1982). Approximately 21 million ha (54% of the land area) is used for agricultural production, and 3.6% are in wetlands. The wetlands are mainly covered by grasses and a few scattered trees. Other land uses take up the remainder of the area.

Data on N_2O fluxes were collected from literature that included published and unpublished materials. Calculation of annual fluxes was done by the multiplication of ecosystem fluxes by area and by time (days). From literature, seasons (soil moisture) and land-use were identified as the two main factors that control N_2O emissions (Riley and Vitoustek, 1995; Verchot *et al.*, 1999; Watson et *al.*, 2000; Castaldi *et al.*, 2004; 2006). The seasons were categorised as dry or wet; where dry was the period with no or little rainfall (May-October), and wet was the rainy period, normally between November-April. The available data from Zimbabwe on N_2O emission was from miombo woodlands, deforested miombo woodlands, grasslands and agricultural land. Currently there is no reported N_2O emission data from *Acacia*, mopane, teak (*Baikiaea Plurijuga*) and *Terminalia-Combretaceae* woodland in Zimbabwe and a larger part of southern Africa.

RESULTS AND DISCUSSION

N_2O emissions from undisturbed miombo woodlands. Miombo woodlands are potentially an important source of N_2O (IPCC, 2001). However, these estimates are based on very few observations. In Zimbabwe, very few studies have quantified N_2O emissions from miombo woodlands (Wuta 2003; Rees *et al*., 2006; Mapanda *et al*., 2010; 2011). Measured peak fluxes in miombo woodlands were 33.2 µg m^{-2} hr^{-1} (Wuta, 2003). Rees *et al*. (2006) estimated that N losses from miombo woodlands in the form of N_2O were in the order of 0.25-0.54 kg N_2O-N ha^{-1} yr^{-1}, with mean emissions of 0.39 kg N_2O-N ha^{-1} yr^{-1}. Decomposition of litter fall could have contributed to increased N availability, resulting in increased N_2O emissions from the miombo woodland, in particular during the rainy season, when soil moisture is favourable for decomposition and denitrification. In addition, woodland soils retain moisture for a longer time than the cleared and uncultivated lands, resulting in higher N_2O emissions (Rees *et al*., 2006; Mapanda *et al*., 2010; 2011).

N_2O emissions from deforested miombo woodlands. Deforestation affects the soil

physical, chemical and biological characteristics, which all influence biogeochemical reactions leading to N_2O emissions. For instance, the conversion from forest to pasture has been shown to change soil organic carbon and nitrogen contents, as well as rates at which soil organic matter are turned over and during which mineral N is formed (Reiners *et al.*, 1994). Land-use change from woodland to bare soil or grassland can significantly affect ecosystem properties and biogeochemical reactions and, hence, GHG fluxes; and such changes often bring about an acceleration of decomposition of the residual litter. Rees *et al.* (2006) reported that the initial pulse of N_2O at the beginning of the rain season was associated with a large increase in soil respiration and a resulting loss in organic carbon in the soils which are higher in disturbed ecosystems.

Wuta (2003) reported a reduction in N_2O losses from deforested miombo woodland (14.3 µg N_2O-N m^{-2} hr^{-1}) compared with undisturbed miombo woodlands (33.2 µg N_2O-N m^{-2} hr^{-1}), and the decline was attributed to lower litter addition in the deforested areas. Mapanda *et al*. (2010) reported N_2O emissions of 10 µg N_2O-N m^{-2} hr^{-1} from miombo woodlands on clay soils compared with 21.7 µg N_2O-N m^{-2} hr^{-1} from a recently deforested area on similar soils (Table 1). On sandy soils, the N_2O fluxes also increased after deforestation from 7.7 to 19.6 µg N_2O-N m^{-2} hr^{-1}. Similar observations were made by Melillo *et al.* (2001), who reported emissions that were 250% higher during the first 2 years after deforestation compared with undisturbed forest emissions. High emissions in the deforested areas were attributed to increased mineralisation and N availability, and reduced N uptake following the clearing of trees (Mapanda *et al.*, 2010). In addition, there was a large amount of leaf litter that was left in the plots after the trees were removed, which may have contributed to increased soil mineral N.

