

REFEREED PAPER

COMPARISON OF GREENHOUSE GAS EMISSIONS FROM TRASHED AND BURNT SUGARCANE CROPPING SYSTEMS IN SOUTH AFRICA

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Abstract

It is well known that agriculture emits greenhouse gases (GHGs) to the atmosphere, thus contributing to human-induced climate change. Of particular concern are carbon dioxide (CO₂), nitrous oxide (N₂O) and methane (CH₄). In sugarcane cropping systems, the soil is able to sequester significant quantities of carbon (C); however, the degree to which C can be sequestered is influenced by a number of management choices, one of which is deciding whether to trash or burn at harvest. In this study, existing literature on GHG emissions from sugarcane cropping systems is reviewed. Although a number of excellent studies have been conducted on this topic, knowledge gaps severely limit our ability to accurately estimate GHG emissions. The ability of the mechanistic DSSAT-Canegro model, coupled with other approaches, to estimate annual emissions from trashed and burnt systems for the Maidstone mill area, is demonstrated. Findings show that while trashed systems can sequester significantly more C up to a point, the higher moisture regime that generally occurs for these systems means that relatively higher losses of N₂O as a result of denitrification can potentially occur, emphasising the need for precision nitrogen management. Finally, mitigation measures to reduce GHG emissions are discussed and future research needs outlined.

Keywords: greenhouse gases, carbon sequestration, trashing, burning, DSSAT, Canegro

Introduction

Until the 1980s, soil carbon (C) research was focused mainly on its role in maintaining optimal soil physical, chemical and biological properties. Thereafter, because of increasing concerns on larger-scale environmental issues, research has seen a shift to soil C sequestration and greenhouse gas (GHG) emissions.

A number of studies have shown that human activities (including agriculture) have contributed to enhanced release of GHGs into the atmosphere and accelerated climate change (Weier, 1998; Park et al., 2003). Over the past 50 years, average temperatures have increased

by approximately 0.2 °C per decade (SA DNT, 2010). Greenhouse gas emissions and climate change are therefore demanding increased research attention, especially because of market pressures to estimate and mitigate carbon dioxide (CO₂), nitrous oxide (N₂O) and methane (CH₄) emissions into the atmosphere (Rein, 2010).

In 2009, during the Copenhagen Climate Change Summit, South Africa announced active participation in reducing domestic GHG emissions by 34% and 42% by 2020 and 2025, respectively (SA DNT, 2010). As a result of this, South African industries need to take action to account for their GHG emissions and, where possible, to find ways to mitigate them. Carbon dioxide, N₂O and CH₄ (from human and natural sources) are the main contributors to the global warming effect and contribute about 72-83%; with chlorofluorocarbons (CFCs) contributing the remaining significant fraction of 12-25% (Weier, 1998).

Carbon dioxide, N₂O and CH₄ differ in atmospheric lifespan and thus have different GHG potencies. Carbon dioxide is the least potent of the three and is the GHG against which all other GHGs are compared. Nitrous oxide and CH₄ are considered 296 and 23 times more potent than CO₂, respectively, over a 100 year period (Dalal *et al.*, 2003). These values are referred to as global warming potentials (GWPs) and are used to convert emissions into carbon dioxide equivalents (CO₂eq).

In this paper, work from previous studies is reviewed to compare emissions of GHGs from trashed and burnt sugarcane cropping systems. Based on suggested approaches and results from a simulation study, emission estimates are made for a typical burnt and trashed cropping system in South Africa, and estimates are then scaled up to the mill region level. Finally, measures to mitigate GHG emissions are discussed, and future research required to further our understanding on GHG emissions from sugarcane cropping systems in South Africa is suggested.

Carbon and nitrogen partitioning in sugarcane

During photosynthesis, CO₂ is taken up by the sugarcane plant and sequestered as other forms of C and stored in the plant biomass (roots, stalks, leaves and flowers). Typically the green leaves make up 12%, the brown leaves 13%, the stalks 60% (Donaldson *et al.*, 2008) and the roots 17% (Rostron, 1974) of the total dry biomass of sugarcane. In all parts of the sugarcane plant, as a result of a lack of qualitative information, the assumption is that C comprises 45% of the total biomass (Donalson *et al.*, 2008).

In addition to storing C, the sugarcane plant contains significant quantities of N. Values for the above-ground portions for variety N14 grown under irrigation in Pongola are 0.77% N based on dry matter mass (DM) for green leaves, 0.27% N in the stalks and 0.32% N in the brown trash (Donaldson *et al.*, 2008). Similar values were reported for N14 by Thompson (1991).

Greenhouse gas emissions from sugarcane cropping systems

Carbon dioxide

Only limited information is available on the emission of CO₂ from sugarcane fields (Weier, 1998). Crops are often assumed to be CO₂ neutral, as they sequester similar amounts of C as are returned to the atmosphere over the growth cycle (Denmead *et al.* 2010).

