Field Crops Research 119 (2010) 331–341

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

A legume rotation crop lessens the need for nitrogen fertiliser throughout the sugarcane cropping cycle

Sarah E. Park[a,*], Tony J. Webster[b], Heidi L. Horan[c], Andrew T. James[d], Peter J. Thorburn[c]

[a] CSIRO Ecosystem Sciences, GPO Box 284, Belleden Street, Canberra ACT 2601, Australia
[b] CSIRO Ecosystem Sciences, GPO Box 12139, Earlville BC Qld 4870, Australia
[c] CSIRO Ecosystem Sciences, 306 Carmody Road, St Lucia Qld 4067, Australia
[d] CSIRO Plant Industry, 306 Carmody Road, St Lucia Qld 4067, Australia

ARTICLE INFO

Article history:
Received 27 March 2010
Received in revised form 28 July 2010
Accepted 2 August 2010

Keywords:
Mineralisation
Soil organic matter
Decomposition
N balance
Soybean
Leichhardt

ABSTRACT

While the amount of nitrogen (N) contributed to agricultural soils by above ground legume biomass can be over 300 kg N/ha when grain is not harvested, its availability to subsequent sugarcane crops is uncertain. In Australia it is generally accepted that inorganic N fertiliser applied to the sugarcane *(Saccharum officinarum* L.) crop in the first year (termed the plant crop) following a 'good' legume fallow crop that is not harvested can be substantially reduced, or even eliminated. However, current recommendations do not consider the carry over of legume N to crops beyond the plant crop (termed ratoons), for which standard N fertiliser rates are considered necessary. Based on a simple field experiment extending the duration of a soybean (*Glycine max* L.) fallow and two sugarcane crops (plant and first ratoon), cropping system simulation was used to provide a first estimate of how long and how much soybean N remains available for uptake by sugarcane following a soybean break crop. The soybean and sugarcane rotation plot was carried out at Mossman, Queensland over 3 years during which crop yield, plant N, and total soil C and mineral N were measured. The soybean variety Leichhardt produced 9 t/ha (±0.7) above ground dry weight, containing 301 kg N/ha (±36) which contributed to the soil N stores. After independently developing parameter values for Leichhardt, model simulations were run. The model explained 91% of the variation observed in soil mineral N to a depth of 1.5 m. Additional legume and sugarcane rotation simulations were run for the Burdekin and Bundaberg sugarcane regions. Across all three study sites the simulations suggested that legume N was available to the sugarcane crop up to the fourth ratoon. Acknowledging the limitations of this initial exploratory study, it is hypothesized that potential reductions in fertiliser application rate could be up to approximately 100% in the first ratoon, and 60%, 25% and 10% in the subsequent ratoons. These findings require further validation but suggest a potential economic and environmental win–win outcome from refining N management practices in sugarcane-legume rotation cropping systems in Australia and other countries.

1. Introduction

Growing legumes as a rotation break crop has a long history (Chorley, 1981). It is widely practiced today in both industrial and subsistence production systems worldwide (e.g. George et al., 1995; Becker and Johnson, 1998; Biederbeck et al., 2005), including sugarcane (Pramanee et al., 1997; Nixon and Simmonds, 2004; Garside and Bell, 2001). The inclusion of a legume fallow within a sugarcane cropping cycle is practiced to reduce populations of detrimental soil organisms (Pankhurst et al., 2003, 2005; Shoko and Zhou, 2009), provide nitrogen (N) through biological fixation (Garside et al., 1996; Shoko and Tawira, 2007), and for weed suppression (McMahon et al., 1989; Cheruiyot et al., 2003).

Legume break crops were a common feature of Australian sugarcane production until the 1970s, when regulations on the amount of land required to be under fallow were lifted (Garside and Bell, 2001). Their promotion over the past few decades has focused on improved soil health and increased crop productivity. However, the N input into cropping systems may have contributed to environmental problems (Crews and Peoples, 2004). These problems are of particular concern in Australia where pollution of ground waters (Thorburn et al., 2003), impacts on the Great Barrier Reef (Brodie et al., 2008) and high emissions of nitrous oxide (Thorburn et al., 2010) have been observed. The use of management practices to reduce greenhouse gas emissions from agricultural production is of broader international interest (Robertson et al., 2009).

---

* Corresponding author. Tel.: +61 02 6242 1736; fax: +61 02 6242 1555.
E-mail address: sarah.park@csiro.au (S.E. Park).

0378-4290/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.fcr.2010.08.001

The amount of N contained in above ground soybean biomass can be over 300 kg N/ha when grain in not harvested (Garside et al., 1996) and approximately 60 (Schroeder et al., 2007) to 75% (Bell et al., 2003) less if grain is harvested. The amount of N in legume residues that is available to the subsequent sugarcane crops depends on soil processes. Immobilisation and mineralisation rates of N can vary significantly with on-farm management practices, including whether the grain is harvested or retained with the legume residues (Bell et al., 2006), and climate and soil conditions (Garside et al., 1998; Robertson and Thorburn, 2007a). Nonetheless, it is generally accepted that the amount of inorganic N fertiliser applied to the sugarcane plant crop can be substantially reduced, or even eliminated, following a legume fallow crop (Garside et al., 1997). General practice is for sugarcane growers to then revert to standard N fertiliser rates for all subsequent ratoon crops. This assumes that there is no carry over of legume N available beyond the plant crop. The duration and magnitude of any N carry over from soybean and potential reductions in rates of N fertiliser are, as yet, unquantified. It is therefore rational to conclude that any carry over of legume N beyond the plant crop that is not accounted for through reduced N fertiliser applications, will increase the potential for greater environmental losses of N and reduced profitability of sugarcane systems containing legume break crops.

Determining the duration and magnitude of legume N carry over, subsequent uptake by ratoon crops, profitability and environmental losses would require a comprehensive and long-term experiment based on different rates of N fertiliser and the presence and absence of a legume break crop. Whilst a published example of such an experiment has not been produced to date, probably due to the amount of resources required to undertake it, the combination of short-term field-base research and a simulation study approach detailed here, provides the opportunity to scope the potential for further enquiry and R&D investment.

We have used a simple experimentation and simulation approach to undertake a scoping study of the potential of best management practice recommendations for legume rotation break crops to address both economic and environmental concerns. From this we assess how long soybean N may remain available for uptake by subsequent sugarcane ratoon crops. The results are used as the basis for producing the first published estimates of potential reductions in N fertiliser use for the sugarcane ratoon crops grown within a sugarcane-legume rotation. If these preliminary results are found to be universal across sugarcane production systems, current N management strategies could be refined to account for legume N supply to ratoon crops, thereby reducing fertiliser costs to growers and lowering the potential for environmental N losses.

2. Materials and methods

In this study we used the APSIM (Agricultural Production Systems Simulator) (v. 5.3) cropping systems model (Keating et al., 2003) to simulate the yield response of sugarcane crops grown after a ley soybean crop to different amounts of N fertiliser. Before undertaking this modeling analysis, we (a) parameterised the legume variety Leichhardt in APSIM with independent data and (b) verified predictions of crop growth and N response against observed data from a sugarcane-legume rotation plot (Fig. 1). This combined approach of using field and simulation data has been previously found to be useful for optimising management practices in a cropping systems setting, where there are complex interactions between inputs, crop growth and soil processes (Lisson et al., 2005).

2.1. General configuration of the APSIM model

The APSIM model was used to simulate the growth of soybean and sugarcane in rotation at Mossman, Burdekin and Bundaberg. Model configuration included the soil water module SOILWAT2, the soil nitrogen module SOILN2 and the surface organic matter module SurfaceOM (Probert et al., 1998), with parameters for sugarcane residue decomposition (Thorburn et al., 2001). Crop modules SUGARCANE (Keating et al., 1999) and Soybean (Robertson et al., 2002) were also used. As the sugarcane module in APSIM has already been validated across a wide range of locations and management practices (Keating et al., 1999; Thorburn et al., 2001, 2005), this provided confidence in using standard APSIM sugarcane parameter values to simulate sugarcane growth and extrapolate the results beyond the observed field data.

