Estimating nitrate leaching under a sugarcane crop using APSIM-SWIM.

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Abstract: The Lower Burdekin Delta (LBD) is located on the dry-tropical coastal strip in North Queensland, Australia. The region is Australia's largest sugar producing area with approximately 38,000 hectares of land under sugarcane. However, the LBD also borders the Great Barrier Reef World Heritage Area (GBRWHA). Thus industry, community, and federal, regulatory and environmental organisations are interested in ascertaining the magnitude of nitrate leaching from the root zone and potential implications for the GBRWHA. Direct measurement of nitrate leaching is problematic, thus it is likely that modelling will play an ever-increasing role in guiding experimental work and decision-making. The difficulty in monitoring nitrate leaching also raises concerns with respect to capturing data for the purpose of calibrating and verifying models. However, other crop/soil parameters that directly affect the amount of nitrate leaching are more readily measured (e.g., soil hydraulic properties, matric potential, crop yield, fertilizer application timing, and initial soil N). Thus, parameterising/calibrating a model to such data raises the expectation that associated model outputs related to nitrate leaching will be useful. We used APSIM (Agricultural Production Systems Simulator), with constituent crop-growth, soil-water, and nitrogen transformation modules (Sugar, APSIM-SWIM, Soiln2) to model the 2001/2002 sugarcane ratoon crop at Kalamia, field 48, within the LBD and found the measured and modelled soil water nitrate loads at 1.5 m depth to be of a similar order. This result suggests that the modelled nitrate leaching values are likely to be indicative of the magnitude of nitrate leaching that occurs under field 48. Subsequent sensitivity analyses identified the timing and mode of fertilizer application as key parameters over which management control might be exploited to minimise the flux of nitrate to groundwater.

Keywords: *Modelling; nitrate leaching; groundwater; APSIM; SWIM*

1. INTRODUCTION

The Lower Burdekin Delta (LBD) and Burdekin Haughton Water Supply Scheme (BHWSS) comprise Australia's largest sugar producing region (Fig.1) with 80,000 hectares under sugarcane. Annual sugar cane yields from the combined LBD and BHWSS are of the order of 9M tonnes with an average yield of 117 tonnes per hectare giving 1.5Mt of sugar. Some 80% of Australia's sugar production goes to the domestic market and the remainder is exported. Thus the region is of national significance as an export dollar earner.

The Great Barrier Reef World Heritage Area (GBRWHA) borders this region, and greater industry, community and political emphasis on the environmental sustainability of agricultural enterprises, has increased the focus on quantifying the impacts, and assessing the sustainability, of farming practices within the LBD and BHWSS. Managers of the GBRWHA are particularly interested in the fate of water borne nutrients (e.g. nitrate) lost during farming activities because such contaminants have the potential to affect reef health (Williams, 2001). Such contaminants have the potential to be delivered to the GBRWHA via direct farm runoff, and groundwater discharge, to rivers, with subsequent riverine discharge into the Great Barrier Reef Lagoon, and via 'wonky holes' (Stieglitz and Ridd, 2000); springs on the seabed that express coastal groundwater via subterranean paleochannels. Nitrate/nutrient leaching is also of concern if ground water is used as drinking water, as often occurs within the LBD.

Traditional farming practices within the region typically involve application of significant amounts of nitrogenous fertilizer (~200 kg N/ha per crop). Combined with abundant supplies of irrigation water and annual rainfall (1100 mm/yr) received as large events during a distinct wet season, the potential exists for farm related nitrate flux to rivers via both runoff and deep-drainage to ground water. The issue of quantifying deep drainage water quality and quantity at a site in the LBD is the focus of this study.

Most field-based trials suffer from a mismatch of desired number of measurement sites and available resources to perform monitoring. The strategy we have used is to select measurement sites to represent the major soil types and characterise these to enable simulation modelling. This allows separation of management and biophysical variables. Once verified, this model can be more generally employed to provide estimates of nitrate leaching within the LBD and BHWSS. This study details the development of such a model for Field 48 at Kalamia, within the LBD, and its verification. The model is then used to examine the sensitivity of the modelled nitrate–nitrogen (NO3-N) flux to mode of fertiliser application.