Studies on the conversion of natural grassland to sugarcane under burning (bare soil conditions) demonstrated that organic C decreased in all soils regardless of texture (Domniny *et al.* 2002; Li and Mathews, 2010). This indicates that, despite being a grass, sugarcane under burnt conditions is not able to maintain the same soil organic matter (SOM) levels as natural grassland. On the other hand, a comparison of grassland and trashed sugarcane showed that the SOM under trashed sugarcane soils was higher than under grassland (Haynes and Graham, 2004), implying that soils under trashed sugarcane production may be an effective C sink. A strong relationship between clay content and organic matter has been observed for soils in the South African sugar industry (Miles *et al.*, 2008). A soil's clay content and the initial organic matter content will therefore influence the maximum amount of sequestered organic C a soil can hold. For example, a sandy soil with a C content of 0.5% will typically contain about 19 tons C/ha (33 tons organic matter/ha); while a clay soil with a C content of 2% will contain around 63 tons C/ha (just more than 100 tons organic matter/ha). Clay soils therefore have a much higher capacity to sequester C relative to sandier soils. Soil properties that slow mineralisation of organic matter will reduce CO₂ emissions. For example, waterlogged conditions, low temperatures, high base status and variable surface charge will retard C mineralisation. Evidence of this is the natural accumulation of organic matter in soils found in low lying areas in the landscape that are often waterlogged. On the other hand, well aerated soils, high temperatures, sandy textures, acidity, lack of soil structure and low charge surfaces encourage C mineralisation (Oades, 1988).

Few studies have been done to compare CO₂ emissions from burnt and trashed sugarcane cropping systems. Weier (1996) observed that CO₂-C emissions ranged from 175-290 kg/ha for a trashed treatment and from 83-182 kg/ha for a burnt treatment over a 10-day period for a sugarcane field in Hawaii. It was reported that these emissions appeared to be reduced by the presence of N fertiliser.

Nitrous oxide

Nitrogen oxides are released from soil-plant systems into the atmosphere as a result of biological nitrification and denitrification and chemical denitrification (Bouwman, 1998). Soil NO₃⁻, NH₄⁺, soluble and readily decomposable C, temperature, and water and oxygen availability will all play major roles in influencing the quantities of this gas lost from the soil (Dalal *et al.*, 2003). As with CO₂, a lack of past research and the existence of challenges associated with measuring N₂O emissions from sugarcane cropping systems means that only limited data is available to guide estimates of the emissions of this gas for sugarcane. However, in Hawaii, Balasubramanian and Kanehiro (1976) found that for four out of six soils tested, denitrification was the major process of N loss, and N₂O constituted 30-50% of gaseous N losses. Chapman *et al.* (1994) reported that a suspected 41% of applied fertiliser urea was lost as a result of denitrification, and Vallis *et al.* (1996) observed that 25-60% of

applied fertiliser N was not recovered in the crop or soil. In Australia, Weier *et al.* (1996) measured denitrification N losses of 247-1673 g N/ha/day from a fine textured, poorly drained soil over three days, representing 3.2-19.7% of applied N. The proportion of this N loss as N₂O ranged from 45-78%, and this proportion was observed to be strongly influenced by soil NO₃⁻ concentration and soil water content. The authors observed that for better-drained, more coarsely-textured soils, N losses due to denitrification were <1% of applied N. Also in Australia for a burnt sugarcane crop produced in northern New South Wales (NSW) on an estuary floodplain, Denmead *et al.* (2010) measured very high N₂O emissions of 72.1 kg/ha (45.9 N₂O-N), and emissions were noted to persist at substantial rates over a period of five months. The N₂O emission factor of 21% noted by Denmead *et al.* (2010) was thought to be extremely high compared to the emission factor (~1.25%) often used in GHG inventories. It must, however, be highlighted that the soils in this study were acid peat (Shroeder *et al.*, 2011) and therefore not typical of the sugarcane growing regions of Australia (Shroeder *et al.*, 2007). A similar denitrification study conducted in the central region of the Queensland sugarcane industry on well-drained alluvial soils showed N₂O emissions substantially less than those that occurred in NSW (Wang *et al.*, 2008).

In contrast to N₂O production in soil, the contribution to N₂O emissions as a result of crop residue burning is estimated to be relatively small (Crutzen and Andreae, 1990; Weier, 1998). An N₂O:N emission ratio of 0.7±0.3% has been derived to estimate N₂O emissions from burnt residue (Crutzen and Andreae, 1990). In laboratory studies investigating biomass burning, it has been observed that N₂O, NO, NH₃, HCN and CH₃CN represented about 25% of plant N emitted, another 20% was emitted as high molecular weight compounds, as much as 50% emitted as N₂ and around 10% remained in the ash (Crutzen and Andreae, 1990; Lobert *et al.*, 1990).

