Nitrogen management following crop residue retention in sugarcane production

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Abstract
Sugarcane crop residues (known as trash) contain substantial amounts of nitrogen (N) and other nutrients. The availability of N in trash is complicated because most of the N cycles through the soil organic matter. To gain insights into the impacts of trash management on sugarcane production and the long-term fate of N contained in trash, a simulation study was conducted with the APSIM-Sugarcane cropping systems model. Simulations were conducted over 100 years for three different soil types combined with climatic data from five locations from Bundaberg to Tully. Trash management and N fertiliser application rates were varied in the simulations. The simulation study showed that sugarcane yields have potential to respond positively to trash retention in the range of environments considered. However, achieving these higher potential yields will require that N application not be reduced following the switch from burning to conserving residues. The results of the simulations also indicate that average environmental losses of N are likely to be greater from trash conserving systems at all rates from N fertiliser applications and so particular care should be exercised to avoid over-application of N fertiliser. Simulation results also illustrate a potential negative, short-term impact of trash blanketing on sugarcane yields due to the immobilisation of N by the decomposing trash. Implications of this disequilibrium period on the results of short-term trash management trials and the transition from trash burning to conserving systems are discussed. The simulations undertaken in this study obviously have limitations, and these are discussed.

Key Words
Denitrification, fertiliser response, green cane harvesting, leaching, mineralisation, soil organic matter

Introduction
Sugarcane crop residues, known as trash, contain considerable quantities of dry matter and nutrients, particularly nitrogen (Wood 1991; Ball-Coelho *et al*. 1993; Mitchell *et al*. 2000). When sugarcane is burnt either pre- and/or post-harvest, 70–95 % of the dry matter and nitrogen (N) are lost from the system, with lower losses of other nutrients (Mitchell *et al*. 2000). Thus green cane harvesting and retaining a trash ‘blanket’ on the soil surface (a system known as GCTB) has a considerable effect on organic matter conservation, nutrient cycling and N fertility of the soil. Trash blanketing is now the normal method of trash management in most parts of the Australian sugar industry. However, fertiliser recommendations in the industry have historically been based on burnt cane systems, as this was the dominant method of trash management when the recommendations were developed. Thus there is a need to develop new recommendations for GCTB systems. This is especially important for N because; (1) it is required in large amounts to maximise sugarcane yields, and hence the profitability of sugarcane production, and (2) its availability is complicated because of its cycling through soil organic matter and the environmental implications of off-site losses.

Many field experiments have been conducted comparing GCTB and burnt systems. In these experiments, increases in soil organic matter and total N in trash blanketed treatments are small, confined to the surface soil, and poorly related to the age of the experiments (Thorburn *et al*. 2000; Van Antwerpen *et al*. 2001). However, microbial activity is clearly stimulated by trash blanketing (Sutton *et al*. 1996; Graham *et al*. 1999), even after only short periods of trash retention (Robertson and Thorburn 2001). Ng Kee Kwong *et al*. (1987) and Basanta *et al*. (2003) showed that crop uptake of N from a trash blanket in the season following deposition of the trash was negligible and the N was mainly immobilised in the soil organic matter. Despite the insights gained in these studies, it is still uncertain how N management recommendations for GCTB systems should differ from those for burnt systems because the trash management experiments conducted to date have been undertaken at a single rate of applied N fertiliser since long-term experimental N response data for GCTB systems do not exist in most regions. However, the fact that N is recycled in GCTB systems rather than lost through trash burning suggests that N fertiliser rates could be lowered in GCTB systems (Calcino *et al*. 2000).

The complexity of the N cycle and the long time scales involved in soil organic matter cycling make simulation-based approaches to this N management problem attractive. Over the last 10 years there has been considerable progress made in our ability to simulate sugarcane production systems (Keating *et al*. 1999), including their response to variations in N and trash management (Thorburn *et al*. 2005). In this paper, we take advantage of these advances and use a simulation approach to gain insights into the long-term fate of N contained in trash and identify the N fertiliser management implications of trash retention.