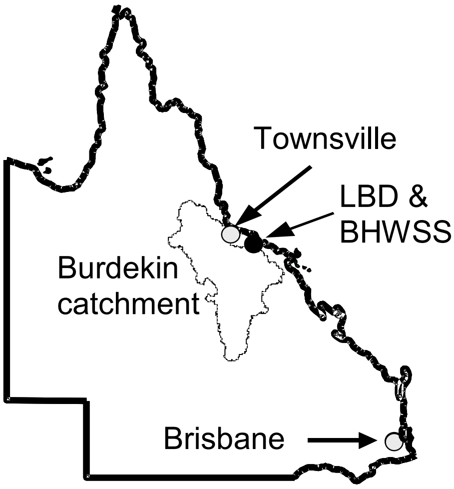

Figure 1. Map of the state of Queensland, Australia, showing the location of the LBD and BHWSS, plus the Burdekin catchment (thin line).

2. MODELLING

2.1. Introduction

Within this study we utilise the Agricultural Production Systems Simulator (APSIM, McCown et al., 1996). APSIM is a modelling framework that allows the coupling of various one-dimensional models from separate research efforts into a single simulation. It is used extensively within Australia to study interactions between plants, soil, water, and nutrients (McCown et al., 1996).

APSIM was configured with the following process related modules; *Sugar* – sugar cane growth module; *SoilN2* – soil carbon and nitrogen dynamics; *Irrigate* – irrigation scheduling; *Residue2* – surface residues, *Met* – meteorological information; *Fertiliz* – fertilizer; and *Apswim* – soil water and solute balance. There is a choice between two soil water balance modules; *Soilwat* (Probert et al., 1997), a 'tipping bucket' model and *Apsim-SWIM (Apswim)* that is based on numerical solution of the Richards and advection-dispersion equations. *Apswim* is derived from, the Soil Water Infiltration and Movement model (SWIM, Verburg et al., 1996). *Apswim* is used here as it provides greater scope for evaluating the effects of soil condition, weather, and management on infiltration and crop growth (Connolly et al., 2002).

2.2. Modelling strategy

The Kalamia farming system model described here was calibrated to field data collected over the 2000/2001 growing season. It was then employed to model the 2001/2002 season, and its predictive ability, particularly with respect to the water balance, evaluated.

Water balance is given by

$$ET + Ro + Dr = I + Ra + \Delta S \qquad (1)$$

where ET is evapotranspiration, Ro is runoff, Dr is net deep drainage (i.e., outflow less inflow), I is irrigation, Ra is Rainfall and ΔS is the change in storage.

Irrigation and rainfall are provided as input to the model. Runoff was calibrated to observation, leaving the Dr and ET as model output. To enhance the accuracy of any modelled drainage the model was also calibrated to measurements of matric potential at 20 and 50 cm depth.

The model output also includes soil water nitrate concentrations and, though uncalibrated, these should be useful for the purposes of investigating the relative effects of management actions on nitrate leaching. As such, we investigate the sensitivity of nitrate flux from the root zone to the mode of fertiliser application.

2.3. Parameterisation and Calibration

The general parameterisation strategy was to derive model parameters directly or indirectly from field data collected at Kalamia. Where measurements were not available, published data, or expert knowledge was employed.

Discretisation

Apswim was configured with 55 nodes discretising 0 to 2.5 m depth of soil profile, with nodes lying on all soil boundaries. The lower boundary is represented by a water table.

Soils

To 2.5 m depth, the Kalamia soil-profile comprises five horizons, grading from highly structured silty clay (0-0.35m) to medium clay (0.35-0.65m) to coarse sand below 1 m depth. The soils were monitored for water content and matric potential at depths of 0.2, 0.5 and, 1.5 m using TDR and Campbell 229 Matric Potential sensors.

Weather

Weather records were collected at Kalamia Mill some 3 km from the field site. Therefore, it is possible that recorded rainfall may differ from that at the site in the weather file.

Measured Evapotranspiration (ET)

ET was calculated, from the weather data, using potential ET (FAO method) and crop factors according to Inman-Bamber and McGlinchey (2003).

Measured Solute Flux

Leachate was collected in the field for each irrigation event using Teflon suction samplers inserted 1.5m beneath the crop (Klok et al., 2003). Leachate NO_3-N concentration (mg/L)) was then combined with estimated deep drainage (ML) to give a seasonal NO_3-N loading (kg/ML).

Soil hydraulic properties

Soil hydraulic properties were obtained via field and laboratory studies (Table 1). It was necessary to calibrate the value of the derived Brooks-Corey (1964) parameter, λ, for horizon 2 to reproduce the relatively lower matric potentials observed at 20 cm depth compared to 0.5 m.

Table 1. Brooks-Corey parameters (α, λ, θ_r, θ_s) and saturated hydraulic conductivity, K_s, for the 5 soils. Where α is -1/air-entry-value, λ is pore size distribution parameter, and θ_r and θ_s are residual and saturated water contents, respectively.

