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# Australian Journal of Agricultural Research

Volume 49, 1998


A journal for the publication of original contributions towards the understanding of an agricultural system

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Academy of Science

*Aust. J. Agric. Res.*, 1998, **49**, 363–77

# Use of the APSIM wheat model to predict yield, drainage, and $NO_3^-$ leaching for a deep sand

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*Abstract*. High rates of drainage and leaching of nitrates in deep sands in Western Australia are contributing to groundwater recharge and soil acidification in this region. Strategies are being sought to increase water and nitrogen (N) use in the legume-based cropping systems. Choice of appropriate management strategies is complicated by the diversity of soil types, the range of crops, and the inherent season to season variability. Simulation models provide the means to extrapolate beyond the bounds of experimental data if accurate predictions of key processes can be demonstrated. This paper evaluates the accuracy of predictions of soil water content, evapotranspiration, drainage, inorganic N content in soil, nitrate ($NO_3^-$) leaching, wheat growth, N uptake, and grain yields obtained from the Agricultural Production Systems Simulator (APSIM) model when this was initialised with appropriate information on soil properties and wheat varieties commonly grown on deep sands in the 500 mm rainfall zone west of Moora in Western Australia. The model was found to give good predictions of soil water content, evapotranspiration, deep drainage, and overall $NO_3^-$ leaching. Temporal changes in inorganic N in soil were simulated, although the small concentrations in soil inorganic N precluded close matching of paired observed and predicted values. Crop growth and N uptake were closely predicted up to anthesis, but a poor fit between observed and predicted crop growth and N uptake was noted post anthesis. Reasons for the discrepancies between modelled and observed values are outlined.

The model was run with historical weather data (81 years) and different initial soil water and inorganic soil N profiles to assess the probability of drainage and $NO_3^-$ leaching, and the grain yield potentials for wheat grown on deep sands in the region west of Moora. Simulation showed that the soil water and the soil inorganic N content at the beginning of each season had no effect on grain yield, implying that pre-seed soil $NO_3^-$ was largely lost from the soil by leaching. There was a 50% probability that 141 mm of winter rainfall could drain below $1\cdot5$ m and a 50% probability that 53 kg N/ha could be leached under wheat following a lupin crop, where initial soil water contents and soil $NO_3^-$ contents used in the model were those measured in a deep sand after late March rainfall. Simulated application of N fertiliser at sowing increased both grain yield and $NO_3^-$ leaching. Splitting the N application between the time of sowing and 40 days after sowing decreased $NO_3^-$ leaching, increased N uptake by wheat, and increased grain yield, findings which are consistent with agronomic practice.

The high drainage and leaching potential of these soils were identified as the main reasons why predicted yields did not approach the French and Schultz potential yield estimates based on 20 kg grain yield per mm of rainfall. When the available water was reduced by simulated drainage, simulated grain yields for the fertilised treatments approached the potential yield line.

*Additional keywords:* inorganic N, mineralisation, soil water, lupin–wheat rotations.

 10.1071/AR97095 0004-9409/98/030363$05.00

## Introduction

Higher efficiencies of utilisation of water and nutrient resources are being sought by the grains industry worldwide to improve profitability, and to stall processes which threaten the sustainability of agricultural production systems. In Western Australia, the poor utilisation of growing season rainfall is causing water tables to rise, and salinisation (George *et al.* 1997). The leaching of nutrients in drainage water is thought to be the major contributor to soil acidification (Dolling and Porter 1994; Dolling *et al.* 1994; Dolling 1995). Research is in progress across Australia to determine how crop and soil management can be adjusted to improve the efficiency of utilisation of water and nutrients (Anon. 1996; Anderson *et al.* 1998*a*, 1998*b*). Field-based research is site- and season-specific, and effects may change from year to year depending on the distribution of rainfall. Extrapolation of findings is further complicated by the diversity of soil and crops, and the lack of information on the interactions between crop, soil, and climate variability as they affect drainage and nutrient use. Techniques are needed to extrapolate findings to a wider range of soil types and climates, and to examine the long-term consequences of agricultural practices on water and nutrient use.

Crop models, with appropriate routines to handle soil water and nutrient availability, may assist the extrapolation of research findings across soil types and climatic regions. However, acceptance of outcomes from simulation studies depends on the confidence in the accuracy of models used to predict crop growth, water and nutrient use, drainage, and leaching. Keating *et al.* (1991) used a simulation model to investigate the factors influencing yield response to timing of nitrogen (N) application in a maize production system. Model performance was checked by comparing model output against field measurements. Simulation experimentation provided an assessment of the long-term average effects of these factors, as well as the probabilistic information needed to assess variability in response to management. Other examples of the use of crop models to optimise management practices under variable environments are given by Van Keulen and Seligman (1987), Stapper and Harris (1989), Fischer *et al.* (1990), Meinke *et al.* (1993), Savin *et al.* (1995), and Thornton *et al.* (1995).

The Agricultural Production Systems Simulator (APSIM) is the most advanced cropping system used in Australia to study interactions between plant growth, soil water, N, and residues (McCown *et al.* 1996). The APSIM wheat model (Probert *et al.* 1995, 1998; Keating *et al.* 1997) has been tested against field observations (Asseng *et al.* 1995; Keating *et al.* 1995, 1997; Probert *et al.* 1995, 1996, 1998; Meinke *et al.* 1997), and it has been used to study yields and drainage, in wheat–sorghum rotations (Keating *et al.* 1995), to investigate yields, drainage, and soil N in a long-term fallow experiment (Probert *et al.* 1995; Turpin *et al.* 1996), and to analyse the dynamics of water and N in fallow systems (Probert *et al.* 1998).