Materials and Methods

Simulations

The general approach of this study was to conduct simulations of sugarcane yield and environmental losses of N at different rates of applied N fertiliser to each of two trash management systems (trash burnt and trash retained at harvest). Simulations were conducted for a combination of three different soil types and five different climates, giving 15 soil type–climate combinations. The soil types were (according to the Australian Soil Classification) a Red Kandosol, a Brown Chromosol and a Brown Dermosol (Table 1). The soils were chosen to represent a range of soils found in the Australian sugar industry (although not the entire range) and, importantly, data were available for the derivation of model parameters (described below). Climate data were obtained from the Australian Bureau of Meteorology Silo database for Abergowrie (upper Herbert), Burdekin, Bundaberg, Mackay and Tully. These locations were chosen to provide a range in climates, and all, except Bundaberg, were the sites of previous investigations of trash blanketing (Thorburn *et al*. 2000). For the Burdekin and Bundaberg climates, irrigation was applied in the simulations. Irrigation was applied when the soil dried to a pre-determined extent. Total irrigation applications within a crop were capped at 800 mm for the Burdekin climate and 400 mm for the Bundaberg climate. Simulations for the other three climates had no irrigation. N was applied as urea at 75 mm soil depth, 8 weeks after planting/harvest in all simulations. Potential sugarcane yields were predicted – there was no allowance made in the simulations for factors such as pests and diseases, lodging, water logging, stool damage during harvest, etc., which will limit yields in the field.

Table 1. Properties (0-0.2 m) of the three soils used in the simulations.

	Red Kandosol	Brown Chromosol	Brown Dermosol
Soil texture	loam/sandy loam	loam/clay loam	silty clay
Organic C (%)	0.8	1.0	1.2
C : N ratio	12.3	18.0	10.3
Bulk density (kg/m^3)	1.50	1.51	1.32
Drained Upper Limit* (%)	28.4	30.0	36.5
Lower Limit* (%)	12.8	17.0	22.5

*Soil water parameters used in the SoilWat model (Probert *et al*. 1998), analogous to field capacity and wilting point.

The simulations were conducted over 100 years. For the 1st 25 years, the trash and N fertiliser management system was the same in all simulations – trash burnt with 160 kg/ha of N fertiliser applied to ratoon crops and 75 % of that applied to plant crops. This allowed the simulated plant-soil system to come to some equilibrium and not be overly affected by the impacts of the initial values chosen for the model parameters. At the end of 25 years, different trash and N fertiliser management systems were introduced to the simulations. Management systems were (1) removal of 95 % of trash at harvest, equivalent to trash burnt both pre- and post-harvest (Mitchell *et al* 2000), and (2) varying N fertiliser application rates from 0 to 300 kg/ha (in 30 kg/ha increments) on ratoon crops, with plant crops receiving 75 % of that applied to the ratoon crops (as is recommended N management). Two cropping cycles were simulated. The first consisted of a 15 months long crop planted in autumn (known as a plant crop) followed by four 13 month ratoon crops and a short fallow. The second consisted of an early spring plant crop (12 months long). Simulations were started in two years, 1901 and 1904. Results from the four cropping by starting year combinations were averaged to remove bias possibly caused by temporal patterns in climate or cropping cycle specifics (e.g., planting time, fallow length, etc.).