Methane

Crop residue burning can release significant quantities of CH₄. Emissions measured for the smouldering phase following burning of trash yielded a CH₄ emission factor of 0.4% from an original sugarcane fuel C content of 6 t/ha (Galbally *et al.*, 1992). For the site in the estuary floodplain under burnt sugarcane production in Australia (as described previously in this paper), Denmead *et al.* (2010) measured CH₄ emissions of 19.9 kg/ha over a period of 392 days. At a different site that was trash-blanketed, net emissions were essentially zero. In contrast, Weier (1996) observed that trash-blanketed soils could act as a sink for CH₄ (soil bacteria oxidise CH₄ to CO₂, which is a much less potent GHG).

Not much is known about how system characteristics affect CH₄ uptake or emissions (Weier, 1998). Studies in England showed that soil cores taken from a soil fertilised with inorganic N showed much slower rates of oxidation when exposed to CH₄ compared to a soil which had received no N. Interestingly, soil cores taken from soils which had received a mixture of inorganic (ammonium) and organic N fertiliser oxidised at a rate similar to that of the soil core without any N fertiliser (Powlson, 1994). In a study in which sugarcane trash (15 t/ha) was applied to the surface, Weier (1999) observed CH₄ emissions ranging from 297-1005 g CH₄-C/ha when plots were fertilised with urea, and CH₄ consumption ranging from 442-467 g CH₄-C/ha when plots were fertilised with ammonium sulphate. The reason for this difference is not yet fully understood.

Precursors and indirect emissions

In addition to the GHGs discussed above (CO₂, N₂O, CH₄), carbon monoxide (CO), oxides of nitrogen (NO_x), non-methane volatile organic compounds (NMVOCs), and ammonia (NH₃) can also be emitted as a result of sugarcane production. Carbon monoxide, NO_x gases and NMVOCs are often called 'ozone precursors' as they contribute to the formation of the GHG ozone in the presence of sunlight (IPCC, 2006). Nitrogen oxides and NH₃ play important roles in the N cycle and can be re-deposited on other terrestrial or aquatic systems and potentially be transformed to N₂O. For this reason these gases, although not always used in GHG emission estimates, are often reported in GHG inventories.

GHG emissions from sugarcane production in a South African context

Currently about 75% of the SA sugar industry's 423 000 ha is harvested each year, of which approximately 90% is burnt at harvest (SACGA, 2009). Burning is practiced to facilitate stalk harvest (usually done manually) and transportation, but unfortunately this practice encourages CO₂, N₂O and CH₄ emissions (Galdos et al., 2009), the extent of which is not yet fully understood. In addition, very little work has been done in South Africa to quantify GHG emissions from burnt and trashed sugarcane systems. For this reason, a simulation study was done to estimate and compare GHG emissions for a typical trashed and burnt sugarcane cropping system in South Africa.

Simulation study

The Canegro sugarcane model was recently included into the DSSAT (Decision Support System for Agrotechnology Transfer) framework (Jones *et al.*, 2003; Singels *et al.*, 2008) enabling increased functionality with regards to C and nutrient dynamics modelling. For general approaches used in the model, readers are referred to Tsuji *et al.* (1998), and more specifically to Singels *et al.* (2008) for a description of the simulation of sugarcane growth, Ritchie (1998) for a description of the simulation of the soil water balance, and van der Laan *et al.* (2011) for additional information on C and N modelling approaches.

The model was initialised to represent a typical sugarcane cropping system for South Africa. A sandy loam soil with 1.2% organic C in the topsoil and a profile depth of 1.45 m was used. Sugarcane was grown on an annual cycle and harvested in October every year. A plant crop followed by eight ratoon crops was simulated for each cropping cycle. Long-term weather data (1929-2009) was obtained from a weather station located at Mount Edgecombe on the east coast of South Africa (29°42'15' S, 31°2'45' E; 96 masl). This region can be classified as having a sub-tropical climate with a long-term mean annual precipitation of 953 mm, and mean temperature of 23.5 °C. For the trashed system, 95% of non-harvested aboveground crop material was returned to the soil as a trash blanket, while for the burnt system 95% of this crop residue (including all C and N) was simulated to be lost from the system as a result of burning. As is currently common practice in South Africa, the trashed system was fertilised with limestone ammonium nitrate (LAN) while the burnt system was fertilised with urea. The equivalent of 80 kg N/ha was applied to the plant crop for each system. Thereafter the equivalent of 140 kg N/ha was applied in a single application to each ratoon crop following harvest for the burnt system. In order to compensate for N being returned to the soil as a result of crop residue mineralisation in the trashed system, a reduced rate of 70 kg

N/ha was applied in a single application to each ratoon crop. For both systems a tillage event to a depth of 15 cm was simulated to occur at planting every nine years. The simulation was run as a continuous sequence over an 80 year period. In order to facilitate the interpretation of results, additional attention was given to the final 10 years of the simulation. In addition to DSSAT-Canegro simulation outputs considered, the ratio of N_2/N_2O released to the atmosphere during the denitrification process was calculated in a separate spreadsheet using the approach developed by Del Grosso *et al.* (2000). The release of CH_4 and N_2O from the burning of residues was also estimated separately using the amount of trash residue simulated by DSSAT-Canegro and the approach suggested by EIIP (1999). Using this approach, the CH_4 -C emissions factor is 0.005 of residue C and the N_2O emissions factor is 0.007 of residue N. Indirect emissions resulting from NH_3 volatilisation losses and N leaching losses were estimated using an emission factor of 0.01 and 0.0075, respectively (IPCC, 2006).