2.2. Parameters for the soybean variety Leichhardt

The soybean variety Leichhardt (Lawn and Imrie, 1994) had not previously been parameterised in APSIM. The National Soybean Improvement Program varietal evaluation database was therefore interrogated and parameter estimates for Leichhardt were

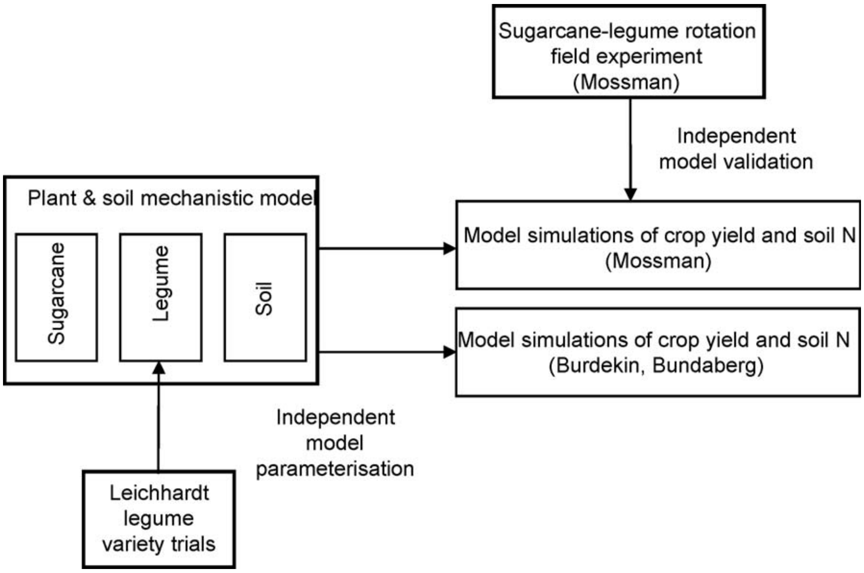

Fig. 1. Systems analysis of sugarcane production containing (a) a plant and soil mechanistic model, (b) independent data on the legume variety Leichhardt and (c) a sugarcane-legume rotation experiment.

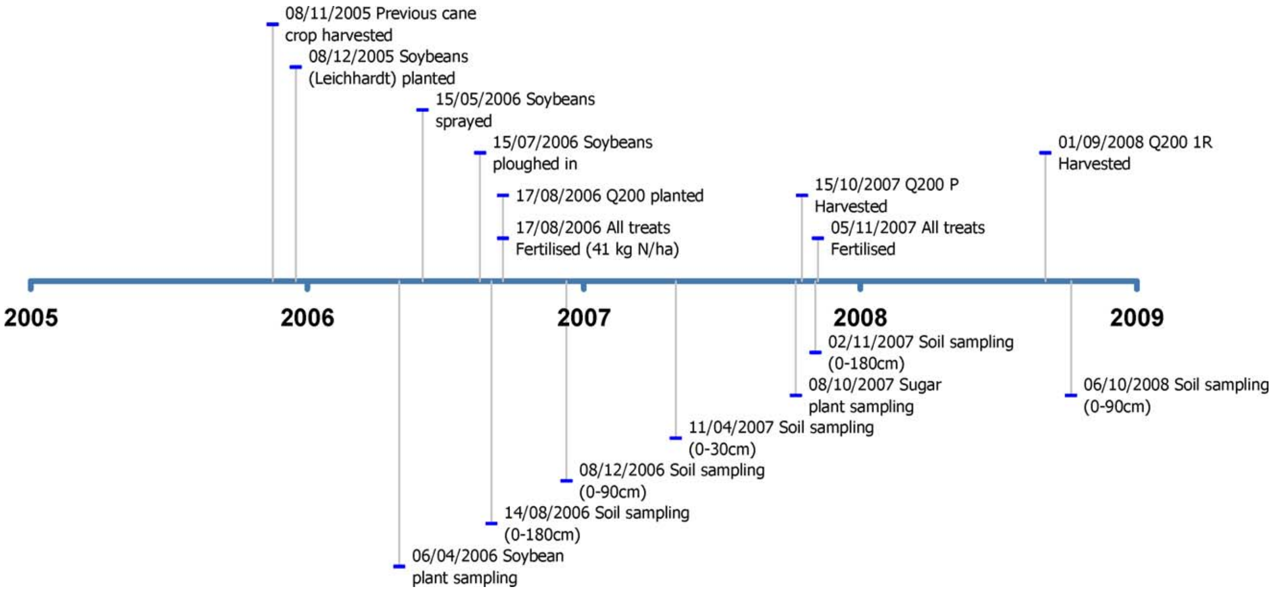

Fig. 2. Dates of key management activities in legume-sugarcane rotation experiment conducted at Mossman.

derived from the phenology data and temperature records for 28 trials in which Leichhardt was grown. These trials were sown between 2000 and 2007 at a range of summer and winter planting dates at Ayr and Walkamin in north Qld. Defining parameter values required estimating thermal time (i.e. the number of day degrees, °Cd) in each phenological stage of the plant's development. This was done by calculating daily mean temperature for the duration of the breeding trials using the Queensland Department of Natural Resources, Mines and Energy SILO patched point datasets (Jeffrey et al., 2001). Daily units of thermal time were calculated using a base temperature of 6.5 °C and an optimum growth temperature of 30 °C and summed for each phenological stage. Phenological stage and day degrees were calculated as: emergence to end of juvenile phase = 60 °Cd; end of juvenile phase to floral initiation = 700–2000 °Cd; floral initiation to flowering = 24 °Cd; flowering to start grain fill = 270 °Cd; start grain fill to end grain fill = 900 °Cd; end grain fill to maturity = 40 °Cd, and maturity to ripe = 5 °Cd. Thermal time requirement for end of juvenile phase to floral initiation depends on the duration of the photoperiod (within the range 11–17 h).

2.3. Sugarcane-legume rotation field data from Mossman site

A soybean and sugarcane rotation plot was established at Mossman in the wet tropics (16°25′54″ S; 145°23′34″ E). Soil texture at the site was a fine sandy loam to light medium clay duplex. Annual average rainfall for the period 1924 to 2005 was 2365 mm, annual average solar radiation 19.8 $\mathrm{MJ/m^2}$, and annual average maximum and minimum temperatures 29.3 and 21.2 °C, respectively (SILO patched point datasets (Jeffrey et al., 2001)). On 8 December 2005, 30 days after the previous sugarcane crop had been sprayed out with glyphosate, soybean (*Glycine max* cv. Leichhardt) seed was inoculated with bacteroids of *Bradyrhizobium japonicum*, strain CB1809, and directly drilled below the sugarcane residue with two rows of soybean sown into each sugarcane mound, producing a density of 25 $\mathrm{plants/m^2}$ (Fig. 2). The soybean crop was grown through the local wet season under rainfed conditions and sprayed out on 15 May 2006 using the industry standard practice of applying glyphosate (450 g/L) at a rate of 2.0 L/ha. Soybean crop residues (including grain) were ploughed in on 15 July 2006. On 17 August 2006 sugarcane (*Saccharum officinarum* cv. Q200) was planted into the site and three replicates containing sugarcane were established approximately 15.1 m wide (each containing 9 rows spaced at 1.68 m) and 280 m long. For the sugarcane plant crop, all three replicates were fertilised at planting with 41 kg N/ha (the farmer's standard basal fertiliser application rate) referred to as 'NS'. For the first sugarcane ratoon crop, each of the three replicate plots was given a different rate of N fertiliser. From that point onwards, the experiment therefore became an un-replicated field trial based on an N fertiliser treatment containing three levels of application (i.e. only the soybean and sugarcane plant crops were replicated). The application rates for the first sugarcane ratoon crop were calculated using: (a) the farmer's standard fertiliser rate, referred to as 'NF'; (b) the N-replacement formula, assuming sugarcane requires 1.0 kg N for every tonne harvested (Thorburn et al., 2007) (Eq. (1)) and using the site's long-term average sugarcane yield of 100 t/ha as requested by the farmer, referred to as 'NR', and (c) the same N-replacement formula as (b) amended to take account of N provided by the soybean fallow crop (Eq. (2)), referred to as '$\mathrm{NR_L}$':

$$\mathrm{NR} = Y \times 1.0 \tag{1}$$

$$\mathrm{NR_L} = Y \times 0.7 \tag{2}$$

where *Y* is mean sugarcane yield for the site. The multiplier rate of 0.7 was determined for the $\mathrm{NR_L}$ treatment by using 10% as a conservative estimate of the proportion of legume N likely to be available for uptake by the first ratoon crop, assuming a soybean yield of 300 kg N/ha (Garside et al., 1996). The N fertiliser rates for the first ratoon crop under NF, NR and $\mathrm{NR_L}$ treatments therefore resulted in 125, 104 and 73 kg N/ha, respectively, being applied to the non-replicated plots.

The sugarcane plant crop was mechanically harvested on 15 October 2007 and fresh weight yield (t/ha) determined for each plot using a commercial weighbridge. The same method was used to determine yield produced from the first ratoon crop harvest on 1 September 2008. During the 3-year rotation field plot, soils were sampled at three randomly chosen locations within each treatment plot at between approximately 4–11-month intervals using 50 mm diameter steel tubes inserted to the depths shown in Fig. 2. Once the sugarcane crop had been planted, at each of the three locations within the plot, soil cores were taken from both within the crop row and from the inter-row space and bulked together. Soil cores were split into 0.3 m increments and soil mineral N

Table 1
APSIM parameter values for the Mossman region for organic carbon (C), ammonium (NH_4), nitrate (NO_3) and soil pH to a depth of 2 m.