Model configuration and parameterisation
Simulations were undertaken with the APSIM cropping systems simulator. The model was configured to consist of modules for soil N and C (APSIM-SoilN; Probert *et al*. 1998), soil water (APSIM-SoilWat; Probert *et al*. 1998) and sugarcane residue (APSIM-Residue; Thorburn *et al*. 2001a) dynamics, and sugarcane growth (APSIM-Sugarcane; Keating *et al*. 1999). The modules are one-dimensional, use a daily time-step and are driven by climatic data. The dynamics of water, N, C and roots are simulated in soil layers (to 1.5 m in the case of this study), with water (and associated nitrate) moving between layers where gradients exist. N mineralisation, N immobilisation and nitrification are explicitly described in each layer, as are the N losses from denitrification and leaching. Soil moisture and temperature affect all soil N cycling processes. The soil water module is a "cascading bucket" water balance model. The presence of plant residues on the soil surface affects runoff (and hence infiltration) and evaporation. The sugarcane module uses intercepted radiation to produce assimilates, which are partitioned into leaf, cabbage (defined as the immature top of the stalk plus green leaf sheaths), structural stalk, roots and sugar. These processes are responsive to radiation and temperature, as well as water and N supply. Farming operations (such as fertilisation, planting, incorporation of crop residues through cultivation, or burning of crop residues) were specified through the APSIM-Manager module.

Model parameters were generally based on measured soil data. These data came from studies of the impact of trash blanketing on soil N for the Brown Chromosol and Brown Dermosol (Thorburn *et al*. 2000) and an N rate study for the Red Kandosol (Thorburn *et al*. 2003). Values of bulk density, soil C:N ratio and the initial soil organic C (Table 1) were set equal to values measured in the soils. Parameters for the soil water model, drained upper limit and lower limit (Table 1), were derived from measurements of water retention at –33 kPa and –1.5 MPa and, where available, measurements of water content in the field. The layer 'structure' of the soil models was the same for all three soils: the soil was divided into seven soil layers, with a total depth of 1.5 m.

Results
In all simulations, the potential sugarcane yields varied markedly between each crop (an example is shown in Figure 1) in response to climatic differences over the different growing seasons, as expected. This variability did not overshadow the consistent impacts simulated for different trash and N fertiliser managements systems. Thus for simplicity, simulated average N responses are presented (for example, sugarcane yield shown in Figure 2).

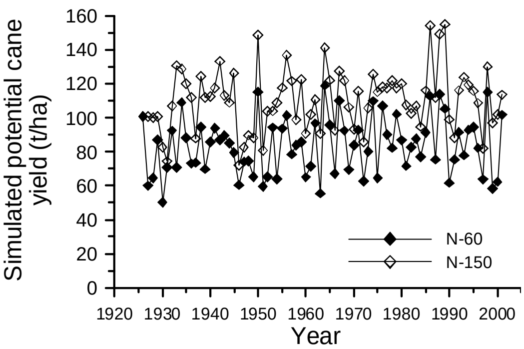

Figure 1. Example of simulated cane yield each year for two different N fertiliser application rates in a trash blanketed system at Mackay on a Brown Chromosol soil.

As expected, sugarcane yields are simulated to increase with increasing amounts of applied N until a yield plateau is reached, and no further response to N occurs. Maximum sugarcane yields are simulated to be highest for the Burdekin climate and lowest for the Abergowrie climate, as anticipated from the radiation and rainfall (and irrigation in the Burdekin) at these locations. Generally, sugarcane yields simulated in the GCTB systems are greater than those in the burnt systems at all rates of applied N (Figure 2). The yield increase is more affected by climates than soil types, being greatest at Bundaberg and least at Tully. For the Tully climate and the Brown Dermosol soil, yields in both trash management systems are similar at N application rates of 120-150 kg/ha. The magnitude of the simulated yield increases in the GCTB system generally agree with **long-term** field experimental results on soils with unrestricted drainage (Wood 1991, Chapman *et al*. 2001). The increases in yield in the GCTB systems are due to lower water stress in the simulations compared with the burnt system (data not shown).