Simulated aboveground dry matter (ADM) production varied widely from season to season and was positively correlated with rainfall (trashed: $R^2=0.67$, burnt: $R^2=0.71$). Average ADM production was 41.5 t/ha for the trashed system and 38.6 t/ha for the burnt system. Trashing therefore led to an increase in production of 7% for this simulation study, which was a result of increased soil water availability due to lower evaporation rates for the trashed system (rather than due to variances in N availability to the crop as confirmed by the model). This is consistent with observations from the long-term burning and trashing (BT1) trial (Thompson, 1976; van Antwerpen *et al.*, 2002) for which 10% higher fresh mass cane yields are on average observed for the trashed compared to the burnt treatment

Soil organic C percentage in the top 20 cm soil layer was observed to increase from 1.10 to 1.21% for the trashed system and decrease from 1.10 to 0.67% for the burnt system after 80 years of cultivation (Figure 1a). For the trashed system, the majority of this gain in soil organic C occurred within the first 20 years following the commencement of cultivation, and around this time the system appears to have reached equilibrium with regards to soil organic C. For the burnt system a net loss of C from the 0-20 cm layer is still occurring following 80 years of cultivation and equilibrium has not yet been reached. For the 20-40 cm soil layer, soil organic C levels are very similar for both systems and are observed to decrease from 0.58 to 0.50% (Figure 1b). Considering the entire soil profile, trashing led to a 1.4 t/ha increase in C content while burning led to a 13.7 t/ha loss of C for the soil studied in this simulation exercise (Figure 1c). After 80 years of cultivation, therefore, the trashed system contained 15.1 t C/ha more than the burnt system.