	Soil depth							
	0–15	15–30	30–45	45–60	60–90	90–120	120–150	150–200
C (%)	5.25	5.25	2.30	0.33	0.33	0.33	0.33	0.33
NH_4 (kg/ha)	4.872	4.872	2.835	2.835	4.050	0.065	0.077	0.045
NO_3 (kg/ha)	63.336	63.336	65.002	65.002	41.715	0.065	0.099	0.020
pH	4.84	4.83	4.83	4.80	4.89	4.84	4.80	4.81

determined by extraction in 2 M KCl with NO_3-N measured using EPA method 353.1 and NH_4-N measured colorimetrically (Rayment and Higginson, 1992). In summary, this method reduces nitrate to nitrite with hydrazine sulfate and the nitrite that is originally present plus the reduced nitrate is determined by diazotizing with sulfanilamide and coupling with N-(naphthyl)-ethylenediamine dihydrochloride to form a highly colored azo dye which is measured colorimetrically. For each 0.3 m sample, C was also determined using combustion on a LECO CNS 2000 (LECO Corporation, 2003a).

Soybean plants were sampled at half pod-fill stage (6 April 2006) by collecting all above ground plant material from a 0.5 m length of crop row at 3 randomly chosen locations within each treatment plot (Morrison et al., 1999). Sugarcane stalks were sampled for total N content prior to the plant and first ratoon harvests by collecting 15 stalks from each treatment, which is the industry standard sampling regime for determining N concentration (Muchow et al., 1993; Thorburn et al., 2003). The sugarcane stalks were collected by randomly selecting three stalks from within each of the middle five rows of sugarcane in each plot (thereby avoiding a minimum of guard rows on each side). The sugarcane stalks were partitioned into stem, dead leaf, green leaf and cabbage to enable total N to be determined for both the portion of the crop exported at harvest and crop residues retained in the field (i.e. trash). Plant total N was determined for both soybean and partitioned sugarcane stalks by combustion on a LECO CNS 2000 (LECO Corporation, 2003b). Sugarcane leaf samples were also collected from the plant crop around mid-season for analysis (Schroeder et al., 2007).

2.4. Simulation of field data from Mossman

APSIM was used to simulate the growth of soybean and sugarcane in rotation using the same experimental design and agronomic management detailed above for the field data produced at Mossman and daily climate data obtained from the SILO patched point datasets (Jeffrey et al., 2001). In order to simulate the soybean being sprayed out, the crop was terminated and the above ground biomass transferred to the surface residue pool, and the roots added to the soil fresh organic matter (FOM) pool. When the soybeans were ploughed into the soil, all surface material was incorporated into the top 200 mm of soil (simulated by transferring it to the soil FOM pool). Default APSIM settings for biological N fixation were used in the simulations. This meant that fixation of N by the soybean crop only occurred when demand for soil N could not be satisfied via mass flow and diffusion (Robertson and Carberry, 1998). Soil parameters used in the model were based on a well drained medium to heavy clay soil of alluvial origin (Murtha and Smith, 1994). This common soil parameter file has been used in previous simulation studies to represent a common soil type found in the Mossman region (Webster et al., 2009). Parameter values for organic carbon (C), ammonium (NH_4), nitrate (NO_3), and soil pH to a depth of 2 m are shown in Table 1.

By using the above method it was possible to produced parameter values for the model simulations without reference to data gathered from the field. This enabled the performance of APSIM to simulate sugarcane crop yield and soil mineral N dynamics in the legume-sugarcane rotation plot undertaken at Mossman to be validated by independently produced data. Goodness of fit of the model to observed soil mineral N was assessed by calculating the root mean squared deviation (RMSD).

2.5. Simulation of N response curves for a range of biophysical, climatic and management conditions at Mossman

Long-term simulations (106 years) were undertaken to estimate the response curves for N fertiliser applied to sugarcane crops grown in rotation with soybean or bare fallow at Mossman. The simulated cropping cycles represented common agronomic practices in the region and consisted of a 12.5-month plant crop, planted 15 August at a density of 10 plants/m^2, followed by four 12.5-month ratoons simulated at densities of 9.5, 9.03, 8.57 and 8.15 plants/m^2, respectively. The simulated decline crop densities represented a 5% reduction in the number of stalks surviving following each harvest; this amount being inline with personal observation. The soybean break crop simulation included the crop being planted, and after the fourth ratoon (8 December), being terminated mid-May and incorporated into the soil in mid-July. In the simulated bare fallow rotation, harvest of the fourth ratoon was followed by a 9.5-month bare fallow. For both cropping system simulations, production was rainfed and sugarcane residues were retained to provide a green cane trash blanket (GCTB). Both rotation scenarios were run for 12 different rates of N fertiliser, with the application rate being determined as a function of the N exported in the previous crop, as per the N-replacement approach (Thorburn et al., 2007). Following this approach, between 0 and 2.0 kg N was applied for every tonne of cane harvested in the previous crop (actual replacement multipliers were 0, 0.27, 0.54, 0.72, 0.90, 0.99, 1.08, 1.26, 1.44, 1.62, 1.80 and 2). In the case of a sugarcane plant crop, the simulated yield of the last ratoon crop in the previous sugarcane cropping cycle was used to determine the amount of N fertiliser. Use of the replacement approach meant that annual N application rates were not consistent through time, but varied according to previous yield, however we report N response curves for mean amount of N applied over the duration of the simulations. Fertiliser was applied to the plant crop at planting and to the ratoon crops 42 days after simulating harvest. The model was run using observed daily climate data for the period 1900 to 2005 sourced from the Queensland Department of Natural Resources, Mines and Energy SILO patched point datasets. In order to synchronise the sugarcane crop cycles across both the soy and bare fallow treatments throughout the duration of the 106 years of simulations, the soybean crop was first planted in 1900, and the bare fallow started in 1901. The simulation output for the first 4 cropping cycles (up to 1923) were discarded so that the model could reach equilibrium and the initial values chosen for the model parameters would not impact results (Lisson et al., 2000). The remaining data (1924–2005) were used for analysis.

Further simulations were conducted to consider the impact of the soybean crop on the sugarcane yield and the amount of N fertiliser required to achieve 97% maximum potential yield, compared to a sugarcane and bare fallow rotation. Parameterisation of the bare fallow simulations was identical to the soybean–sugarcane rotation simulations, without the growth of the soybean break crop.

Table 2
Summary of simulated legume and sugarcane rotations grown under different biophysical and climatic conditions and agronomic management. GCTB: green cane trash blanket.

Location	Soil type	Irrigation	Management of legume residues	Management of plant crop (variety, crop duration (months), trash management)	Management of ratoon crops (no. of ratoon crops, crop duration (months), trash management)
Mossman	Fine sandy loam to light medium clay duplex	None	Ploughed in	Q200, 12.5, GCTB	4, 12.5, GCTB
Burdekin site 1	Alluvial clay	23.3ML	Left on surface	Q117, 15, burnt	3, 13, burnt
Burdekin site 2	Sandy clay loam	23.3ML	Left on surface	Q117, 15, burnt	3, 13, burnt
Burdekin site 3	Sandy clay	23.3ML	Left on surface	Q117, 15, burnt	3, 13, burnt
Burdekin site 4	Sandy clay	23.3ML	Left on surface	Q117, 15, burnt	3, 13, burnt
Bundaberg	Clay loam	1.5ML	Left on surface	Q124, 12-month, GCTB	4, 12, GCTB

The yield target was set at 97% maximum potential yield due to the extended asymptotes found for the simulated N response curves for the ratoon crops and the reduced financial returns achievable per unit of N fertiliser applied as yields approach a maximum.

2.6. Model simulations for Burdekin and Bundaberg

In order to initiate a broader consideration of potential reductions in the rates of N fertiliser in other areas of the Australian sugarcane industry, similar N response curves were also produced from simulated soybean and sugarcane rotations grown in the Burdekin dry tropics and the Bundaberg area of Queensland. Summary details of soil and crop management for these simulations are shown in Table 2. Further details of soils for the Burdekin sites can be found in Stewart et al. (2006) and Thorburn et al. (2009), and soil and crop management details for Bundaberg in Bell et al. (2006).

3. Results

3.1. Goodness of fit of the model to observed data from the field plot at Mossman

The soybean crop grown in the field trial at Mossman produced 9 t/ha (±0.7) above ground dry weight biomass containing 301 kg N/ha (±36). The model predicted above ground dry weight to be 11 t/ha, an over-estimation of 22%, and N content to be 394 kg/ha, an over-estimation of 24%.

Mean cane fresh weight from the plant crop was 110 t/ha (Table 3). This figure is reported in line with the sugarcane industry convention of recording millable stalk yield. The model simulated mean cane fresh weight from the plant crop was 104 t/ha, an under-estimate of only 6%. The sugarcane crop grown at Mosman produced 54.5 t/ha (±0.5) above ground dry weight containing 133 kg N/ha (±1.7). These data compared to model simulations of 36.7 t/ha and 162 kg N/ha, respectively, resulting in an under-estimation of 33% for above ground dry weight and an over-estimation of 18% for N content. Observed commercial cane sugar (c.c.s) in the plant crop was high at 15.1. Industry standard mid-season leaf testing showed no indication of N stress in the crop. There was minimal variation in the observed yield of cane produced across the three N fertiliser treatments in the first ratoon. Cane yields produced in the first ratoon ranged from 81 to 83 t/ha, showing minimal variation in response to N fertiliser rate despite the highest N application rate being over 40% more than the lowest. Given that there was no account taken of the potential contribution of N derived from biological N fixation by the soybean crop used when calculating the reduction in N fertiliser applied to the first ratoon, and knowledge that fixation by soybeans can contribute a substantial additional amount of N to the soil (Chapman and Myers, 1987; Garside et al., 1996; Ncube et al., 2009), this would suggest the reductions in N fertiliser used in this study have potential to be reduced further. The model performed well in predicting cane yield in the first ratoon across the full range of N fertiliser treatments (73–125 kg N/ha), producing an average over-estimation of only 3%.