	K_s (cm/h)	α (1/cm)	λ	θ_r	θ_s
Soil1 ZC	0.055	0.021	0.19	0.21	0.42
Soil 2 MC	0.508	0.027	0.8$^+$	0.27	0.43
Soil 3 ZLC	1.15$^\#$	0.027	1.11$^\#$	0.21	0.37
Soil 4 FS	6*	0.031	1.59	0.07	0.39
Soil 5 KS	21*	0.043	2.1	0.04	0.41
* Book value # Interpolated + Calibrated					

Matric potential

Apswim was calibrated to reflect the matric potential, ψ, observed at depths of 0.2 m (ψ_{20}) and 0.5 m (ψ_{50}) (Fig. 2) during the 2000/2001 season. Modelled matric potential at depths of 0.2 and 0.5 m can be influenced by manipulation of soil parameters such as hydraulic conductivity and λ. However, the parameter that exerts significant control over matric potential at these depths is that of the root exploration factor within the coarse sand layer of the soil profile. By controlling the rate at which roots can advance through this layer toward the capillary fringe, the amount of extraction from the upper layers, and thus matric potential, can be influenced. Modifying the root exploration factor for the coarse sand layer is justified, as during placement of instrumentation it was observed that most root mass is confined to the clay layers (see also Nable et al. 1998).

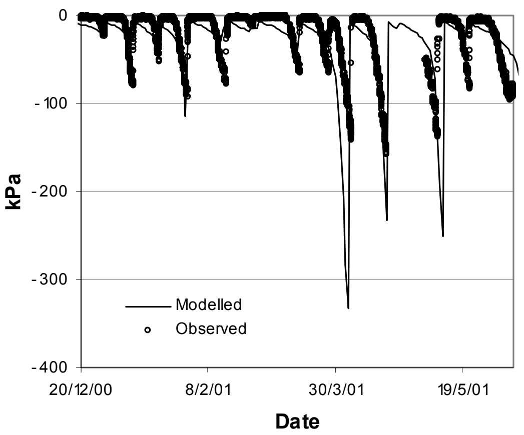

Figure 2. Modelled vs observed ψ_{50} (calibration) for the 2000/2001 season.

Irrigation

Irrigation water, pumped from ground water, has a background concentration of 2 mg/L NO_3-N. The periods, and times of irrigation were recorded at the field site over the course of each growing season. All such data served as input to the model.

Runoff

The runoff equation used in *Apswim* is given by

$$R=\begin{cases}0, & h\le h_0\\ 3600\frac{1}{nL_0}(h-h_0)^2\sqrt{s}, & h>h_0\end{cases} \qquad (2)$$

where L_0 is the slope length, n is Manning's roughness coefficient, s is slope gradient, $h-h_0$ is runoff depth that depends on surface storage parameters. Estimated values of n, L_0, and s were employed and runoff was calibrated through modification of the surface storage parameters. An iterative process was involved in balancing the effects of runoff calibration and matric potential calibration (via the root exploration factor); as each affects the other.

Roots

Obtaining an initial root length density (RLD) proved problematic. Nable et al (1998) conducted a comprehensive analysis of root length densities at another site at Kalamia. However, the clay

return to menu

profile at that site was 0.5m thick compared to the approximately 1 m at our field site. Thus, that data could not readily be adapted to our needs. The data of Ball-Coelho et al. (1992) were not considered appropriate due to different cultivar and soil types.

We chose to obtain initial RLD distributions by modelling a plant crop under the 2000/2001-parameterisation regime. However, such an initial root length density distribution was unsuccessful. Such a distribution allowed the modelled ratoon crops to immediately access water from the capillary fringe, and meant that matric potentials in the clay layers were not drawn down to observed levels.

At harvest, APSIM uniformly decreases root length densities by 17% at all depths, in line with the observations presented by Ball-Coelho et al. (1992). However, within the literature, estimates of root dieback after harvest range as high as 100% (e.g., Clements, 1980). Ball-Coelho et al. (1992) raise the possibility that such discrepancies may be due to variation between cultivars. This potential variation combined with the other factors detailed above led us to simulate dieback of roots below 1.2 m depth (i.e., in the coarse sand layer) after harvest. Given the scope of the possibilities for an initial RLD distribution this ‘calibration’ does not seem unreasonable.

Crop growth

The sugar module was parameterised to model a ratoon sugarcane crop (cultivar Q96) at Kalamia. No calibration to actual crop yield was required.

3. RESULTS

3.1. Cropping

APSIM accurately represented crop yield. The actual yield for the 2001/2002 season was 129 t/ha and the modelled yield 131 t/ha. Evapotranspiration (ET) was overestimated by APSIM (Fig. 3) with total modelled ET exceeding that measured by 73 mm (5%).