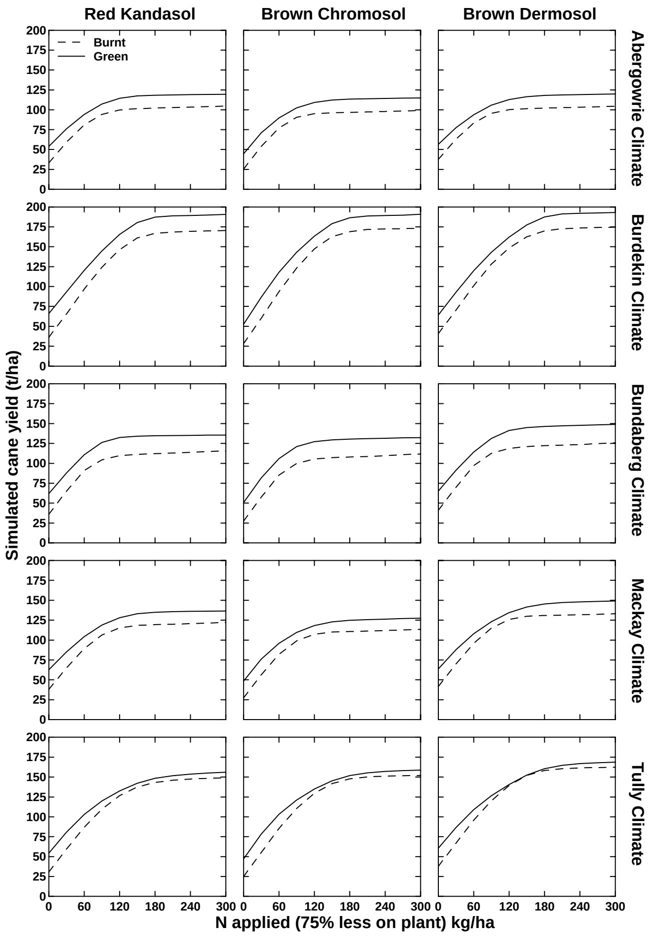

Figure 2. Simulated long-term average sugarcane yield response to applied N fertiliser for GCTB and trash burnt systems.

The N rates at which sugarcane yields are simulated to plateau in the burnt systems are approximately 160 kg/ha in most cases except for the Burdekin climate where it is approximately 200 kg/ha (Figure 2). These N rates are in accord with previous experience in the Australian sugar industry (Chapman 1994, Calcino *et al*. 2000). Interestingly, yields are simulated to plateau at similar fertiliser N rates in the GCTB systems, despite the N recycled in the trash blanket.

As has been simulated previously (Keating *et al*.1997, Thorburn *et al*. 2001b), losses of N to the environment by both leaching (Figure 3) and denitrification (Figure 4) were simulated to increase with increasing rates of applied N fertiliser at all sites and soil types, particularly at N rates where yields plateaued. Leaching losses were affected by both soil types, being highest in the Red Kandosol, and climate, being lowest for the Burdekin (Figure 3). The impact of soil type is more due to soil water characteristics than organic matter. For example, the Red Kandosol soil has the highest simulated leaching losses for each climate, but has lowest organic matter (Table 1) and highest sub-soil permeability (the value of the relevant model coefficient being 25 % higher; data not shown) of the three soils. Denitrification losses (Figure 4) varied less across the soil-climate combinations simulated than did leaching. Unlike leaching losses, denitrification losses were simulated to be least for the Red Kandosol for each climate. The impact of climate in the simulations is largely due to differences in sugarcane yields – climates resulting in higher yields have lower N losses. However, it is also affected by rainfall with the Tully climate simulated to have higher losses relative to its yield.

In all soils and for all climates, N losses (Figures 3 and 4) are simulated to be higher under the GCTB system than the burnt system. This indicates that not all of the additional N recycled in the GCTB systems is taken up by the crop. Soil organic matter concentrations are higher in GCTB soils, both experimentally (Wood 1991, Thorburn *et al*. 2000) and in the simulations (data not shown). This increased soil organic matter results in higher soil N mineralisation rates and a greater probability that nitrate is in soil solution during times when conditions are favourable for N losses.