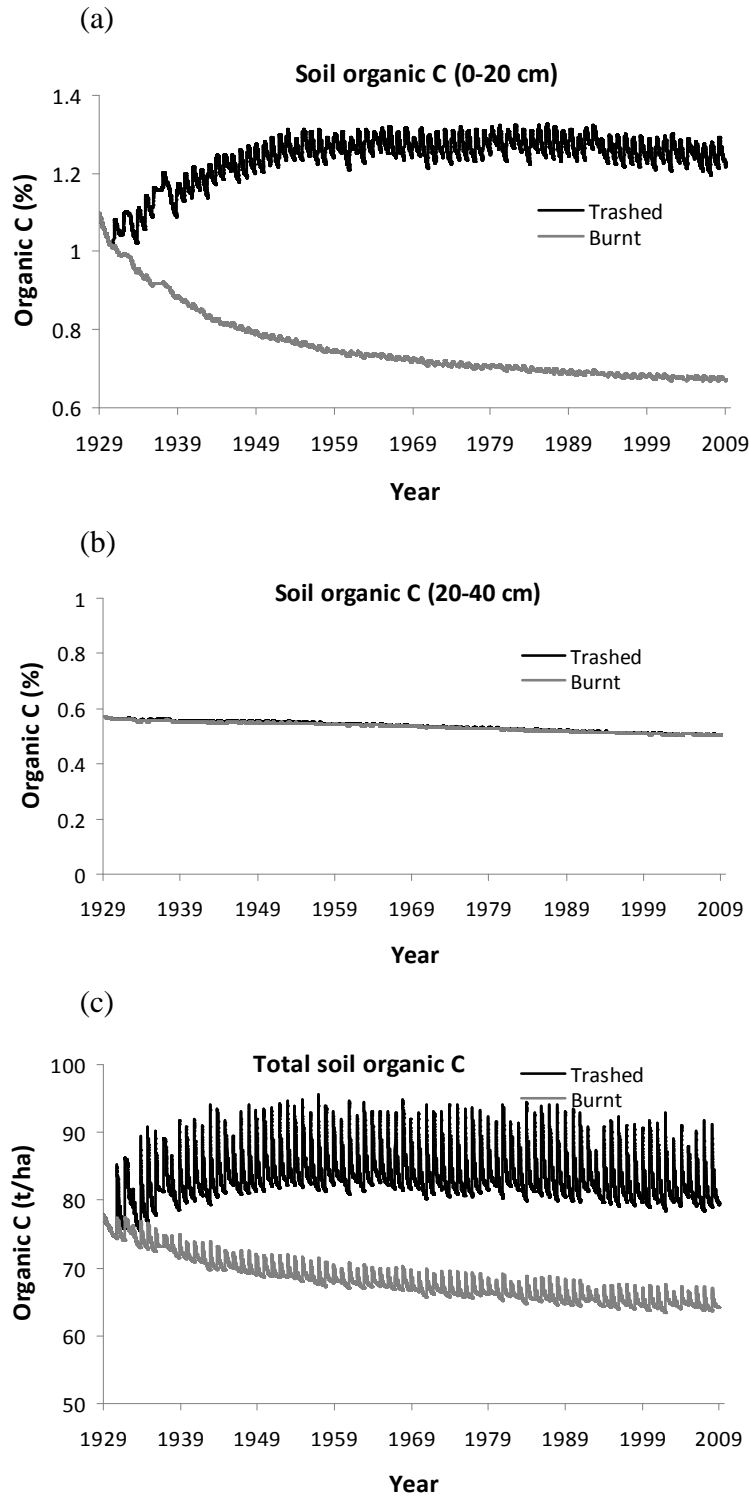


Figure 1. Soil organic carbon (C) percentage in the 0-20 cm soil layer (a) and the 20-40 cm soil layer (b) and total organic C mass in the soil profile (c) over the 80 year simulation period.

A closer analysis of GHG emissions for these two systems was done using the final 10 years of the simulation study (2000-2009, see Table 1). As expected, denitrification losses were higher for the trashed than for the burnt system. This is a result of more frequent saturation periods, a larger soluble organic C fraction in the soil and generally higher soil NO_3^- levels. Nitrous oxide losses as a result of denitrification were observed to vary widely between seasons, and ranged from 0.1-47.5 kg N/ha for the trashed system and 0-11.9 kg N/ha for the burnt system. The average ratio of N_2 to N_2O released during the denitrification process for this period was estimated at 3.2 for the burnt and 3.7 for the trashed system. Although higher gaseous N losses were observed as a result of denitrification for the trashed system, for the burnt system much higher volatilisation losses (ranging from 8.0-36.9 kg N/ha) were simulated as a result of the use of urea as fertiliser N source. Average emissions of CH_4 and N_2O from the burnt sugarcane residues were estimated at 60.1 kg $\text{CH}_4\text{-C/ha/season}$ and 1.7 kg $\text{N}_2\text{O-N/ha/season}$, respectively. Estimates of CH_4 and N_2O emissions could not be made for the residues decomposing on the soil surface in the trashed system, and further research is required to achieve this. Excluding emissions from decomposing surface residues, the average emission of GHGs was 2522 kg $\text{CO}_2\text{eq/ha/season}$ for the burnt system and 3443 kg $\text{CO}_2\text{eq/ha/season}$ for the trashed system. High variations can be observed for CO_2eq emissions between seasons.

Upscaling emission estimates

The simulation above provides seasonal estimates of CO_2eq emissions from a trashed and burnt system for a climate representative of the Maidstone milling region in South Africa. Within this region around 30 000 ha are cultivated with sugarcane and an estimated 90% of the cane is burnt prior to harvest and receives urea as fertiliser N source. The remaining 10% is therefore assumed to be trashed and receive LAN as fertiliser N source. Based on per hectare emissions estimated for the simulation study above, regional CO_2eq emissions can be estimated at 78.3 kt CO_2eq per season for this region. This represents 0.4% of the estimated CO_2eq emissions from agriculture in South Africa for the year 2000 (DEAT, 2009). Adoption of trashing practices in half the area (15 000 ha) in this region will potentially increase emissions to 181.2 kt CO_2eq per season, while only leading to the sequestration of around 190 kt CO_2eq in the soil over a period of ~20 years (although yield per unit area will also potentially increase). The importance of precision N management in reducing N_2O emissions is clearly highlighted from these results. Due to the lack of measured data to validate model outputs, this information should not be used for decision making or to inform policy.

Mitigation of GHG emissions from sugarcane cropping systems

Strategies to mitigate GHG emissions from sugarcane cropping systems will fall into three broad categories: (a) reducing emissions, (b) enhancing sequestration, and (c) avoiding/displacing emissions (Smith *et al*, 2008). Mitigation measures forming part of these strategies are discussed in more detail below.

Table 1. Estimated losses of important greenhouse gases from a burnt and trashed sugarcane cropping system in South Africa.

Date	BURNT							TRASHED				
	Soil processes			Residue burning			CO ₂ -e	Soil processes				CO ₂ -e
	Leaching	N ₂ O	NH ₃	N ₂ O	CH ₄	CO ₂ -e	kg/t sucrose	Leaching	N ₂ O	NH ₃	CO ₂ -e	kg/t sucrose
2000	12.8	11.9	36.9	2.1	66.8	5830	529	115.3	47.5	4.0	14315	1296
2001	0	0.9	30.0	1.9	61.6	2356	346	15.8	7.2	3.3	2184	293
2002	0.3	2.8	57.0	2.4	75.8	3454	281	76.6	19.2	4.5	5858	480
2003	0	0.0	8.0	1.6	50.2	1645	1267	0.0	0.9	3.6	290	97
2004	0	0.0	25.0	2.0	62.4	2090	244	0.0	0.1	4.0	40	4
2005	0	0.0	19.7	1.2	39.4	1332	657	0.0	1.3	3.2	381	203
2006	0	0.0	27.6	1.8	58.2	1962	257	0.0	0.9	5.5	295	40
2007	0	0.1	20.6	2.2	69.3	2326	283	9.7	20.4	4.6	6082	599
2008	0	0.9	30.2	2.0	63.8	2431	329	184.8	14.1	3.4	4607	610
2009	0	0.0	23.2	1.7	53.5	1796	404	0.0	1.3	3.3	382	59
Mean	1.3	1.7	27.8	1.9	60.1	2522	460	40.2	11.3	3.9	3443	368