3.2. Matric potential

Due to instrument failure field observations of matric potential data at 0.5 m depth were only recorded for a portion of the growing season. In that period the observed pattern of wetting and drying at 0.5 m depth is well represented by the model (Fig. 4). However, modelled matric potential is generally higher than observed.

3.3. Water Balance

Water balances, generated from observed data and modelling are displayed in Table 2. The net drainage (*Dr*) for observed data is calculated via Eqn 1. In general, there is good agreement between the observed and modelled data. The difference between observed and modelled net drainage is offset, approximately, by the difference in crop *ET*.

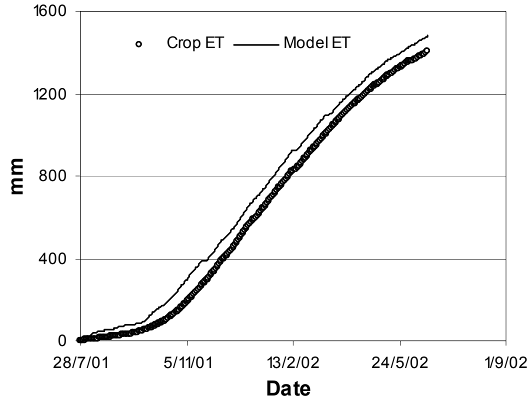

Figure 3. Modelled versus actual ET for ratoon 3.

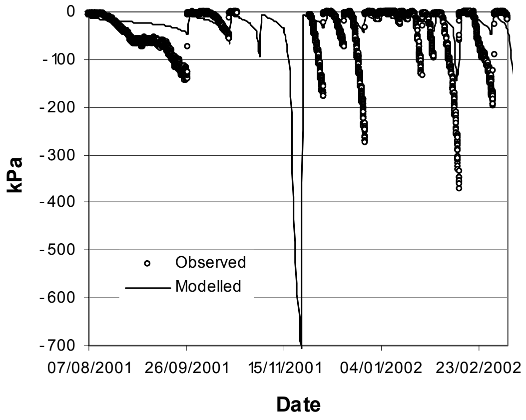

Figure 4. Modelled vs observed ψ at 0.5 m.

While net drainages are represented in Table 2, APSIM allows the calculation on a daily basis of drainage from, and up flow into, the soil profile. Analysis of this data suggests that distinct periods of drainage and inflow occur. Drainage occurs in the period from planting up until about the end of February, due to low *ET* and abundant rainfall (Fig. 5). During this period modelled drainage at 2.5 m is 94 mm. The corresponding drainage through 1.5 m for the same period is 99 mm.

Between March and harvest, rainfall becomes infrequent and cane roots access the capillary fringe of the ground water table. Consequently, the model simulates upward flow (149 mm) to replace crop uptake and maintain the capillary fringe.

Table 2. Observed and modelled water balance components (mm). The right-hand column shows the differences between model and observation.

	Observed	Modelled	Mod.-Obs.
ET	1409	1482	73
Ra	693	693	0
I	1275	1275	0
Dr	18	-54	-72
Ro	541	550	9
Δs	0*	-10	-10
* ΔS assumed 0 in observed case			

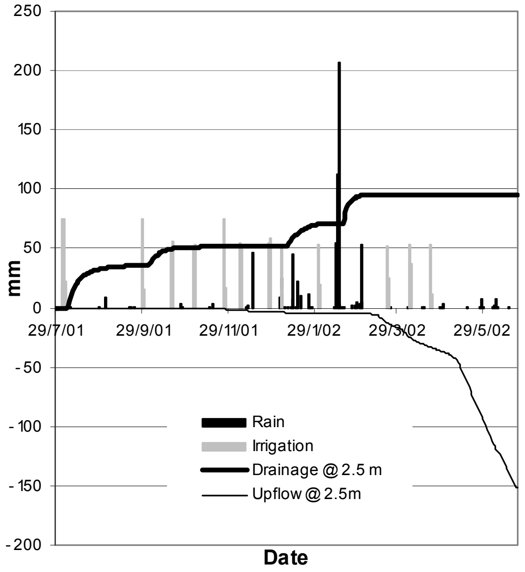

Figure 5. Rainfall, irrigation, drainage at 2.5 m depth, and up-flow through 2.5 m depth. The drainage and up-flow phases are quite distinct.

Solute transport.