Though deforestation resulted in an initial increase in N_2O emissions (Mapanda *et al.*, 2010), the subsequent decline in accumulated biomass could have resulted in lower N_2O emissions in the deforested areas. Davidson *et al*. (2001) suggested that the magnitude and duration of pulses of N availability and N-oxide emissions following site disturbance vary widely in tropical forests and probably depends upon the initial soil site fertility, i.e. the stocks of potentially mineralisable C and N and the rate of vegetation re-growth after the disturbance event. Melillo *et al*. (2001) reported a pulse that lasted up to 2 years following deforestation. However, environmental factors such as soil moisture, pH

TABLE 1. A summary of N_2O fluxes from various ecosystems and management practices

Ecosystem	Author	Measured fluxes (min) (µg N_2O-N m^{-2} hr^{-1})	Measured fluxes (max) (µg N_2O-N m^{-2} hr^{-1})
Miombo	Rees *et al.* (2006)		5.7
	Mapanda *et al.* (2010)	7.7 (sandy soils)	10 (clay soils)
Deforested	Rees *et al*. (2006)		3.2
	Mapanda *et al.* (2010)	19.6 (sandy soils)	21.7 (clay soils)
Grassland	Rees *et al*. 2006		6.0
	Mapanda *et al.* (2010)	1 (sandy)	4.7 (clay)
Burned land	Rees *et al*. (2006)		4.9
	Wuta (2003)		24.7
Wetland	Rees *et al*. (2006)		41.9 (clay)
	Nyamadzawo (2011)		14.2 (sandy)
Cropland	Mapanda *et al.* (2010)	3.3 (clay)	3.4 (sandy)

and temperature will interact with soil organic matter turnover and mineral N in contributing to the overall N_2O emissions, which thus are very site specific as well as variable in time and space. After deforestation, the deforested land will often be taken over by grasslands and/or scattered shrubs. Grasslands usually have lower N_2O emissions than miombo woodlands (Table 1), mainly because of lower litter additions (Mapanda *et al.*, 2010). Similar observations were reported by Melillo *et al*. (2001) in Brazil, that emissions from pastures older than 3 years were 33% lower than emissions from the undisturbed forests. Braga do Carmo *et al*. (2012) made similar observations in an Atlantic forest, which was converted into pastures. The lower emissions from grasslands were attributed to lower mineralisation and to much more efficient N uptake in the grassland than in the forest which left little N available for mineralisation.

N_2O emissions from agricultural soils. The differences in N_2O emissions between fertilised and unfertilised soils are particularly evident in soils which have low available mineral N (Castaldi and Aragosa, 2002; Rees *et al*., 2006). Average emissions of 3.3 -3.4 µg N_2O-N m^{-2} hr^{-1} of N_2O-N were reported on cropped land on clay and sandy loam soils in Zimbabwe (Mapanda *et al*., 2010; Table 1). Such, low N_2O fluxes in cropped land have been attributed to low soil organic carbon (Castaldi *et al*., 2006), and high crop N uptake rates which leaves little N available for denitrification (Mapanda *et al.*, 2011). Emissions depend on many factors; among them, land area under cropping, N application rates and soil types (Castaldi *et al.*, 2006). Agricultural activities may contribute considerably to N_2O emissions, but this would in particular depend on the management of N in inorganic and organic fertilisers as well as N in crop residues (Reay, 2012). High emissions, under cleared and cropped land with fertilisers, can be attributed to an increase in soil mineral-N concentrations from the applied fertilisers (Bouwman *et al.*, 2002). The addition of both organic and inorganic fertilisers to cropped land can increase N_2O production from agricultural lands, because the soil amendments added provide metabolisable C and N required for N_2O production. Inputs of N fertilisers strongly enhance N_2O emissions from soil (Clayton *et al*., 1997).