Reducing emissions

The majority of N₂O emitted into the atmosphere is derived from the soil. As trashed systems have higher levels of C and the potential for longer periods of soil water saturation due to reduced soil surface evaporation, higher denitrification rates can occur for these systems relative to burnt systems. Regardless of whether the system is trashed or burnt, however, it is important to ensure that N fertiliser is accurately applied according to crop demand. Additional N inputs into the system such as via mineralisation and rainfall should be accounted for and more precise N management is recommended by splitting application to limit N₂O losses further.

Using organic fertilisers such as manure in combination with inorganic fertilisers can also play an important role as organic fertilisers can sequester C in the soil, most often do not lead to highly elevated NO₃⁻ and NH₄⁺ levels as is the case for inorganic fertilisers, and there is evidence that manures play a role in promoting the oxidation of CH₄ on soils fertilised with inorganic N (Powlson, 1994).

Enhancing sequestration

Trashing at harvest clearly leads to enhanced sequestration of atmospheric CO₂ and is therefore recommended wherever practical. The amount of C a soil can sequester will be highly correlated with the initial organic C and texture of the soil. Following a change in management (eg. burning to trashing), soil C levels can initially change rapidly, after which this rate of change becomes more stable (Dominy *et al.*, 2002). The adoption of minimum tillage management practices and opting to apply animal manures can also play a major role in the sequestration of C in the soil. Finally, good agronomic practices that achieve high crop yields, such as optimal nutrient and irrigation application, will potentially lead to higher C additions from the crop to the soil.

Planting a green manure during the fallow period will aid the sequestration of C in the soil by preventing soil erosion, thus conserving valuable organic matter in the surface layers (Ayanaba and Okigbo, 1974). In addition to this, and despite any conclusive evidence for the South African sugar industry, green manures will potentially enhance C additions and subsequent sequestration in the soil. It is therefore suggested that further research be conducted on this topic.

Avoiding/displacing emissions

Avoiding and/or displacing emissions can, for example, involve the use of crop residues in electricity or fuel generation, and while this will still lead to the release of CO₂ and other gases during combustion, this C will have been recently captured during photosynthesis as opposed to being of fossil fuel origin (Smith *et al.*, 2008). The recent increase in electricity tariffs to at least R1.18/kWh offered by Eskom for the supplying of electricity has stimulated new interest amongst sugarcane mills in South Africa to investigate sugarcane trash (brown leaves) as a source of energy (NERSA, 2011). In the more medium-term future, the production of fuels, such as bioethanol, could potentially reduce the C footprint of sugarcane cultivation in South Africa even further. Emissions can also potentially be reduced by maximising yields through increasing production per unit land area, per unit fertiliser and per

unit water consumed (Foley *et al.*, 2005). This will reduce the amount of virgin land that needs to be converted to agriculture.

Conclusions

Greenhouse gases from agriculture, representing a form of non-point source air pollution, are extremely difficult to quantify or even estimate. Further research is required to improve our ability to measure emissions from sugarcane-producing soils in South Africa and understand complex interactions. Promising new techniques for the actual measurement of denitrification by means of automated systems (Denmead *et al.*, 2010) and/or manually operated chambers (Wang *et al.*, 2008) have recently been reported in the literature. Primary knowledge gaps, as highlighted in this review, include (a) long-term dynamics of C sequestration in soils under trashed and burnt conditions, (b) CH₄ emissions/sequestration from cultivated soils, (c) N₂O emissions from soil and from residue burning/decomposition, and (d) the role of the precursors/indirect emissions of gases such as CO, NO_x, NH₃ and sulphur dioxide.

Trashing has been shown to lead to higher C sequestration compared to burning, and this sequestration could be enhanced through complementary management practices such as reduced tillage and the possible use of organic fertilisers. Based on findings from this study, however, optimal N management is paramount in reducing GHG emissions (especially in high C containing systems) due to the potency of N₂O as a GHG.

