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

G. NYAMADZAWO1,2, N. CHIRINDA3, F. MAPANDA2, J. NYAMANGARA4, M. WUTA2, P. NYAMUGAFATA2 and J.E. OLESEN1
1Department of Environmental Science, Bindura University of Science Education, Box 1020, Bindura, Zimbabwe
2Department of Soil Science and Agricultural Engineering, University of Zimbabwe, Box MP167, Mount Pleasant, Harare, Zimbabwe
3Department of Agroecology, Aarhus University, Blichers Allé 20, DK-8830, Tjele, Denmark
4International Centre for Research in Semi Arid Tropics (ICRISAT) Matopos, Box 776, Bulawayo, Zimbabwe

Corresponding author: gnyama@yahoo.com

ABSTRACT

Nitrous oxide (N₂O) 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 N₂O emissions in Zimbabwe. Available data on N₂O emission were collected from standing and deforested miombo woodlands, grasslands and agricultural lands. Estimated mean annual N₂O emissions from savanna ecosystems in Zimbabwe were 17.1 Gg N₂O, while annual fluxes from arable land (cultivated and fallow) was 3.19 Gg N₂O. Biogenic N₂O emissions were mainly concentrated in the wet season as N₂O production is strongly enhanced by high soil moisture. During the dry season pyrogenic emissions were also important sources of N₂O, contributing, an estimated 6.7 Gg N₂O annually. Land use change in the form of biomass burning and conversion to grassland or arable land may be considerable source of N₂O, whereas current agricultural practices do not seem to provide a large source of N₂O in Zimbabwe. Seasonally dry savanna ecosystems, thus, constitute an important source of N₂O, which should not be ignored in national and regional estimates of emissions of N₂O. Land-use change from savanna to agricultural production results in an immediate increase in N₂O 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 N₂O emissions and on spatial and temporal variations in N₂O emissions from the different savanna ecosystems.

Key Words: Greenhouse gases, miombo, mopane, savanna

RÉSUMÉ

L’oxyde nitreux (N₂O) 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 N₂O. Les données disponibles sur les émissions de N₂O étaient collectées des régions boisées de Miombo, régions de boisées de miombo, les prairies et des terres agricoles. La moyenne des flux de N₂O 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 influencees par l’humidité élevée du sol. Les émissions pyrogéniques de la saison sèche constituaient 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 µg m\(^{-2}\) hr\(^{-1}\) from recently cleared miombo woodlands on clay and loamy sandy soils respectively; relative to 10 and 7.7 µg 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 µg 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$_2$O emissions in miombo woodlands.

The conversion of deforested land or grasslands to agricultural use can increase N$_2$O 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$_2$O (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$_2$O rather than a source (Glatzel and Stahr, 2001; Chapuis-Lardy et al., 2007). Unlike managed ecosystems such as cropped land in which increased N$_2$O emissions are stimulated by deliberate N input (Rees et al., 2012), N$_2$O 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$_2$O 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$_2$O 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$_2$O emissions (Riley and Vitousek, 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$_2$O emission was from miombo woodlands, deforested miombo woodlands, grasslands and agricultural land. Currently there is no reported N$_2$O 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$_2$O emissions from undisturbed miombo woodlands.** Miombo woodlands are potentially an important source of N$_2$O (IPCC, 2001). However, these estimates are based on very few observations. In Zimbabwe, very few studies have quantified N$_2$O 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$_2$O were in the order of 0.25-0.54 kg N$_2$O-N ha$^{-1}$ yr$^{-1}$, with mean emissions of 0.39 kg N$_2$O-N ha$^{-1}$ yr$^{-1}$. Decomposition of litter fall could have contributed to increased N availability, resulting in increased N$_2$O 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$_2$O emissions (Rees et al., 2006; Mapanda et al., 2010; 2011).