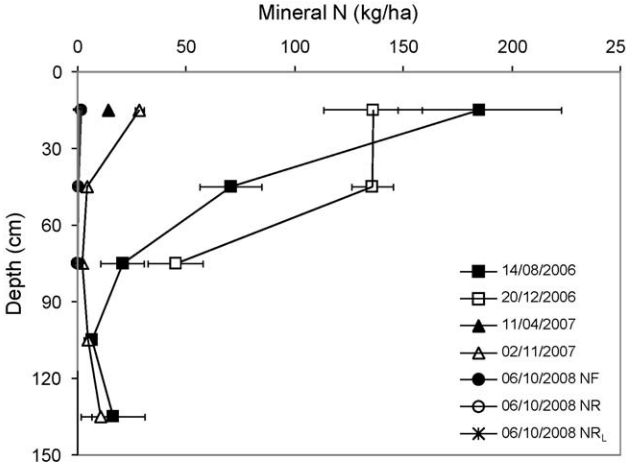

Fig. 3. Mean mineral N (±S.E.) in the soil profile in 0.3 m increments for the five sample dates. No standard error bars displayed for the three treatment results reported for 6 October 2008 (NF – farmer's standard fertiliser rate; NR – N-replacement; NR$_L$ – N-replacement taking into account N supplied from the soybean crop).

In terms of field data, a total of 305 kg (±56) of mineral N was observed in the top 1.5 m of the soil profile on 14 August 2006, about 1-month after the soybean crop had been incorporated (Fig. 3). The

Table 3
Observed (Obs) and predicted (Pred) measures of soybean and sugarcane biomass produced for the 3 N treatments in the Mossman legume-sugarcane rotation plot under different rates of N fertiliser (Fert) and management regimes: NF = the farmer's standard fertiliser rate; NR = the N-replacement formula; NR$_L$ = N-replacement formula amended to take account of N provided by the soybean fallow crop.

Sugarcane crop	Harvest date	NF			NR			NR$_L$		
		Fert	Cane yield (t/ha)		Fert	Cane yield (t/ha)		Fert	Cane yield (t/ha)	
			Obs	Pred		Obs	Pred		Obs	Pred
Plant	15/10/2007	41	107	104	41	111	104	41	111	104
Ratoon 1	01/09/2008	125	83	87	104	81	86	73	82	84

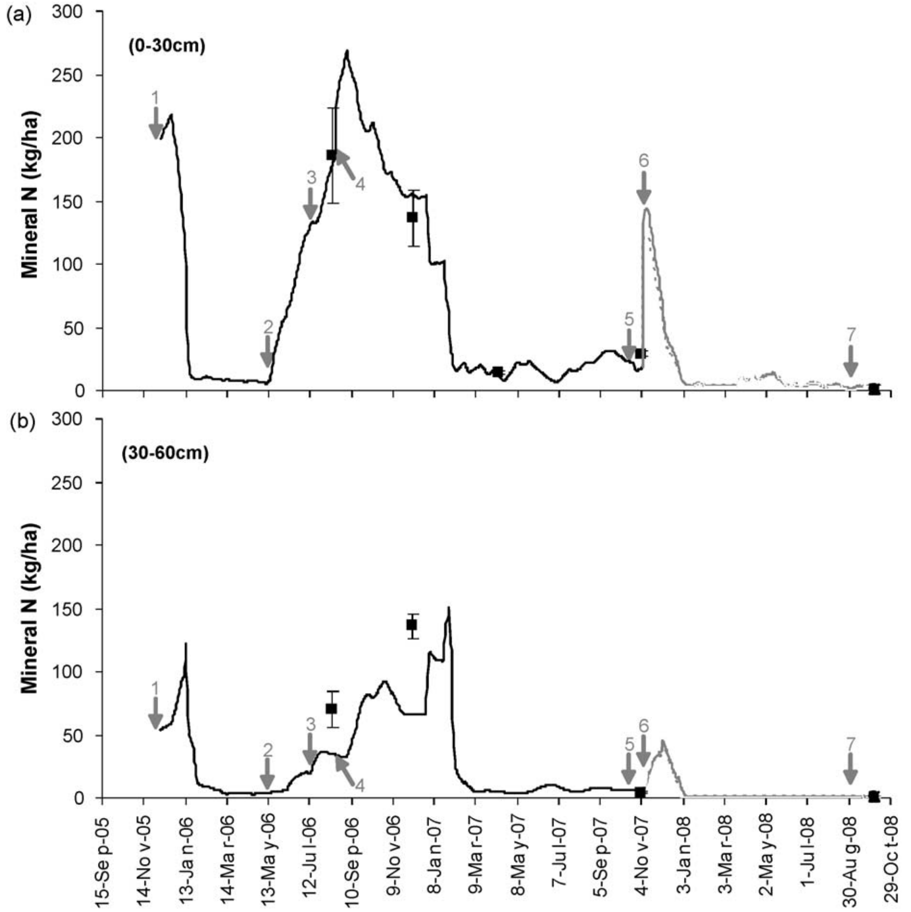

Fig. 4. Observed (black square symbols with standard error bars) and simulated (black solid line) mineral N in the top (a) 0.3 m and (b) 0.3–0.6 m of soil profile for soybean and sugarcane plant crops. Grey solid line shows predicted NF treatment, dashed grey line shows predicted NR treatment, and dotted grey line shows NRL treatment. Black triangle, circle and star symbols (overlapping on 6 Oct 2008) show observed mineral N for NF, NR and NRL, respectively. Grey numbered arrows indicate agronomic events: 1 = soybeans planted (8 December 2005); 2 = soybeans sprayed out (15 May 2006); 3 = soybeans ploughed in; 4 = sugarcane planted and 41 kg N/ha fertiliser applied (17 August 2006); 5 = sugarcane plant crop harvested (15 October 2007); 6 = fertiliser treatments applied (5 November 2007); 7 = 1st ratoon harvested (1 October 2008).

majority of this (61%) was found within the top 0.3 m, and a further 23% at a depth of between 0.3 and 0.6 m. Just over 4 months later (20 December 2006), the amount of mineral N in the top 0.9 m of the soil profile was largely unchanged at 317 kg N/ha, however N in the top 0.3 m had reduced by approximately 50 kg and correspondingly increased by approximately 50 kg in the 0.3 to 0.6 m increment. After a further approximately 4 months (11 April 2007), mineral N in the top 0.3 m of the soil profile had reduced substantially to 14 kg N/ha. Subsequent mineralisation of N resulted in this increasing to 29 kg N/ha when it was measured again nearly 7 months later (2 November 2007). The three samples taken on 6 October 2008 showed there to be virtually no mineral N in the top 0.9 m of the soil profile at Mossman by the end of the first ratoon.

Given the vast majority of mineral N was observed in the top 0.6 m of the soil profile at Mossman, the simulated mineral N is shown for only the two top 0.3 m soil increments (Fig. 4). Fig. 5 shows that APSIM accounted for 91% of the variation in the observed soil mineral N across all 0.3 m increments up to 1.5 m over the 26-month period, with a significant correlation between observed and simulated data ($p < 0.01$).

3.2. Simulation of N response curves for a range of biophysical, climatic and management conditions at Mossman

The simulated average response of sugarcane plant and ratoon crop yields when grown in rotation with a soybean break crop at Mossman under a range of N fertiliser application amounts are shown in Fig. 6. The simulations show no yield response for the plant crop to N fertiliser applied. The first ratoon crop showed increased yield with N fertiliser applications up to 50 kg/ha, with no further response at higher rates of application. In the second and third ratoons, simulated yields responded to increasing amounts of N fertiliser up to around 110 kg/ha. The fourth ratoon crop failed to respond to further applications of N fertiliser beyond approximately 150 kg/ha.

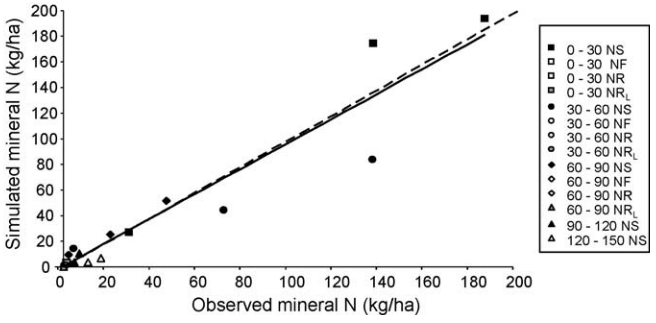

Fig. 5. Observed and simulated mineral N (kg/ha) in 0.3 m increments of the soil profile to a depth of 1.5 m. Dashed line shows 1:1 relationship and solid line shows linear regression. Mineral N: $y = 0.98x + 0.22$, $R2 = 0.91$, $p < 0.01$; RMSD = 62 kg mineral N/ha. Standard error of estimate is 20.961. N treatments: NS – standard basal fertiliser rate; NF – farmer's standard fertiliser rate; NR – N-replacement; NRL – N-replacement amended to take account of N provided by the soybean fallow crop.