Although uncalibrated, normalised modelled soil water nitrate concentrations at 1.5 m depth are of the same order as observations (see Fig. 6). Modelled NO_3-N flux through the 1.5 m depth level is 31.9 kg/ha, all of which occurs during the previously detailed drainage phase. Because drainage at 2.5 m is similar to that at 1.5 m a similar nitrate load will move to and mix with the ground water and its capillary fringe.

The crop accesses capillary fringe water in the latter half of the growing season. Root uptake of NO_3-N below 1.5 m, available as *Apswim* output, is 26.9 kg/ha. Subtracting this value from N flux through 1.5 m gives a net downward movement of 5 kg/ha NO_3-N to ground water and the capillary fringe (Table 3).

For the purposes of sensitivity analysis we examined the influence upon the amount of nitrate leached to ground and capillary fringe waters of three different modes of fertilizer application:

1. Current practice – A single application of 200 kg/ha fertilizer at planting.
2. Split application – One third (66 kg/ha) at plant and two thirds (134 kg/ha) four weeks later for a total of 200 kg/ha.
3. No applied fertilizer – Background concentration of NO_3-N in irrigation water is 2 ppm. This equates to the application of 18 kg/ha NO_3-N over the growing season.

Results and crop yields are displayed in Table 3.

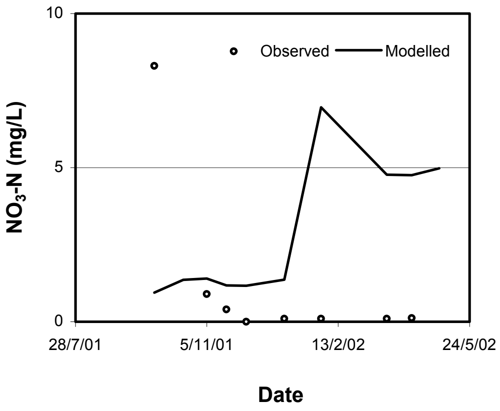

Figure 6. Solute nitrate concentration at 1.5 m.

Table 3. Modelled N flux through 1.5 m depth, plant N uptake below 1.5 m, net N loss to deep drainage, and yield.

	N flux (kg/ha)	N Uptake (kg/ha)	N Loss (kg/ha)	Yield (t/ha)
Normal	31.9	26.9	5	131.6
Split	31.5	26.7	4.8	131.6
None	3.1	5.5	-2.4	132.5

4. DISCUSSION

In general, the model represents the observed farming system and water balance reasonably well. The two discrepancies of interest are the overestimation of both the soil matric potential at 50 cm and ET.

The discrepancy in matric potential may be due to non-optimal parameterisation of the soils. If the hydraulic conductivity of the upper layers is too low, then they will drain more slowly and ψ_{50} will appear overestimated. As a result, more water would be available to roots over time thus reducing potential, water-related stress and possibly resulting in an overestimation of ET.

Notwithstanding any potential difference due to non-optimal parameterisation of the soils, ET lies within 10% of observed and is considered a good result. The divergence of modelled and measured ET primarily occurs early in the cropping season, during the period of drainage to ground water. Thus, modelled drainage may be underestimated by up to 73 mm (42 %), similar to the result observed in Table 2.

If we consider the drainage through 1.5 m depth to be underestimated, then so too will be the modelled NO_3-N flux. At present, the modelling indicates a flux of 31.9 kg/ha corresponding to drainage of 99 mm. A crude estimation of the NO_3-N flux with an additional 73 mm of drainage, based on increasing the modelled NO_3-N flux by the same proportion as drainage, suggests that NO_3-N flux through 1.5 m could be as high as 56 kg/ha. Allowing for the removal of 26.9 kg/ha by crop roots, then between 5 kg/ha and 28.7 kg/ha of NO_3-N may move to ground water. Calculation of an observed NO_3-N flux using net drainage and nitrate concentration data at 1.5 m suggests a loss of 7.5 kg/ha. However, this figure probably underestimates the actual flux because upflow is likely to have occurred.

The results of the sensitivity analysis (Table 3) indicate that split application of fertiliser is likely to have little impact upon the amount of nitrate lost to ground water.

The results also suggest that it should be possible to grow a sugar cane crop for at least one season without the need for added fertilizer. Such practice may have a remedial effect upon ground water nitrate concentrations, as 2.4 kg/ha more of NO_3-N was extracted from below 1.5 m depth than entered via drainage.

The identified periods of drainage and up-flow indicate that potential exists in the investigation of both the timing and mode of fertilizer application to reduce NO_3-N flux to ground water. In addition, future work should investigate the potential of other modes of fertilizer application (e.g., fertigation), and management strategies.

5. ACKNOWLEDGMENTS

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