**N$_2$O emissions from deforested miombo woodlands.** Deforestation affects the soil
physical, chemical and biological characteristics, which all influence biogeochemical reactions leading to N$_2$O 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$_2$O 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$_2$O losses from deforested miombo woodland (14.3 µg N$_2$O-N m$^{-2}$ hr$^{-1}$) compared with undisturbed miombo woodlands (33.2 µg N$_2$O-N m$^{-2}$ hr$^{-1}$), and the decline was attributed to lower litter addition in the deforested areas. Mapanda et al. (2010) reported N$_2$O emissions of 10 µg N$_2$O-N m$^{-2}$ hr$^{-1}$ from miombo woodlands on clay soils compared with 21.7 µg N$_2$O-N m$^{-2}$ hr$^{-1}$ from a recently deforested area on similar soils (Table 1). On sandy soils, the N$_2$O fluxes also increased after deforestation from 7.7 to 19.6 µg N$_2$O-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$_2$O emissions (Mapanda et al., 2010), the subsequent decline in accumulated biomass could have resulted in lower N$_2$O 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>
<thead>
<tr>
<th>Ecosystem</th>
<th>Author</th>
<th>Measured fluxes (min)</th>
<th>Measured fluxes (max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miombo</td>
<td>Rees et al. (2006)</td>
<td>7.7 (sandy soils)</td>
<td>5.7 (clay soils)</td>
</tr>
<tr>
<td></td>
<td>Mapanda et al. (2010)</td>
<td>7.7 (sandy soils)</td>
<td>10 (clay soils)</td>
</tr>
<tr>
<td>Deforested</td>
<td>Rees et al. (2006)</td>
<td>19.6 (sandy soils)</td>
<td>3.2 (clay soils)</td>
</tr>
<tr>
<td></td>
<td>Mapanda et al. (2010)</td>
<td>19.6 (sandy soils)</td>
<td>21.7 (clay soils)</td>
</tr>
<tr>
<td>Grassland</td>
<td>Rees et al. (2006)</td>
<td>1 (sandy)</td>
<td>6.0 (clay)</td>
</tr>
<tr>
<td></td>
<td>Mapanda et al. (2010)</td>
<td>1 (sandy)</td>
<td>4.7 (clay)</td>
</tr>
<tr>
<td>Burned land</td>
<td>Rees et al. (2006)</td>
<td>4.9</td>
<td>24.7</td>
</tr>
<tr>
<td></td>
<td>Wuta (2003)</td>
<td>4.9</td>
<td>24.7</td>
</tr>
<tr>
<td>Wetland</td>
<td>Rees et al. (2006)</td>
<td>41.9 (clay)</td>
<td>14.2 (sandy)</td>
</tr>
<tr>
<td></td>
<td>Nyamadzawo (2011)</td>
<td>41.9 (clay)</td>
<td>14.2 (sandy)</td>
</tr>
<tr>
<td>Cropland</td>
<td>Mapanda et al. (2010)</td>
<td>3.3 (clay)</td>
<td>3.4 (sandy)</td>
</tr>
</tbody>
</table>
Land-use change effects on nitrous oxide emissions

and temperature will interact with soil organic matter turnover and mineral N in contributing to the overall N₂O 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 N₂O 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.

N₂O emissions from agricultural soils. The differences in N₂O 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 N₂O-N m⁻² hr⁻¹ of N₂O-N were reported on cropped land on clay and sandy loam soils in Zimbabwe (Mapanda et al., 2010; Table 1). Such, low N₂O 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 N₂O 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 N₂O production from agricultural lands, because the soil amendments added provide metabolisable C and N required for N₂O production. Inputs of N fertilisers strongly enhance N₂O emissions from soil (Clayton et al., 1997).