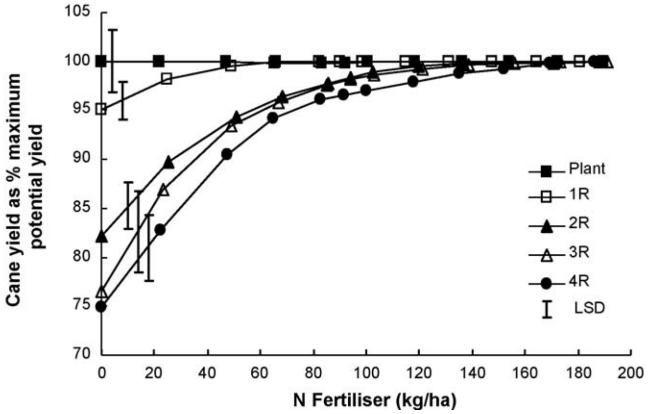

Fig. 6. Simulated N response curves for sugarcane crops grown in rotation with a legume fallow at Mossman. Cane yield expressed as a percentage of the mean maximum potential yield obtainable for a crop during the period 1925 to 2008. LSD = least significant difference ($p = 0.05$).

The long-term (106 years) model simulations showed similar sugarcane mean annual fresh cane yields were produced in the soybean fallow grown in Mossman (92 t/ha) to those produced in the bare fallow rotations (92 t/ha), resulting in similar cumulative sugarcane yields across the duration of a crop cycle (Table 4). The similar yields enabled a direct comparison to be made between the amounts of N fertiliser required to achieve 97% of mean maximum sugarcane yield when grown with and without the soybean break crop. Neither simulations for bare or soybean fallow rotations required N fertiliser to be applied to achieve 97% maximum yield in the plant crop. In contrast, all ratoon crops in both cropping systems showed a yield response to applied N fertiliser. A sugarcane yield of 92 t/ha was achieved in the first ratoon of the soybean rotation following an N fertiliser application of 12 kg/ha. When compared to the 91 kg N/ha required to produce a similar yield from the bare fallow cropping system (93 t/ha), this shows an 87% reduction in the amount of fertiliser applied. The trend for a reduced N fertiliser requirement following a simulated soybean break crop continued through the second, third and forth ratoons, with N fertiliser applications being reduced by approximately 30, 25 and 10%, respectively.

3.3. Model simulations for Burdekin and Bundaberg

The N response curves simulated for Burdekin and Bundaberg conditions showed sugarcane yields from the rotation including the soybean break crop were again similar to those produced when the soybean was removed and a bare fallow simulated (Table 4).

Table 4
Simulated sugarcane yield (fresh weight) response to applied N fertiliser at Mossman, Burdekin and Bundaberg when grown in rotation with (a) a legume fallow crop, and (b) a bare fallow. Mean (and standard error (±)), total sugarcane yield and N fertiliser amounts calculated for the whole crop cycle.

Location	Sugarcane crop	Legume fallow		Bare fallow	
		97% maximum potential yield (t/ha)	Approximately N fertiliser applied (kg/ha)	97% maximum potential yield (t/ha)	Approximately N fertiliser applied (kg/ha)
Mossman	Plant	89	0	89	0
	Ratoon 1	92	12	93	91
	Ratoon 2	94	77	93	113
	Ratoon 3	91	80	92	109
	Ratoon 4	92	100	92	110
	Mean	92 (±0.9)	54 (±20)	92 (±0.7)	85 (±21.5)
	Total	458	269	459	423
Burdekin site 1	Plant	156	28	160	129
	Ratoon 1	139	63	140	142
	Ratoon 2	147	116	147	160
	Ratoon 3	147	150	147	177
	Mean	147 (±3.1)	89 (±24.3)	149 (±3.7)	152 (±9.4)
	Total	589	357	594	608
Burdekin site 2	Plant	182	28	188	118
	Ratoon 1	165	114	166	186
	Ratoon 2	166	117	167	160
	Ratoon 3	164	137	165	157
	Mean	169 (±3.8)	92 (±27.8)	172 (±4.9)	155 (±12.5)
	Total	677	368	686	621
Burdekin site 3	Plant	131	28	134	74
	Ratoon 1	113	40	115	111
	Ratoon 2	120	95	120	117
	Ratoon 3	118	123	118	129
	Mean	121 (±3.4)	65 (±24.6)	122 (±3.8)	108 (±10.6)
	Total	482	258	487	431
Burdekin site 4	Plant	116	28	118	95
	Ratoon 1	104	36	105	93
	Ratoon 2	113	87	113	120
	Ratoon 3	113	115	113	127
	Mean	112 (±2.3)	60 (±23.0)	112 (±2.4)	109 (±7.7)
	Total	446	238	449	435
Bundaberg	Plant	100	42	102	42
	Ratoon 1	109	0	113	37
	Ratoon 2	102	15	113	38
	Ratoon 3	109	43	120	45
	Ratoon 4	118	61	129	62
	Mean	107 (±3.2)	32 (±10.9)	115 (±4.6)	45 (±4.6)
	Total	537	161	577	224

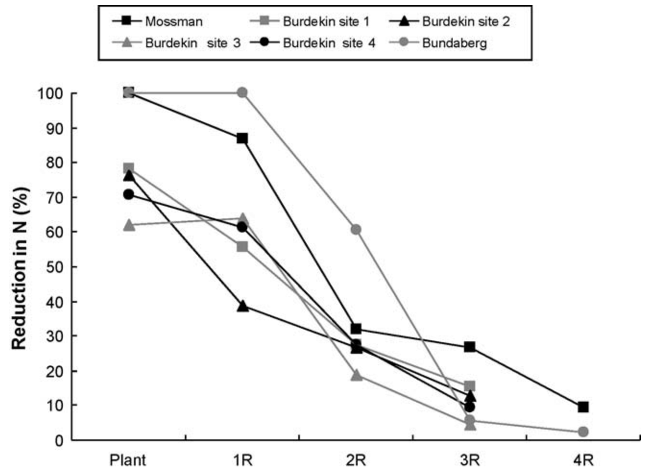

Fig. 7. Comparison of reductions in N fertiliser across a number of long-term (106 years) simulated legume and sugarcane rotations across different biophysical conditions and crop management practices. *R* = ratoon.

The amount of N fertiliser required to achieve 97% of maximum yield was also generally lower in rotations containing a soybean break crop. The general trend across all sites simulated (including Mossman) was for older ratoon crops to require increasing amounts of N fertiliser (Fig. 7). Across all scenarios, the amount of N fertiliser applied to the plant crop to reach 97% of maximum production was between approximately 60% and 100% lower when soybean was grown as a break crop compared with the bare fallow rotation. This reduction was between 40% and 100% in first ratoon crops, between 20% and 60% in second ratoon crops, between 5% and 25% in the third ratoon and between 2% and 10% in the forth ratoon. Simulations over the whole crop cycle show that incorporating a soybean break crop reduces the amount of N fertiliser required to achieve 97% potential yield by approximately 30–40% of the total amount of N required for a crop cycle incorporating a bare fallow.

4. Discussion

The most important issue addressed in this paper is the assumption that N from a well grown legume break crop does not contribute N to sugarcane beyond the initial plant crop. We have shown this assumption not to be valid for the sugarcane production systems studied and simulated, particularly for the first sugarcane ratoon crop. Results from the 3-year field plot in Mossman show 54 kg mineral N/ha was present within 1.5 m of the soil surface at the beginning of the first ratoon growing season, a depth that corresponds to the root zone of sugarcane ratoon crops (Smith et al., 2005). Using a widely used simulation modelling approach to extrapolate the results beyond the duration of the field plot data, it is confirmed that sufficient net mineralisation could provide almost enough mineralised N to grow the plant crop without depressing yield. The virtually identical sugarcane yields observed across the three N fertiliser rates for the first ratoon crop also indicate no response to increasing rates of N fertiliser, and suggest sufficient supplies of N were already present in the root zone. This observation was also supported by model simulations that showed just 7 kg N/ha was needed by the first ratoon crop simulated for Mossman to produce the target yield, i.e. 97% of maximum potential yield (Rabbinge, 1993). This resulted in a reduction of 113 kg N/ha compared with present N fertiliser recommendations (Schroeder et al., 2008). The modelling study also suggests subsequent ratoons benefit from soybean N, with the total reduction in N fertilisation 201 kg N/ha over a 5-year sugarcane production cycle. A general trend of diminishing reductions in N fertiliser requirement following a soybean break crop was also estimated across the full six sites and three growing regions included in the long-term simulations.