REFERENCES

- Ayanaba A and Okigbo BN (1974). Mulching for improved soil fertility and crop production. In: Swedish International Development Authority: FAO of the United Nations. International Institute of Tropical Agriculture, Ibandan, Nigeria, pp 97-119.
- Balasubramanian V and Kanehiro Y (1976). Denitrification potential and pattern of gaseous N loss in tropical Hawaiian soils. *Trop Agric* 53: 293-303.
- Bouwman AF (1998). Nitrogen oxides and tropical agriculture. *Nature* 392: 866-867.
- Chapman LS, Haysom MBC and Saffigna PG (1994). The recovery of ¹⁵N from labelled urea fertilizer in crop components of sugarcane and in soil profiles. *Aust J Agric Res* 45: 1577-1585.
- Crutzen P and Andreae M (1990). Biomass burning in the tropics: Impact on atmospheric chemistry and biogeochemical cycles. *Science* 250: 1669-1678.
- Dalal RC, Wang W, Robertson GP and Parton WJ (2003). Nitrous oxide emissions from Australian agricultural lands and mitigation options: A review. *Aust J Agric Res* 41: 165-195.
- DEAT (Department Environment Affairs and Tourism) (2009). Greenhouse gas inventory South Africa 1999 to 2000. Compilation under the UNFCCC. National Inventory Report. Republic of South Africa.

- Del Grosso SJ, Parton WJ, Mosier AR, Ojima DS, Kulmala AE and Phongpan S (2000). General model for N₂O and N₂ gas emission from soils due to nitrification. *Global Biogeochem Cycles* 14: 1045-1060.
- Denmead O, Macdonald B, Bryant G, Naylor T, Wilson S, Griffith D, Wang W, Salter B, White I and Moody, P (2010). Emissions of methane and nitrous oxide from Australian sugarcane soils. *Agric Forest Meteor* 150: 748-756.
- Dominy CS, Haynes RJ and van Antwerpen R (2002). Loss of soil organic matter and related soil properties under long-term sugarcane production on two contrasting soils. *Biol Fertil Soils* 36: 350-356.
- Donaldson RA, Redshaw KA, Rhodes R and van Antwerpen, R (2008). Season effects on productivity of commercial South African sugarcane cultivars: II. Trash production. *Proc S Afr Sug Technol Ass* 81: 528-538.
- EIIP (1999). *EIIP Volume VIII: Estimating Greenhouse Gas Emissions*. Emission Inventory Improvement Program (US Environmental Protection Agency), Technical Report Series, October 1999.
- Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FSt, Coe MT, Daily GC, Gibbs HK, Helkowski JH, Holloway T, Howard EA, Kucharik CJ, Monfreda C, Patz JA, Prentice IC, Ramankutty N and Snyder PK (2005). Global Consequences of Land Use. *Science* 309: 570-574.
- Galdos MV, Cerri CC and Cerri CEP (2009). Soil carbon stocks under burned and unburned sugarcane in Brazil. *Geoderma* 153: 347-352.
- Galbally IE, Fraser PJ, Meyer CP and Griffith DWT (1992). Biosphere-atmosphere exchange of trace gases over Australia. In: Gifford RM, Barson MM (Eds.), *Australia's Renewable Resources: Sustainability and Global Change*. PJ Grills, Commonwealth Government Printer, Canberra, pp. 117-149 IGBP Workshop No. 14.
- Haynes RJ and Graham M (2004). Composition of the soil microbial community under sugarcane production as indicated by phospholipid fatty acid analysis. *Proc S Afr Sug Technol Ass* 78: 331-342.
- IPCC (Intergovernmental Panel on Climate Change) (2006). *Guidelines for National Greenhouse Gas Inventories: Prepared by the National Greenhouse Gas Inventories Programme*, Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K (Eds.). Institute for Global Environmental Strategies, Hayama, Japan.
- Jones JW, Hoogenboom G, Porter CH, Boote KJ, Batchelor WD, Hunt LA, Wilkens PW, Singh U, Gijssman AJ, Ritchie JT (2003). The DSSAT cropping system model. *Eur J Agron* 18: 235-265.
- Li Y and Mathews BW (2010). Effect of conversion of sugarcane plantation to forest and pasture on soil carbon in Hawaii. *Plant Soil* 335: 245-253.
- Lobert JM, Scharffe DH, Hao WM, Crutzen PJ (1990). Importance of biomass burning in the atmospheric budgets of nitrogen-containing gases. *Nature* 346: 552-554.
- Miles N, Meyer JH and van Antwerpen, R (2008). Soil organic matter data: What do they mean? *Proc S Afr Sug Technol Ass* 81: 324-332.
- NERSA (2011). *Review of Renewable Energy Feed - In Tariffs*. March 2011, 32 pp.
- Nixon DJ, Moodley SL, Schumann AW and Shroeder BL (2005). A laboratory method to simulate field losses of applied nitrogen fertiliser by volatilisation. *Proc S Afr Sug Technol Ass* 79: 220-222.
- Oades JM (1988). The retention of organic matter in soils. *Biogeochem* 5: 35-70.