The input of N-based fertilisers like urea and ammonium and nitrate-containing fertilisers, stimulates N_2O. In Addition the alteration of soil porosity and structure due to agricultural practice can increase N_2O fluxes (Dick *et al.*, 2008; Chirinda *et al.*, 2010). Mapanda *et al*. (2010) reported that application of mineral NO_3^- resulted in far greater N_2O emissions than NH_4^+, suggesting that denitrification was a dominant process over nitrification; thus, the type of fertiliser has an impact on N_2O emissions. Background emissions from non-fertilised agricultural land ranged from 50-320 g ha^{-1} N_2O (emission factors of 0.05-0.3, Table 3). Mapanda *et al*. (2011) reported N_2O fluxes of 408 and 289 g ha^{-1} N_2O on clay soils after applying ammonium nitrate-N (34.5% N) at 60 and 120 kg ha^{-1} ammonium nitrate-N respectively (Table 2). In sandy loam soils at Domboshawa in NE Zimbabwe, the same study revealed total N_2O emissions of 515 and 408 g ha^{-1} ammonium nitrate-N, after applying ammonium nitrate at 60 and 120 kg N ha^{-1}, respectively (Table 2). In the same study, the application of cattle manure with 1.2-1.6 % N, resulted in lower N_2O emissions compared with ammonium nitrate and the application of manure which contained 60 and 120 kg ha^{-1} N resulted in N_2O emissions of 59 and 262 g ha^{-1} N_2O-N, respectively for the whole cropping season. However, the N_2O emission rates for the same manure and fertiliser treatments were much lower (18 to 67 g ha^{-1} N_2O-N) and were not significantly different during the 2008-2009 cropping season (Table 2). Estimated N_2O emissions from cultivation area under different scenarios of inorganic fertiliser and cattle manure application rates are shown in Table 3.

These results suggest that N_2O emissions increase with increasing N application and emissions vary with cropping season (Vinther *et al.*, 2004). N_2O emissions show large variations which are caused by the interaction between environmental factors, crop and soil management. The application of inorganic N resulted in higher N_2O emission compared with cattle manure. Lower emissions in soils amended with cattle manure can be attributed to initial immobilisation of N because of the low quality of the manure (1.2-

TABLE 2. Seasonal N_2O fluxes (g N_2O-N ha^{-1}) from the University of Zimbabwe Farm (UZF) with clay soils and Domboshawa, which had sandy soils (Mapanda *et al.* 2011). The 2007-08 season was 122 days and the 2008-09 season was 116 days

Rates	Clay soil		Sandy soil	
	2007-08	2008-09	2007-08	2008-09
0 kg N ha^{-1}	103	63	324	50
60 kg N ha^{-1} AN	408	22	515	32
120 kg N ha^{-1} AN	289	18	408	31
60 kg N ha^{-1} AN + 60 kg N ha^{-1} manure	157	37	335	32
60 kg N ha^{-1} cattle manure	59	34	257	45
120 kg N ha^{-1} manure	262	67	267	58

Data from Mapanda *et al.* (2011). Measurements during the 2007-08 season were carried over 122 days and during the 2008-09 season over 116 days. AN = Ammonium Nitrate (34.5% N). Cattle manure was removed from cattle pens (1.2-1.6% N), about 5t of manure was added to apply 60 kg manure N

TABLE 3. Estimated national seasonal fluxes of N_2O from arable land at different fertiliser application rates using data from the Domboshawa site