Translating the field plot and model simulation findings into practical N management recommendations will require further field and simulation investigations focusing on the cycling and fate of legume N during the cropping cycle. Using the model output from the long-term simulations in this study, it is seen that N continues to become available more than 4 years after the soybean crop is harvested (over and above that available in a bare fallow system). Over the nearly 70 years of the long-term crop simulations data analysed, this results in an average increase in soil mineral N content of approximately 4% (data not shown). Model output confirms that higher levels of N in rotations containing a soybean crop were immobilised into the soil organic matter (represented by the fresh organic matter and soil microbial biomass pools in APSIM) following crop termination, compared with rotations containing a bare fallow. This increased supply of N enabled net mineralisation and provided a readily available supply of mineral N for uptake by the sugarcane crop. The additional input of N into the system thereby lowered N fertiliser requirement in the simulated soybean rotation necessary to maintain sugarcane yield. The lower quantities of mineralised N simulated in the bare fallow rotations resulted in the sugarcane crops consequently showing a yield response to applications of N fertiliser.

This study contributes a first step in providing a “rule-of-thumb” for reducing N fertiliser application rates following a soybean break crop and demonstrates the usefulness of combining limited observational data with an extensively-validated mechanistic model of crop growth. Operationalising this information in say, the N-replacement approach, would require the appropriate percentage of N contributed from the soybean break crop to each crop in the sugarcane cropping cycle be used to modify the N fertiliser requirement. Whilst the exact percentage reduction in N fertiliser for each crop is yet to be tested in field experiments over a wide range of conditions, the combination of independent model parameterisation, a sugarcane-legume field plot and model simulations presented in this paper is offered as a first step in modifying the balance sheet approach to N fertiliser management to take account of N inputs from organic sources such as legumes. Other target yield based N management strategies (e.g. Schroeder et al., 2007) should similarly look to subtract legume N sources from current recommendations for sugarcane ratoon crops to avoid potential over-fertilisation of ratoons, decrease grower costs and reduce the amount of N available for loss to the environment.

The concept of reducing N fertiliser rates in response to organic N contributions is not new to the Australian sugarcane industry. Green cane trash blanketing (GCTB) may contribute up to 54 kg N/ha to the soil, as well as large quantities of C which increase the ability of the soil to immobilise and subsequently mineralise N (Robertson and Thorburn, 2007a). In response to this contribution of N and resulting enhanced N cycling capacity (Robertson and Thorburn, 2007b), modelling predicts that it is possible to decrease the amount of inorganic N fertiliser applied to sugarcane once the soil has reached a new equilibrium in C (typically a period of greater than 15 years). Long-term changes to N management in response to GCTB differ from those suggested here for legume residues due to the relatively higher amounts of N and lower carbon content of legumes resulting in more immediate changes to soil N cycling.

The similar yields observed in both the soybean and bare fallow rotational systems suggests that net economic benefits from a soybean/sugarcane rotation will only be realised if the relative production costs for growing the soybean fallow are out-weighed by the reduced requirement for N fertiliser. Given that a soybean break crop costs approximately $200–250/ha (Roebeling et al., 2004) and 2008 price of urea is approximately $2.40/kg of N, the fertiliser N saving needs to be in the order of 80–100 kg N/ha to achieve parity.

Over the 5-year crop cycle, savings in N fertiliser were greater than 170 kg N/ha at the Mossman site and all Burdekin sites, but only 63 kg at Bundaberg. Whilst a soybean crop grown at Mossman is unlikely to be harvested for grain due to the coincidence of crop maturity with the wet season, financial gains from harvested soybean grain in drier regions such as the Burdekin and Bundaberg, would need to be taken into consideration in financial analyses.

In addition to the above potential benefits to profitability, aligning rates of N fertiliser more closely to crop N demand by accounting for N contributed from other sources, such as a legume break crop, are generally considered to lower the risk of environmental losses (Hemwong et al., 2009). This is particularly important given increasing scrutiny of land use impacts on reef water quality (e.g. Reef Water Quality Protection Plan (Anon, 2003)) and the identification of sugarcane production as the most likely major source of N found in some stream catchments discharging into the Great Barrier Reef Lagoon (Mitchell et al., 2005). It is therefore concluded from this scoping study that there is sufficient potential for improved economic and environmental outcomes to justify further enquiry and R&D investment into a more extensive sugarcane-legume rotation experiment.

Whilst the above results have been produced for sites in Australia, similar recommended rates of N are typically associated with sugarcane production in Guatemala (Pérez et al., 2008), Mexico (Palma-López et al., 2002), South Africa (Meyer and Wood, 1994) and areas of USA (Anon, 2001; Wiedenfeld and Enciso, 2008), India (Roy et al., 2006). Nitrogen runoff from sugarcane production is also implicated in the degradation of downstream environments in a number of these countries (Liao, 2008; Yu et al., 2008). Possibly the most notable is the Everglades National Park in Florida, USA, where agricultural production has been associated with high concentrations of N in Lake Okeechobee and the downstream wetlands, resulting in loss of native plant species such as sawgrass (*Cladium jamaicense Crantz*) (Capone et al., 1995). Similar to the Great Barrier Reef Marine Park, the Everglades has received national and international recognition as an area of outstanding environmental importance (Maltby and Dugan, 1994) and is thus the target of much surveillance.

Interest and use of legumes in the sugarcane rotation in regions of Brazil (Resende, 2000), the USA (Muchovej, 1995) and Guatemala (Pérez et al., 2008) suggests widespread and substantial reductions in inorganic N fertiliser use may be possible at a global scale through an increased appreciation of the potential contribution of N from soybean crops within the sugarcane rotation. In broader terms, the use of legumes as a rotation crop in combination with other crop species, e.g. cotton (Sankaranarayanan et al., 2010), maize (Ndufa et al., 2009), sorghum (Ncube et al., 2009) and pearl millet (Ghosh et al., 2007), highlights the need for further understanding of the spatial and temporal contribution of N from legume crops.

A secondary issue addressed in this study was the use of an independent dataset to parameterise the soybean variety and provide an initial test of the skill of the APSIM model to simulate the growth of Leichhardt soybean variety. Whilst the simulated biomass and N content for soybean were both over-estimated by approximately 20%, this is unlikely to alter the potential reductions in N fertiliser rates substantially, resulting in application rates that are still well below those presently used across the industry.

Sugarcane yield (cane fresh weight) and N content were simulated reasonably well, and were in line with previous modelling studies (Keating et al., 1999; Inman-Bamber and McGlinchey, 2003; Thorburn et al., 2005). The model was also able to capture well the cycling of soil N stores over the 26-month period within the top 1.5 m of the soil profile. However, above ground dry weight, particularly for sugarcane, was less well simulated by the model. This may have in part resulted from differences between the carbon content of the sugarcane variety grown in Mossman, and that used in the simulations. Notwithstanding this matter, the general model output provides sufficient confidence to continue using the model to assist N management decision-making for both production and environmental optimisation in a sugarcane and soybean rotation.

It is important to note the limitations in APSIM when estimating crop yields and soil N status. The long-term mean yields obtained for sugarcane grown in rotation with either the soybean break crop or bare fallow suggest that there are no additional yield benefits associated with the soybean break crop provided N requirements are satisfied with fertiliser additions. However published data show legume crops offer yield benefits throughout the sugarcane crop cycle due to good establishment of the plant crop (Garside and Bell, 2007) and improved soil health (Pankhurst et al., 2003). Whilst the model is able to reflect yield benefits resulting from an increase in soil carbon and mineral N following the incorporation of soybean residues, other benefits related to crop establishment and soil health are not represented.

In summary, this study provides initial evidence for the continued availability of legume N to sugarcane crops beyond the plant crop. The limited number of sites and management practices included in this study means that more extensive validation is required before sugar industries around the world can support a reduction in the amount of N fertiliser applied to ratoon crops. This study has focused on the Australian sugarcane industry, and more specifically on the amount of N assimilated by the sugarcane crop as represented in N response curves produced for a limited number of biophysical and management scenarios. The clear division in N reduction potential between the four sites in the Burdekin region and those at Mossman and Bundaberg, reflects the substantial influence that soil and management practices have on crop and soil N dynamics in a legume and sugarcane rotation (Bell et al., 2006; Hemwong et al., 2008). It is therefore recommended that any future studies use field experiments to produce empirical response curves. These will enable the model simulation results in this study to be more extensively evaluated and guide the identification of data requirements for developing evidence-based N management recommendations for the sugarcane industry in Australia, and other countries where legumes are a part of the sugarcane production system.

This study describes a proof-of-concept exercise focusing on the combined use of a simple field experiment (with replicated and unreplicated treatments) and an extensively-validated mechanistic model of crop and soil dynamics, to scope potential environmental and economic benefits resulting from reductions in N fertiliser use on sugarcane ratoon crops following a soybean fallow. The scoping exercise has also enabled the identification of specific areas of research that warrant further investigation. These include opportunities to further improve the predictive ability of the model in respect to above ground dry weight, the need for an examination of the magnitude of biological N fixation by the soybean crop in contributing N to soil stores, and an evaluation of the status of soil N over time. Long-term levels of soil N stores have been shown to be unaffected by N fertiliser management, including the N-replacement management regime (Thorburn et al., 2010). This indicates potential for further refinement of the N-replacement approach to account for sources of N in addition to those provided by fertilisers and sugarcane residues. This study shows that by taking the contribution of N from the legume fallow crop into account, sugarcane industries have the potential to demonstrate improvements in sustainable and responsible nutrient management. As a consequence of assuming legume N is only available to the plant crop, current best practice recommendations for N management in sugarcane may be responsible for widespread and systematic over-fertilisation in Australia, and other sugarcane-producing nations.