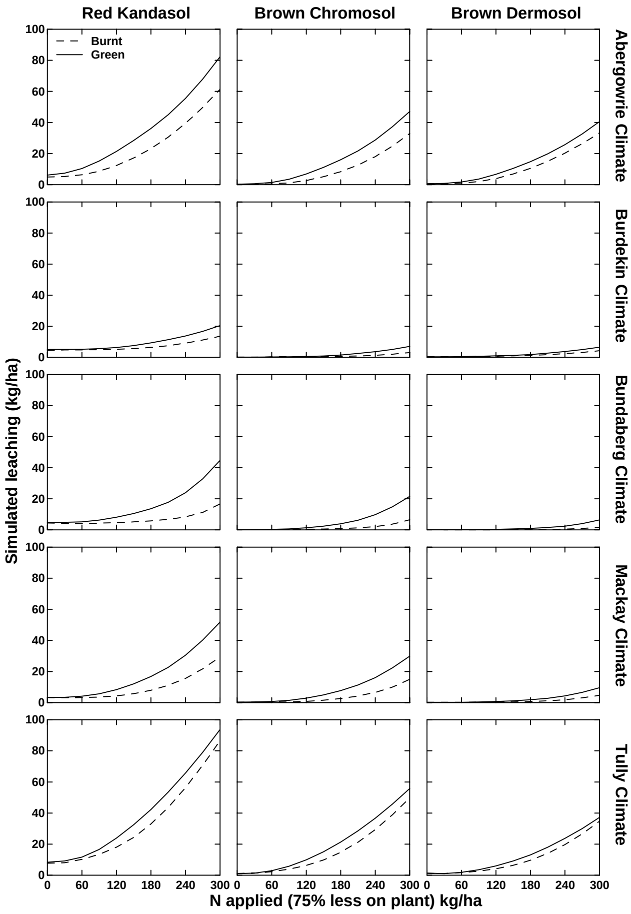

Figure 3. Simulated long-term average nitrate leaching response to applied N fertiliser for GCTB and trash burnt systems.

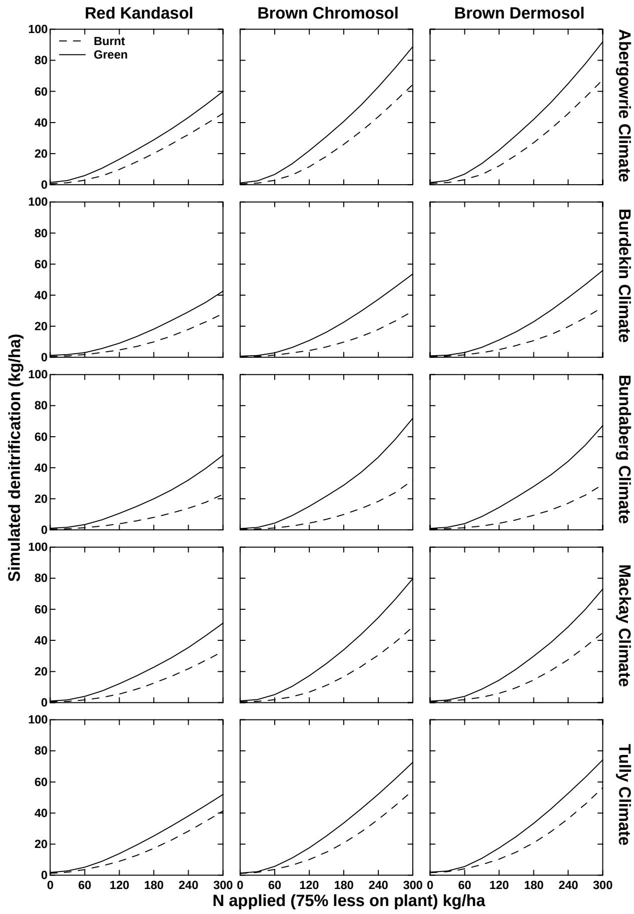

Figure 4. Simulated long-term average denitrification response to applied N fertiliser for GCTB and trash burnt systems.