Arable land (ha)	Fertiliser rates (kg ha^{-1})	Min. fluxes (g ha^{-1} $season^{-1}$)	Max. fluxes (g ha^{-1} $season^{-1}$)	Nat. mini. estimated fluxes (Gg $season^{-1}$)	Nat. max. estimated fluxes (Gg $season^{-1}$)
18.3[c]	nil	50	203	0.51	2.4
2.697[b]	60 AN	32	515	0.08	1.4
2.697[b]	120 AN	31	408	0.08	1.1
2.697[b]	60 kg AN + 60kg manure-N	32	335	0.09	0.9
2.697[b]	60 kg manure-N	45	257	0.12	0.69
2.697[b]	120 kg manure-N	58	267	0.16	0.72

b = cropped area from FAOSTAT (2011), c = fallow land (calculated from difference between agriculcultural and cropped land). Calculation of annual fluxes was done by multiplying the ecosystem fluxes by area by time (days). Seasonal emissions estimated over 166 days

1.6% N) and slow release of mineral N. Similar observations were made by Dick *et al.* (2008) who reported a 158% increase in N_2O emissions following the application of urea compared to 63% after applying manure in savannas of semi arid Mali.

In Zimbabwe, fertiliser application rates range between 15 kg N ha^{-1} for smallholder areas and 120 kg N ha^{-1} for commercial farms. These rates are low when compared to high rates of 400 kg N ha^{-1} in developed countries (Kuikman *et al.*, 2003). Therefore, the impacts of these fertiliser application rates on N_2O emissions, crop may be low. The results suggest that the background emission factors for the Zimbabwean conditions may be smaller than the standards used by the IPCC of 1% (IPCC, 2006). This suggests an over-estimation of N_2O emissions from the seasonally dry ecosystems using the IPCC method. However, with future intensification of agricultural production to meet the growing demand for food, high rates of fertiliser may be used and this may increase N_2O emissions.

Generally, N_2O is produced as a by-product of nitrification and an intermediate product of denitrification or during chemodenitrification (chemical denitrification) of nitrite (NO_2^-) (Granli and Bøckman, 1994). Nitrification takes place under aerobic conditions and is stimulated by the application of NH_4^+ based fertilisers or release or mineral N from organic sources. Application of NO_3^- based fertilisers and improved carbon availability may result in denitrification under moderately reducing conditions (Smith *et al.*, 2007;

Baggs *et al*., 2000). Denitrification may take place in anaerobic micro-sites in the soil, even under otherwise aerobic soil conditions. Such micro-sites can occur after incorporation of carbon rich materials, where the turnover consumes oxygen. The decomposition of organic matter may at high soil moisture levels reduce O_2 levels and increase microbial demand for NO_3^- as an electron acceptor, thereby producing N_2O (Velthof *et al*., 2003). Soil moisture is an important factor in gaseous N emissions because it controls the supply of oxygen and the supply of NH_4^+ and NO_2^- to nitrifying bacteria; and NO_3^- and NO_2^- to denitrifying bacteria by diffusion (Davison, 1993). Other factors that control N_2O release include N mineralisation or other sources of N, soil temperature and availability of easily oxidisable carbon which is an energy source for the microorganisms (Bouwman, 1990). The processes described above can be affected by land-use change in seasonally dry ecosystems.

Emissions from seasonal wetlands. Seasonal wetlands (dambos) are also a potential source of N_2O emissions (Scholes and Scholes, 1998). In Zimbabwe, dambos cover an estimated 1.28 million ha (~3.6% of land area) (Acres *et al.*, 1985), and are mostly used for grazing livestock, as gardens and in some cases as permanent fields. Dambos usually have high amounts of soil organic carbon (SOC) (Mäckel, 1985; Whitlow, 1985). During the dry season when dambos dry out, or when they are drained for agricultural purposes, significant N_2O emissions may be expected from them. Rees *et al.* (2006) reported highest N_2O fluxes (41.9 µg m^{-2} hr^{-1}) from the lowest position on the catena (clay dambo), which was close to the drainage line and was seasonally saturated at Henderson Research station in Zimbabwe (Table 1). Preliminary results from a study by Nyamadzawo *et al*. (2011, Unpublished) reported N_2O-N emissions range of 12.9-15.5 µg m^{-2} hr^{-1} in saturated sandy dambos; and this was attributed to denitrification. The conversions of dambos to agricultural use potentially increase N losses as N_2O. Dambo areas used as gardens generally receive very high inorganic fertiliser application rates of about 350 kg N ha^{-1} (Mapanda *et al.* (2007), thus making them potential sources of N_2O. Grant (1995) reported average losses of between 9-54% of applied N fertiliser (ammonium nitrate) in cultivated dambos through denitrification when dambo soil was saturated immediately after fertilisation. The same study by Grant (1995) revealed that losses of applied N were highest in soils with higher SOC and pH. The risks of N_2O losses increased in soils which were most suitable for cropping (high SOC) or which had been manured, as they had a high turnover rate and consume oxygen, thus creating anaerobic microsites. Nitrous oxide emissions from dambos could be attributed to denitrification during the period of saturation, while nitrification is dominant when the dambos are not saturated during the dry season. So when dambos are cultivated and high rate of N based fertilisers or manure are applied this can potentially result in increased N_2O emissions.