Acknowledgements

We are grateful to Mr Doug Crees for his collaboration on the sugarcane-legume field plot in Mossman. Thanks also to Dr Phil Kokic for statistical advice.

References

Anon, 2001. Sugarcane Production Handbook. LSU AgCenter, Louisiana State University (http://www.agctr.lsu.edu/NR/rdonlyres/807E6478-E556-44A8-8440-16A2CC4BFD4C/3272/pub2859sugarcane4.PDF). Accessed June 2010.

Anon, 2003. Reef Water Quality Protection Plan: For Catchments Adjacent to the Great Barrier Reef World Heritage Area. Queensland Government, Department of Premier and Cabinet, Brisbane, p 44.

Becker, M., Johnson, D.E., 1998. Legumes as dry season fallow in upland rice-based systems of West Africa. Biology and Fertility of Soils 27, 358–367.

Bell, M.J., Halpin, N.V., Garside, A.L., Moody, P.W., Stirling, G.R., Robotham, B.J., 2003. Evaluating combinations of fallow management, controlled traffic and tillage options in prototype sugarcane farming systems at Bundaberg. In: Proceedings of the Australian Society of Sugar Cane Technologists, vol. 25, p. 17.

Bell, M.J., Moody, P.W., Halpin, N.V., Garside, A.L., 2006. Impact of management of cane trash and legume residues on N mineralisation and crop N uptake. In: Proceedings of the Australian Society of Sugar Cane Technologists, vol. 28, pp. 129–141.

Biederbeck, V.O., Zentner, R.P., Campbell, C.A., 2005. Soil microbial populations and activities as influenced by legume green fallow in a semiarid climate. Soil Biology and Biochemistry 37, 1775–1784.

Brodie, J., Binney, J., Fabricius, K., Gordon, I., Hoegh-Guldberg, O., Hunter, H., O'Reagain, P., Pearson, R., Quirk, R., Quirk, M., Thorburn, P., Waterhouse, J., Webster, I., Wilkinson, S., 2008. Synthesis of evidence to support the Scientific Consensus Statement on Water Quality in the Great Barrier Reef. Reef Water Quality Protection Plan Secretariat, Department of Premiers and Cabinet, Brisbane.

Capone, L.T., Izuno, F.T., Bottcher, A.B., Sanchez, C.A., Coale, F.J., Jones, D.B., 1995. Nitrogen concentrations in agricultural drainage water in South Florida. Transactions of the ASAE 38, 1089–1098.

Chapman, A., Myers, R., 1987. Nitrogen contributed by grain legumes to rice grown in rotation on the Cununurra soils of the Ord Irrigation Area, Western Australia. Australian Journal of Experimental Agriculture 27, 155–163.

Cheruiyot, E.K., Mumera, L.M., Nakhone, L.N., Mwonga, S.M., 2003. Effect of legume-managed fallow on weeds and soil nitrogen in following maize (Zea mays L.) and wheat (Triticum aestivum L.) crops in the Rift Valley highlands of Kenya. Australian Journal of Experimental Agriculture 43, 597–604.

Chorley, G., 1981. The agricultural revolution in Northern Europe, 1750–1880 – nitrogen, legumes, and crop productivity. Economic History Review 34, 71–93.

Crews, T.E., Peoples, M.B., 2004. Legume versus fertilizer sources of nitrogen: ecological tradeoffs and human needs. Agriculture Ecosystems and Environment 102, 279–297.

Garside, A.L., Bell, M.J., 2001. Fallow legumes in the Australian sugar industry: review of recent research findings and implications for the sugarcane cropping system. In: Proceedings of the Australian Society of Sugar Cane Technologists, vol. 23, pp. 230–235.

Garside, A.L., Bell, M.J., 2007. The value of legume breaks to the sugarcane cropping system – cumulative yields for the next cycle, potential cash returns from the legume, and duration of the break effect. In: Proceedings of the Australian Society of Sugar Cane Technologists, vol. 29, pp. 299–308.

Garside, A.L., Berthelsen, J.E., Richards, C.L., 1997. Effect of fallow history on cane and sugar yield of a following plant cane crop. In: Proceedings of the Australian Society of Sugar Cane Technologists, vol. 19, pp. 80–86.

Garside, A.L., Berthelsen, J.E., Richards, C.L., Toovey, L.M., 1996. Fallow legumes on the wet tropical coast: some species and management options. In: Proceedings of the Australian Society of Sugar Cane Technologists, vol. 18, pp. 202–208.

Garside, A.L., Noble, A.D., Berthelsen, J.E., Richards, C.L., 1998. Fallow histories: effects on nitrogen contribution, growth and yield of plant and ratoon crops of sugarcane. In: Proceedings of the Australian Society of Sugar Cane Technologists, vol. 20, pp. 104–111.

George, T., Ladha, J.K., Garrity, D.P., Torres, R.O., 1995. Nitrogen dynamics of grain legume-weedy fallow-flooded rice sequences in the tropics. Agronomy Journal 87, 1–6.

Ghosh, P.K., Bandyopadhyay, K.K., Wanjari, R.H., Manna, M.C., Misra, A.K., Mohanty, M., Subba Rao, A., 2007. Legume effect for enhancing productivity and nutrient use-efficiency in major cropping systems – an Indian perspective: a review. Journal of Sustainable Agriculture 30, 59–86.

Hemwong, S., Cadisch, G., Toomsan, B., Limpinuntana, V., Vityakon, P., Patanothai, A., 2008. Dynamics of residue decomposition and N_2 fixation of grain legumes upon sugarcane residue retention as an alternative to burning. Soil and Tillage Research 99, 84–97.

Hemwong, S., Toomsan, B., Cadisch, G., Limpinuntana, V., Vityakon, P., Patanothai, A., 2009. Sugarcane residue management and grain legume crop effects on N dynamics, N losses and growth of sugarcane. Nutrient Cycling in Agroecosystems 83, 135–151.

Inman-Bamber, N.G., McGlinchey, M.G., 2003. Crop coefficients and water-use estimates for sugarcane based on long-term Bowen ratio energy balance measurements. Field Crops Research 83, 125–138.

Jeffrey, S.J., Carter, J.O., Moodie, K.B., Beswick, A.R., 2001. Using spatial interpolation to construct a comprehensive archive of Australian climate data. Environmental Modelling & Software 16, 309–330.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M., Smith, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. European Journal of Agronomy 18, 267–288.

Keating, B.A., Robertson, M.J., Muchow, R.C., Huth, N.I., 1999. Modelling sugarcane production systems I. Development and performance of the sugarcane module. Field Crops Research 61, 253–271.

Lawn, R.J., Imrie, B.C., 1994. Register of Australian oilseed cultivars Glycine max (L.) Merr. (soybean) cv. Leichhardt. Australian Journal of Experimental Agriculture 34, 297–298.

LECO Corporation, 2003a. Organic Application Note: Carbon, Nitrogen, and Sulphur Testing in Soil/Plant Tissue, Form No. 203-821-002.

LECO Corporation, 2003b. Organic Application Note: Carbon and Nitrogen in Plant Tissue, Form No. 203-821-171.

Lisson, S.N., Inman-Bamber, N.G., Robertson, M.J., Keating, B.A., 2005. The historical and future contribution of crop physiology and modelling research to sugarcane production systems. Field Crops Research 92, 321–335.

Lisson, S.N., Robertson, M.J., Keating, B.A., Muchow, R.C., 2000. Modelling sugarcane production systems. II: analysis of system performance and methodology issues. Field Crops Research 68, 31–48.

Maltby, E., Dugan, P.J., 1994. Wetland ecosystem protection, management and restoration: an international perspective. In: Davis, S.M., Ogden, J.C. (Eds.), Everglades: The Ecosystem and its Restoration. St Lucia Press, Delray Beach, Florida.

McMahon, G.G., Williams, R.C., McGuire, P.J., 1989. The effects of weed competition on ratoon sugar cane yield. In: Proceedings of the Australian Society of Sugar Cane Technologists, vol. 10, pp. 88–92.

Meyer, J.H., Wood, R.A., 1994. Nitrogen management of sugarcane in South Africa. In: Proceedings of the Australian Society of Sugar Cane Technologists, vol. 15, pp. 93–104.

Mitchell, C., Brodie, J., White, I., 2005. Sediments, nutrients and pesticide residues in event flow conditions in streams of the Mackay Whitsunday Region, Australia. Marine Pollution Bulletin 51, 23–36.

Morrison, M.J., Voldeng, H.D., Cober, E.R., 1999. Physiological changes from 58 years of genetic improvement of short-season soybean cultivars in Canada. Agronomy Journal 91, 685–689.