Since decomposing trash blankets have the potential to immobilise considerable amounts of N (Ng Kee Kwong *et al*. 1987, Basanta *et al*. 2003), N stress may develop and limit sugarcane yields following the switch from burning to retaining trash. To investigate this through the simulations, yields with N applied at optimum rates in the burnt system were compared to those in the GCTB system at various N rates. Examples of this analysis are shown in Figure 5 for the Bundaberg climate with Red Kandosol soil and Mackay climate with Brown Chromosol soil. In these examples, the cumulative difference (increase or decrease) between simulated yields in the GCTB (at various rates of N) and burnt (at optimum N) systems are shown through time. The **cumulative** differences are shown as they remove the impacts of large year-to-year variability (e.g., Figure 1) on depiction of the results. In both examples the optimum N application rates in the burnt system was approximately 150 kg/ha on ratoon crops (Figure 2). At the rates of N applied to GCTB shown in Figure 5, simulated yields tend to be lower (i.e., the cumulative difference is increasingly negative) immediately following the switch from trash burning to trash retention. The duration of this period of yield depression varies depending on the rate of N – e.g. it is 15 to 20 years with 120 kg/ha of N, to 2 to 4 years at 180 kg/ha of N. It is not until after this time that the yield benefits simulated for the GCTB systems occur, and it may take some time (5-15 years for the examples in Figure 5) for the cumulative yield benefit of the GCTB system to be positive.

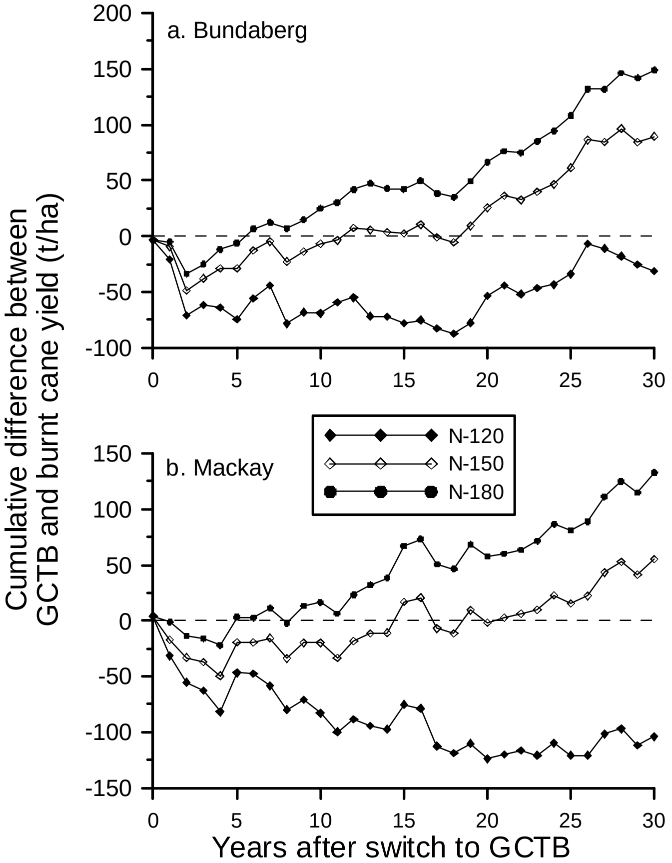

Figure 5. Simulated change in cumulative difference in sugarcane yield between GCTB (at three different rates of N fertiliser) and trash burnt (at 150 kg/ha application of N fertiliser) systems with increasing time after changing from the burnt to the GCTB system for (a) Bundaberg climate and Red Kandosol soil and (b) Mackay climate and Brown Chromosol soil.

Discussion

This simulation study has shown that sugarcane production has the potential to respond positively to trash retention in a wide range of environments, from Bundaberg to Tully (Figure 2), provided soils have good internal drainage. This is widely recognised from both experiments (Wood 1991, Chapman 2001) and anecdotal accounts. However, this study also shows that achieving these production benefits (i.e. higher potential yields) makes use of the trash N that is recycled in the soil-crop system. From a production perspective therefore, N application rates should not be reduced following the switch from a burnt to GCTB system, provided there is an expectation that cane yields will be higher. Linking N management with yield expectations has not been recognised in previous recommendations of N management following the change to a GCTB system (Calcino *et al*. 2000, Basanta *et al*. 2003). Previous recommendations have implicitly assumed similar target yields in both burnt and GCTB systems and so, logically, suggested N applications be reduced. Where it is expected that yields will not increase under GCTB, e.g. in areas with poor drainage or crops harvested early in cool areas, the recommendation to reduce N application rates may be sound. However, the issue requires further study because the partitioning of the re-cycled N between crop uptake and environmental losses is uncertain.