Effects of burning. Burning is an important management practice which can be used to effect land-use change, hence it affects N_2O emissions from seasonally dry ecosystems. An example is the burning of litter during land clearing for cropping. Pyrogenic emissions are an important source of N_2O and are mostly concentrated in the dry season (July to October), whereas the biogenic emissions would be expected to be continuous throughout the year (Scholes and Andreae, 2000). Fire seems to have little effect on the biogenic emissions of N_2O between November and June, a period when precipitation has the greatest influence. After burning, nitrification and denitrification processes are significantly reduced because of the effects of fire on soil microorganisms and reduced levels of biomass N and this may result in low N_2O emissions (Castalidi and Argosa, 2002). More recently, Castaldi *et al.* (2010) found no significant differences in N_2O-N emissions at different moisture levels after burning in a study in Congo savanna and this was attributed to the reduction in above ground biomass which partly contributed to the activity of the grass roots, reduction in the autotrophic and heterotrophic components of the soil and due to in part to killing of microflora. Wuta (2003) reported N_2O-N emissions of 24.7 µg m^{-2} hr^{-1} after burning in woodlands and attributed the reduction in N_2O

emissions to the loss of carbon and mineral N during burning, and also to the effects of the fire on soil microorganisms. Burning causes significant N losses from seasonally dry ecosystems in Zimbabwe and N_2O-N losses from burning were estimated at 2.36 Gg yr^{-1} (Chenje *et al*., 1998). Scholes and Andreae (2000) gave N_2O-N emissions estimates of 6.7 Gg yr^{-1} from burning in Zimbabwe (Table 4). The work by Chenje *et al.* (1998) and Scholes and Andrea (2000) suggests that burning is the single largest contributor to atmospheric N_2O during the dry season in Zimbabwe and in Southern Africa. The practice of burning grasslands and woodlands should be strongly discouraged in order to reduce N_2O emissions.

Rainfall and nitrous oxide emissions. Rainfall affects biogeochemical processes of ecosystems and, hence N_2O emissions from the seasonally dry ecosystems. Soil moisture, which is controlled by season, seems to have a much greater influence on N_2O emissions from upland soils of the savannas. The link between rainfall and the emission of nitrous oxide in Zimbabwe is shown in the work by Rees *et al*. (2006), who reported that N_2O fluxes varied with soil moisture content, as fluxes were lowest in October (before the rains) and peaked (42 µg m^{-2} hr^{-1}) between 15 and 45 days after the rains. Scholes *et al*. (1997) reported the same trend at the nutrient poor savanna grasslands in Nylsvley, South Africa where N_2O emissions peaked at the beginning of the rain season before stabilising as the season progressed. The addition of water to dry soil results in higher microbial activity. The flush in N_2O emissions soon after the rains are possibly a result of the response of microbial communities to alteration in water supply as the initial pulse of N_2O is associated with a large increase in soil respiration (Rees *et al.*, 2006). Though N_2O emission occurs at all moisture contents, increasing the water content up to saturation results in increased N_2O emissions (Riley and Voustek, 1995). Soil water content influences diffusion conditions in the soil and thus impacts the supply of oxygen (Robertson and Tiedje, 1987) which in turn controls the amount of N_2O emitted.