The input of N-based fertilisers like urea and ammonium and nitrate-containing fertilisers, stimulates N₂O. In addition the alteration of soil porosity and structure due to agricultural practice can increase N₂O fluxes (Dick et al., 2008; Chirinda et al., 2010). Mapanda et al. (2010) reported that application of mineral NO₃ resulted in far greater N₂O emissions than NH₄⁺, suggesting that denitrification was a dominant process over nitrification; thus, the type of fertiliser has an impact on N₂O emissions. Background emissions from non-fertilised agricultural land ranged from 50-320 g ha⁻¹ N₂O (emission factors of 0.05-0.3, Table 3). Mapanda et al. (2011) reported N₂O fluxes of 408 and 289 g ha⁻¹ N₂O 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 N₂O emissions of 515 and 408 g ha⁻¹ N₂O after applying 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 N₂O emissions compared with ammonium nitrate and the application of manure which contained 60 and 120 kg ha⁻¹ N resulted in N₂O emissions of 59 and 262 g ha⁻¹ N₂O, respectively for the whole cropping season. However, the N₂O emission rates for the same manure and fertiliser treatments were much lower (18 to 67 g ha⁻¹ N₂O-N) and were not significantly different during the 2008-2009 cropping season (Table 2). Estimated N₂O emissions from cultivation area under different scenarios of inorganic fertiliser and cattle manure application rates are shown in Table 3.

These results suggest that N₂O emissions increase with increasing N application and emissions vary with cropping season (Vinther et al., 2004). N₂O 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 N₂O 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$_2$O fluxes (g N$_2$O-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.

<table>
<thead>
<tr>
<th>Rates</th>
<th>Clay soil</th>
<th>Sandy soil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2007-08</td>
<td>2008-09</td>
</tr>
<tr>
<td>0 kg N ha$^{-1}$</td>
<td>103</td>
<td>63</td>
</tr>
<tr>
<td>60 kg N ha$^{-1}$ AN</td>
<td>408</td>
<td>22</td>
</tr>
<tr>
<td>120 kg N ha$^{-1}$ AN</td>
<td>289</td>
<td>18</td>
</tr>
<tr>
<td>60 kg N ha$^{-1}$ AN + 60 kg N ha$^{-1}$ manure</td>
<td>157</td>
<td>37</td>
</tr>
<tr>
<td>60 kg N ha$^{-1}$ cattle manure</td>
<td>59</td>
<td>34</td>
</tr>
<tr>
<td>120 kg N ha$^{-1}$ manure</td>
<td>262</td>
<td>67</td>
</tr>
</tbody>
</table>

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$_2$O from arable land at different fertiliser application rates using data from the Domboshawa site

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

b = cropped area from FAOSTAT (2011), c = fallow land (calculated from difference between agricultural 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.

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$_2$O emissions 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$_2$O 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$_2$O emissions.

Generally, N$_2$O 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 of 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; 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$_2$O emissions following the application of urea compared to 63% after applying manure in savannas of semi-arid Mali.
Land-use change effects on nitrous oxide emissions

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\textsubscript{2} levels and increase microbial demand for NO\textsubscript{3}\textsuperscript{-} as an electron acceptor, thereby producing N\textsubscript{2}O (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\textsubscript{4}\textsuperscript{+} and NO\textsubscript{2}\textsuperscript{-} to nitrifying bacteria; and NO\textsubscript{3}\textsuperscript{-} and NO\textsubscript{2}\textsuperscript{-} to denitrifying bacteria by diffusion (Davison, 1993). Other factors that control N\textsubscript{2}O 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\textsubscript{2}O 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\textsubscript{2}O emissions may be expected from them. Rees et al. (2006) reported highest N\textsubscript{2}O fluxes (41.9 µg m\textsuperscript{-2} hr\textsuperscript{-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\textsubscript{2}O-N emissions range of 12.9-15.5 µg m\textsuperscript{-2} hr\textsuperscript{-1} in saturated sandy dambos; and this was attributed to denitrification. The conversions of dambos to agricultural use potentially increase N losses as N\textsubscript{2}O. Dambo areas used as gardens generally receive very high inorganic fertiliser application rates of about 350 kg N ha\textsuperscript{-1} (Mapanda et al. (2007), thus making them potential sources of N\textsubscript{2}O. 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\textsubscript{2}O 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\textsubscript{2}O emissions.