- Park S, Antony G, Lisson SN and Thorburn PJ (2003). A method for exploring the potential of agronomic practices to manage the greenhouse gas balance in sugarcane primary production. *Proc Aust Soc Sug Cane Technol* 25: 21.
- Powlson DS (1994). Quantification of nutrient cycles using long-term experiments. pp 97-115 In: RA Leigh and AE Johnston (Eds) *Long-term Experiments in Agricultural and Ecological Sciences* CAB International, UK.
- Rein PW (2010). The carbon footprint of sugar. *Proc Int Soc Sug Cane Technol* 135: 427-434.
- Ritchie JT (1998). Soil water balance and plant stress. pp 41-54 In: Tsuji GY, Hoogenboom G, Thornton PK (Eds) *Understanding options for agricultural production. System approaches for sustainable agricultural development*. Kluwer Academic Publishers, Dordrecht, The Netherlands.
- Rostron H (1974). Radiant energy interception, root growth, dry matter production and the apparent yield potential of two sugarcane varieties. *Proc Int Soc Sug Cane Technol* 15: 1001-1010.
- SACGA (2009). Confidential Document: Statistical Data: 1999/2000-2008/2009. South African Cane Growers' Association, Mount Edgecombe, South Africa.
- SA DNT (2010). Discussion Paper for Public Comment: Reducing Greenhouse Gas Emissions: The Carbon Tax Option.
<http://www.treasury.gov.za/public%20comments/Discussion%20Paper%20Carbon%20Taxes%2081210.pdf>
- Schroeder BL, Panitz JH, Wood AW, Moody PW and Salter B (2007). Soil specific nutrient management guidelines for sugarcane production in the Bundaberg district. Bureau of Sugar Experiment Stations Technical Publication TE07004, BSES Limited, Indooroopilly, Australia.
- Schroeder BL, Panitz JH, Wood AW, McGuire P, Beattie R and Aitken RL (2011). Accelerating the adoption of the best-practice nutrient management: Condong, Broadwater and Harwood districts. Short-course manual. Bureau of Sugar Experiment Stations Limited, Indooroopilly, Australia.
- Singels A, Jones M, van den Berg M (2008) DSSAT v4.5 Canegro Sugarcane Plant Module Scientific Documentation. International Consortium for Sugarcane Modelling.
<http://sasri.sasa.org.za/misc/icsm.html>.
- Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, McCarl B, Ogle S, O'Mara F, Rice C, Scholes B, Sirotenko O, Howden M, MaAllister T, Pan G, Romanenkov V, Schneider U, Towprayoon S, Wattenbach M and Smith J (2008). Greenhouse gas mitigation in agriculture. *Phil Trans R Soc B* 363: 789-813.
- Thompson GD (1976). Water use by sugarcane. *SA Sug J* 60: 627-635.
- Thompson GD (1991). The growth of sugarcane variety N14 at Pongola. Mount Edgecombe Research Report No.7, South African Sugar Association Experiment Station, Mount Edgecombe, South Africa.
- Tsuji GY, Hoogenboom G and Thornton PK (Eds) (1998). Understanding options for agricultural production. System approaches for sustainable agricultural development. Kluwer Academic Publishers, Dordrecht, Netherlands.
- Vallis I, Catchpoole VR, Hughes RM, Myers RJK, Ridge DR, Weier KL (1996). Recovery in plants and soils of ¹⁵N applied as subsurface bands of urea to sugarcane. *Aust J Agric Res* 47: 355-370.
- van Antwerpen, R, Thorburn PJ, Horan, H, Meyer JH and Bezuidenhout CN (2002). The impact of trashing on soil carbon and nitrogen: II: Implications for sugarcane production in South Africa. *Proc S Afr Sug Technol Ass* 76: 269-280.
- van der Laan M, Miles N, Annandale JG, du Preez CC (2011). Identification of opportunities for improved nitrogen management in sugarcane cropping systems using the newly developed Canegro-N model. *Nutr Cycl Agroecosyst* DOI: 10.1007/s10705-011-9440-6.

- Wang WJ, Moody PW, Reeves SH, Salter B and Dalal RC (2008). Nitrous oxide emissions from sugarcane soils: Effects of urea forms and application rate. *Proc Aust Soc Sugar Cane Technol* 30: 87-94.
- Weier KL (1996). Trace gas emissions from a trash blanketed sugar-cane held in tropical Australia. pp 271-272 In: Wilson, JR, Hogarth, DM, Campbell, JA and Garside AL (Eds) *Sugarcane; Research towards efficient and sustainable production*. CSIRO Division of Tropical Crops and Pastures, Brisbane.
- Weier KL (1998). Sugarcane fields: Sources or sinks for greenhouse gases? *Aust J Agric Res* 49: 1- 9.
- Weier KL (1999). N₂O and CH₄ emission and CH₄ consumption in a sugarcane soil after variation in nitrogen and water application. *Soil Biol Biochem* 31: 1931-1941.
- Weier KL, McEwan CW, Vallis I, Catchpoole VR and Myers RJK (1996). Potential for biological denitrification for fertiliser nitrogen in sugarcane soils. *Aust J Agric Res* 47: 67-79.