Research gaps. The effects of land use change on N_2O emissions remain uncertain due to the paucity of measurements as there are very few datasets on N_2O emissions in undisturbed dry savannas, and in seasonally ecosystems that have under gone land use change. There is need for further studies on the effects of land-use change from forested to cleared land, burning, and ploughing on N_2O emissions as most of the data are estimates with little ground truthing. Measurements have shown generally low emissions from agricultural land use. However, there may be several causes of this, which needs to be explored. Some of the reasons may be the lower soil organic matter contents and the high rates of degradation of organic matter and turnover. However, these high turnover rates could possibly cause large, but short-lived, peaks

TABLE 4. Summary of estimates N_2O fluxes from different ecosystems in Zimbabwe

Ecosystem/practice	Ecosystem flux (µg N_2O-N m^{-2} hr^{-1})	Area (million ha)	Estimated emission (Gg N_2O-N yr^{-1})
Woodland and forests	5.7-10	15.4	5.45 (3.8-7.1)
Landuse change; forest-grasslands	3-21.7	0.327	0.18 (0.04-0.31) Gg
Dambo wetlands	14.2-41.9	1.28	1.6 (0.8-2.3)
Biomass burning	4.9-24.7	-*	2.4-6.7**
Agricultural land-cropped	3.3-3.4	2.697	0.39 (0.38-0.4)
Agricultural land-fallow/grasslands	1-5.9	18.3	2.75. (0.8-4.7)
Total		38	17.1 (8.2-21.5)

Number in bracket is the range. Calculation of annual fluxes was done by the intergration of ecosystem fluxes by area by time (days). *Area burnt was variable, data was not available. ** Largest estimate available from literature was used

of N_2O emissions following fertilisation or soil incorporation of organic matter. Such peaks are easily missed in monitoring programs, unless very frequent measurements are made. There is thus need for more studies on the spatial and temporal variations in N_2O emissions from cropped land across rainfall and fertility gradients. The lack of consistence in the behaviour of N_2O emissions due to mineral fertiliser and/or manure additions constitutes a research gap and merits future research and the need for long term experiments on the effects fertiliser on N_2O emissions. Pastures and grazed grasslands are also a potential source of N_2O emissions; however, there is no data available from this land-use in Zimbabwe. Most work on the effects of landuse change on N_2O emissions in Zimbabwe has been carried out in miombo woodlands and there are no studies that have been carried out to evaluate the effects of landuse changes in other woodlands e.g. *Acacia*, *Colophospermum mopane* (mopane), *Baikiaea plurijuga* (teak), and *Terminalia-Combretaceae*. There is also need for further work to quantify the spatial and temporal variations in N_2O emissions from seasonal wetlands. These emerging research issues will help to shape our understanding of the contribution of seasonally dry ecosystems to national and regional N_2O emissions.

CONCLUSION

Miombo woodlands, a seasonally dry ecosystem in Zimbabwe contributes towards biogenic emissions during the wet season. From the available data deforestation of miombo woodlands resulted in an immediate (>100%) increase in N_2O emissions; however, the emissions decrease with time. Land-use change to agriculture, were manure and nitrogen based fertilizers are used results in increased N_2O emissions. Burning contributes significantly to N_2O emissions during the dry season. The dry season pyrogenic emissions are important sources of N_2O, and may contribute emissions of about 6.7 Gg annually. Seasonally dry savanna ecosystems, thus, constitute an important source of N_2O, which should not be ignored in national and regional estimates of emissions of the gas. The greatest challenge in making estimates from seasonally dry ecosystems of Zimbabwe is the scarcity and paucity of data, and a complete lack of data on N_2O emissions from some of the savanna ecosystems. Despite the large uncertainties on N_2O emissions, the estimates from this review help to indicate the importance and potential contribution of seasonally dry ecosystems towards regional N_2O emissions.

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