**Effects of burning.** Burning is an important management practice which can be used to effect land-use change, hence it affects N\textsubscript{2}O 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\textsubscript{2}O 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\textsubscript{2}O 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\textsubscript{2}O emissions (Castalidi and Argosa, 2002). More recently, Castaldi et al. (2010) found no significant differences in N\textsubscript{2}O-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\textsubscript{2}O-N emissions of 24.7 µg m\textsuperscript{-2} hr\textsuperscript{-1} after burning in woodlands and attributed the reduction in N\textsubscript{2}O
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\(_2\)O-N losses from burning were estimated at 2.36 Gg yr\(^{-1}\) (Chenje et al., 1998). Scholes and Andreae (2000) gave N\(_2\)O-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 Andreae (2000) suggests that burning is the single largest contributor to atmospheric N\(_2\)O 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\(_2\)O emissions.

**Rainfall and nitrous oxide emissions.** Rainfall affects biogeochemical processes of ecosystems and, hence N\(_2\)O emissions from the seasonally dry ecosystems. Soil moisture, which is controlled by season, seems to have a much greater influence on N\(_2\)O 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\(_2\)O 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\(_2\)O 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\(_2\)O 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\(_2\)O is associated with a large increase in soil respiration (Rees et al., 2006). Though N\(_2\)O emission occurs at all moisture contents, increasing the water content up to saturation results in increased N\(_2\)O emissions (Riley and Voustea, 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\(_2\)O emitted.

**Research gaps.** The effects of land use change on N\(_2\)O emissions remain uncertain due to the paucity of measurements as there are very few datasets on N\(_2\)O emissions in undisturbed dry savannas, and in seasonally ecosystems that have undergone 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\(_2\)O 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

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**TABLE 4. Summary of estimates N\(_2\)O fluxes from different ecosystems in Zimbabwe**

<table>
<thead>
<tr>
<th>Ecosystem/practice</th>
<th>Ecosystem flux (µg N(_2)O-N m(^{-2}) hr(^{-1}))</th>
<th>Area (million ha)</th>
<th>Estimated emission (Gg N(_2)O-N yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woodland and forests</td>
<td>5.7-10</td>
<td>15.4</td>
<td>5.45 (3.8-7.1)</td>
</tr>
<tr>
<td>Landuse change; forest-grasslands</td>
<td>3-21.7</td>
<td>0.327</td>
<td>0.18 (0.04-0.31) Gg</td>
</tr>
<tr>
<td>Dambo wetlands</td>
<td>14.2-41.9</td>
<td>1.28</td>
<td>1.6 (0.8-2.3)</td>
</tr>
<tr>
<td>Biomass burning</td>
<td>4.9-24.7</td>
<td>-*</td>
<td>2.4-6.7**</td>
</tr>
<tr>
<td>Agricultural land-cropped</td>
<td>3.3-3.4</td>
<td>2.697</td>
<td>0.39 (0.38-0.4)</td>
</tr>
<tr>
<td>Agricultural land-fallow/grasslands</td>
<td>1-5.9</td>
<td>18.3</td>
<td>2.75 (0.8-4.7)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>38</strong></td>
<td><strong>17.1 (8.2-21.5)</strong></td>
</tr>
</tbody>
</table>

Number in bracket is the range. Calculation of annual fluxes was done by the integration of ecosystem fluxes by area by time (days). *Area burnt was variable, data was not available. ** Largest estimate available from literature was used.
of N₂O 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 N₂O emissions from cropped land across rainfall and fertility gradients. The lack of consistence in the behaviour of N₂O 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 N₂O emissions. Pastures and grazed grasslands are also a potential source of N₂O emissions; however, there is no data available from this land-use in Zimbabwe. Most work on the effects of landuse change on N₂O 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 N₂O 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 N₂O 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 N₂O emissions; however, the emissions decrease with time. Land-use change to agriculture, where manure and nitrogen based fertilizers are used results in increased N₂O emissions. Burning contributes significantly to N₂O emissions during the dry season. The dry season pyrogenic emissions are important sources of N₂O, and may contribute emissions of about 6.7 Gg annually. Seasonally dry savanna ecosystems, thus, constitute an important source of N₂O, 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 N₂O emissions from some of the savanna ecosystems. Despite the large uncertainties on N₂O emissions, the estimates from this review help to indicate the importance and potential contribution of seasonally dry ecosystems towards regional N₂O emissions.

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