This study has also illustrated the potential negative, short-term impact of trash blanketing on sugarcane yields (Figure 5) due to the immobilisation of N by the decomposing trash. While the immobilisation of trash N has been demonstrated experimentally before (Ng Kee Kwong *et al*. 1987, Basanta *et al*. 2003) its potential impact on yield has not. As both soil organic matter concentrations and soil N mineralisation rates increase following the change to trash blanketing, there is a sufficient N supply in the soil-crop system to allow the trash blanket to decompose without creating N deficits – the system comes into a new equilibrium. The results of these simulations suggest that it takes at least 5 years for this equilibrium to be reached, possibly longer if there is less available N. These results have interesting implications. Short-term trash management trials have the potential to produce different results depending on the trash management history of the site and the rate of N applied during the trial. If trash was previously burnt, short-term yield results may reflect this period of disequilibrium rather than the true yield potential of GCTB at the site. Higher than recommended (160 kg/ha; Calcino *et al.* 2000) applications of N to trash trials (such as ~ 200 kg/ha; Chapman *et al.* 2001) would also impact on the results, minimising the disequilibrium effects in the GCTB treatment and allowing positive yield responses to occur soon after trash was retained. Details of pre-experiment management are seldom given and might explain some of the disparity in results obtained from many trash trials. It is also interesting to note that the widespread adoption of GCTB in the Australian sugar industry through the 1980's and early 1990's occurred at a time where **average** N fertiliser use in the industry (~ 2 kg N/t cane) was greater than that required for maximum sugarcane production (< 1.5 kg N/t cane). Thus, it is likely that the phase of disequilibrium following the widespread adoption of trash blanketing was minimised by the plentiful N supply. With the recent trend of lower N applications relative to sugarcane yields, there may be more short-term negative experiences for those growers who are adopting trash blanketing now.

The results of the simulations also indicate that average environmental losses of N are likely to be greater from GCTB systems at all rates on N fertiliser applications (Figures 3 and 4). The denitrification results (Figure 4) are consistent with those of the short-term study of Weier *et al*. (1998). However, there are no other experimental comparisons of N losses under different trash management systems, especially at different N application rates. Despite the lack of experimental experience to support the simulation results in this area, this study suggests that it is important to avoid N fertiliser applications greater than recommended rates in GCTB systems.

As noted in the Introduction, the simulation-based approach taken in this study was necessary because of the dearth of experimental information, both in Australia and overseas, about the interactions between trash management and N fertiliser management in sugarcane production systems. More experimental information would be highly valuable to establish the accuracy of some aspects of the simulation results, and provide insights into the processes controlling the interactions between trash and N fertiliser management. There are many limitations to a simulation-based approach, and some of these were described in the Methods section. Others include the climates and soil types not considered in this study. One notable absence in the soil types is soil high in organic C, as the soils represented in this study came from a relatively narrow range (0.8-1.2 %, Table 1). However, a similar, but more limited, analysis undertaken with a soil high in organic C (4.2 %) by Thorburn *et al*. (2002) produced very similar patterns in results suggesting the results of this study may have some generality. Another possible limitation is that the change from potential yields in the simulations to actual yield obtained in the field may change the implications for N management in a GCTB system. An example of this may be lodging, water logging and other factors restricting yields, so that there is little difference in those in burnt and GCTB systems. However, considering target yields, e.g. whether a yield increase is expected in a GCTB system, will be a valuable step in deciding on modifications needed to N fertiliser management regimes.

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