Muchovej, R.M., 1995. Rotational Crops for Sugarcane grown on Mineral Soils. Florida Cooperative. Extension Service, Institute of Food and Agricultural Science, University of Florida, p. 6.

Muchow, R.C., Wood, A.W., Spillman, M.F., Robertson, M.J., Thomas, M.R., 1993. Field techniques to quantify the yield-determining processes in sugarcane. I. Methodology. In: Proceedings of the Australian Society of Sugar Cane Technologists, vol. 25, pp. 336–343.

Murtha, G.G., Smith, C.D., 1994. Key to the Soils and Land Suitability of the Wet Tropical Coast: Cardwell – Cape Tribulation. CSIRO Division of Soils and Queensland Department of Primary Industries.

Ncube, B., Dimes, J.P., van Wijk, M.T., Twomlow, S.J., Giller, K.E., 2009. Productivity and residual benefits of grain legumes to sorghum under semi-arid conditions in south-western Zimbabwe: unravelling the effects of water and nitrogen using a simulation model. Field Crops Research 110, 173–184.

Ndufa, J.K., Gathumbi, S.M., Kamiri, H.W., Giller, K.E., Cadisch, G., 2009. Do mixed-species legume fallows provide long-term maize yield benefit compared with monoculture legume fallows? Agronomy Journal 101, 1352–1362.

Nixon, D.J., Simmonds, L.P., 2004. The impact of fallowing and green manuring on soil conditions and the growth of sugarcane. Experimental Agriculture 40, 127–138.

Palma-López, D.J., Salgado García, S., Obrador Olán, J.J., Trujillo Narcía, A., Lagunes Espinoza, L., Cruz, J.Z., Bello y, A.R., Carrera Martel, M.A., 2002. Integrated System for Recommending Fertilization Rates in Sugar Cane (ISRFD), vol. 20. Terra, pp. 347–358.

Pankhurst, C.E., Magarey, R.C., Stirling, G.R., Blair, B.L., Bell, M.J., Garside, A.L., 2003. Management practices to improve soil health and reduce the effects of detrimental soil biota associated with yield decline of sugarcane in Queensland, Australia. Soil Tillage Research 72, 125–137.

Pankhurst, C.E., Stirling, G.R., Magarey, R.C., Blair, B.C., Holt, J.A., Bell, M.J., Garside, A.L., 2005. Quantification of the effects of rotation breaks on soil biological properties and their impact on yield decline in sugarcane. Soil Biology and Biochemistry 37, 1121–1130.

Pérez, O., Hernández, F., López, A., l Balañá, P., Solares, E., Maldonado, A., 2008. The use of green manures as an alternative to improve productivity and sustainability of the sugarcane crop. Sugar Journal 70, 14–21.

Pramanee, P., Boontum, A., Lairungreong, C., Thumthong, P., Sruttaporn, C., Thongyai, C., 1997. Soil properties and sugarcane yield improvement by green manuring. Thai Journal of Agricultural Science 30, 219–232.

Probert, M.E., Dimes, J.P., Keating, B.A., Dalal, R.C., Strong, W.M., 1998. APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. Agricultural Systems 56, 1–28.

Rabbinge, R., 1993. The ecological background of food production. Crop protection and sustainable agriculture. In: Ciba Foundation Symposium, vol. 177, John Wiley and Sons, New York USA, pp. 2–23.

Rayment, G.E., Higginson, F.R., 1992. Australian Laboratory Handbook of Soil and Water Chemical Methods. Inkata Press, Melbourne.

Resende, A., 2000. A fixacao biologica de nitrógeno (FBN) como soporte da productividade e fertilidade nitrogenada dos solos da cultura de caña de azucar: uso de adubos verdes. Thesis for Maestrs degree in Soil Science, Universidad de Rio de Janeiro, Brazil, p. 145.

Robertson, M.J., Carberry, P.S., 1998. Simulating growth and development of soybean in APSIM. In: Proceedings of the 10th Australian Soybean Conference, Brisbane, 15–17 September, pp. 130–136.

Robertson, M.J., Carberry, P.S., Huth, N.I., Turpin, J.E., Probert, M.E., Poulton, P.L., Bell, M., Wright, G.C., Yeates, S.J., Brinsmead, R.B., 2002. Simulation of growth and development of diverse legume species in APSIM. Australian Journal of Agricultural Research 53, 429–446.

Robertson, G.P., Paul, E.A., Harwood, R.R., 2009. Greenhouse Gases in Intensive Agriculture: contributions of individual gases to the radiative forcing of the atmosphere. Science 289, 1922–1925.

Robertson, F.A., Thorburn, P.J., 2007a. Decomposition of sugarcane harvest residue in different climatic zones. Australian Journal of Agricultural Research 45, 1–11.

Robertson, F.A., Thorburn, P.J., 2007b. Management of sugarcane harvest residues: consequences for soil carbon and nitrogen. Australian Journal of Soil Research 45, 13–23.

Roebeling, P.C., Bohnet, I., Smith, M., Westcott, D., Kroon, F., Hartcher, M., Hodgen, M., Vleeshouwer, J., 2004. Landscapes Toolkit for triple-bottom-line assessment of land use scenarios in Great Barrier Reef catchments. In: Zerger, A., Argent, R. (Eds.), MODSIM 2005 International Congress on Modelling and Simulation, pp. 711–717, December, 2005.

Roy, R.N., Finck, A., Blair, G.J., Tandon, H.L.S., 2006. Plant nutrition for food security – a guide for integrated nutrient management. FAO Fertilizer and Plant Nutrition Bulletin 16, FAO, Rome.

Sankaranarayanan, K., Praharaj, C.S., Nalayini, P., Bandyopadhyay, K.K., Gopalakrishnan, N., 2010. Legume as companion crop for cotton. Journal of Cotton Research and Development 24, 115–126.

Schroeder, B., Panitz, J., Wood, A., Moody, P., Salter, B., 2007. Soil-specific Nutrient Management Guidelines for Sugarcane Production in the Bundaberg District. BSES Limited Technical Publication TE07004, p. 76.

Schroeder, B., Panitz, J., Wood, A., Moody, P., Salter, B., 2008. Accepting the Adoption of Best-practice Nutrient Management: Wet Tropics. BSES Technical Report. Brisbane.

Shoko, M.D., Tawira, F., 2007. Benefits of soyabeans as a breakcrop in sugarcane production systems in the South Eastern Lowveld of Zimbabwe. Sugar Journal 70, 18–22.

Shoko, M.D., Zhou, M., 2009. Nematode diversity in a soybean–sugarcane production system in a semi-arid region of Zimbabwe. Journal of Entomology and Nematology 1, 25–28.

Smith, D.M., Inman-Bamber, N.G., Thorburn, P.J., 2005. Growth and function of the sugarcane root system. Field Crops Research 92, 169–183.

Stewart, L.K., Charlesworth, P.B., Bristow, K.L., Thorburn, P.J., 2006. Estimating deep drainage and nitrate leaching from the root zone under sugarcane using APSIM-SWIM. Agricultural Water Management 81, 315–334.

Thorburn, P.J., Biggs, J.S., Attard, S.J., Kemei, J., 2009. Environmental impacts of fully irrigated sugarcane production. Agriculture Ecosystems and Environment.

Thorburn, P.J., Dart, I.K., Biggs, I.M., Baillie, C.P., Smith, M.A., Keating, B.A., 2003. The fate of nitrogen applied to sugarcane by trickle irrigation. Irrigation Science 22, 201–209.

Thorburn, P.J., Meier, E.A., Probert, M.E., 2005. Modelling nitrogen dynamics in sugarcane systems: recent advances and applications. Field Crops Research 92, 337–351.

Thorburn, P.J., Probert, M.E., Robertson, F.A., 2001. Modelling decomposition of sugarcane surface residues with APSIM-Residue. Field Crops Research 70, 223–232.

Thorburn, P.J., Webster, A.J., Biggs, I.M., Biggs, J.S., Park, S.E., Spillman, M.F., 2007. Innovative management of nitrogen fertiliser for a sustainable sugar industry. In: Proceedings of the Australian Society of Sugar Cane Technologists, vol. 29, pp. 85–96.

Thorburn, P.J., Webster, A.J., Biggs, J.S., Biggs, I.M., 2010. Meeting global environmental challenges of sugarcane production through an innovative nitrogen fertiliser management system. Plant and Soil.

Yu, K., DeLaune, R.D., Tao, R., Beine, R.L., 2008. Nonpoint source of nutrients and herbicides associated with sugarcane production and its impact on Louisiana coastal water quality. Journal of Environmental Quality 37, 2275–2283.

Webster, A.J., Thorburn, P.J., Roebeling, P.C., Horan, H.L., Bigg, J.S., 2009. The expected impact of climate change on nitrogen losses from wet tropical sugarcane production in the Great Barrier Reef region. Marine and Freshwater Research 60, 1159–1164.

Wiedenfeld, B., Enciso, J., 2008. Sugarcane responses to irrigation and nitrogen in semiarid South Texas. Agronomy Journal 100, 665–671.