The aims of this paper are: (*i*) to evaluate the performance of the APSIM wheat model by comparing model output with detailed field measurements of wheat crops grown on a deep sandy soil which supports at least 25% of the Western Australian wheatbelt; and (*ii*) using historic climate data, to establish the probability of grain yield, with and without fertiliser N, and the probability of drainage and $NO_3^-$ leaching in deep sands in relation to soil profile water and inorganic N contents at the break of season. The model is applied to explain the low water use efficiency in wheat production on deep sands.

## Materials and methods

### *APSIM wheat model*

The APSIM wheat model consists of wheat, soil water, N, and residue modules linked within APSIM (McCown *et al.* 1996). Wheat, soil N, and soil water modules (Probert *et al.* 1995, 1998; Keating *et al.* 1997) were derived from the CERES models of Ritchie *et al.* (1985) and Jones and Kiniry (1986), which had been widely tested and applied in several studies (Ritchie 1985; Otter-Nacke *et al.* 1986; Toure *et al.* 1994; Savin *et al.* 1995; Thornton *et al.* 1995).

### *Evaluation of the APSIM wheat model for a deep sand in Western Australia*

The model was evaluated using data on soil water, soil N transformations, and wheat growth which were collected in experiments conducted 14 km west of Moora, Western Australia (annual average rainfall 459 mm; range 203–790 mm). The soil was a deep yellow sand Uc5·22 (Northcote *et al.* 1975) with some non-wetting characteristics at the surface, and soil compaction and soil acidity at a depth of 15–30 cm.

A detailed description of the treatments, experimental design, and measurements undertaken is outlined by Anderson *et al.* (1998*a*, 1998*b*). In brief, frequent measurements of crop growth, soil water, and soil N were carried out in wheat crops growing in 1994 after wheat, and in 1995 after lupin, for the zero N (N0) fertiliser treatments. Fewer measurements were undertaken on crops which received 50 kg N/ha (N50) of fertiliser N in 1994 and 90 kg (N90) N/ha in 1995. Crops in the previous year were harvested for grain and the stubble was grazed by sheep. The quantities of plant residue used to initialise the model are shown in Table 1.

Evapotranspiration was measured in 1995 in an adjacent wheat crop (fertilised with 55 kg N/ha) using a Bowen ratio technique (Dunin *et al.* 1989). Soil profile water contents at 10–150 cm depth were measured every 30 min using time domain reflectrometry (Anderson *et al.* 1998*b*). Soil water content in each layer was interpolated by averaging measured values for depths above and below each layer. Soil was sampled by depth at different times of the growing season and extracted for inorganic N (Anderson *et al.* 1998*a*). Soil

**Table 1. Quantities of plant residue (t/ha), the C : N ratio of residues, and the rate of potential decomposition of residue per day used to initialise the model for 1994 (wheat) and 1995 (lupin) growing seasons**

Data are based on 1996 measurements for wheat and lupin residues

| Residue type | 1994 | 1995 |
|---|---|---|
| Above-ground | | |
| Amount (t/ha) | 2·5 | 4·5 |
| C : N ratio | 70 | 25 |
| Decomposition rate (1/day) | 0·05 | 0·1 |
| Root residues | | |
| Amount (t/ha) | 1·5 | 1·5 |
| C : N | 40 | 20 |

**Table 2. Bulk density (BD), lower limit of plant-available water (LL), drained upper limit of water (DUL), organic carbon (OC), fraction of active soil organic material as microbial biomass (fbiom), and fraction of inert organic matter (finert) recorded at various soil depths which were used to initiate the APSIM model for deep sand**

| Depth (cm) | BD (g/cm$^3$) | LL (v/v) | DUL (v/v) | OC (%) | fbiom | finert |
|---|---|---|---|---|---|---|
| 0–5 | 1·58 | 0·03 | 0·18 | 0·90 | 0·04 | 0·1 |
| 5–10 | 1·68 | 0·03 | 0·13 | 0·90 | 0·04 | 0·1 |
| 10–20 | 1·67 | 0·06 | 0·12 | 0·39 | 0·03 | 0·1 |
| 20–30 | 1·78 | 0·06 | 0·11 | 0·10 | 0·02 | 0·2 |
| 30–50 | 1·85 | 0·06 | 0·10 | 0·01 | 0·01 | 0·8 |
| 50–70 | 1·80 | 0·07 | 0·10 | 0·01 | 0·01 | 0·9 |
| 70–90 | 1·80 | 0·08 | 0·10 | 0·01 | 0·01 | 0·9 |
| 90–120 | 1·80 | 0·09 | 0·11 | 0·01 | 0·01 | 0·9 |
| 120–150 | 1·80 | 0·11 | 0·12 | 0·01 | 0·01 | 0·9 |
| Total (mm) | | 117 | 167·5 | | | |

**Table 3. Concentrations (mg N/kg) of ammonium ($NH_4^+$) and nitrate ($NO_3^-$), and total inorganic nitrogen (TIN, kg N/ha) recorded at various soil depths (cm) which were used to initialise the APSIM for the 1994 and 1995 growing seasons at Moora**

| Depth | 1994[A] | | | 1995[B] | | |
|---|---|---|---|---|---|---|
| | $NH_4^+$ | $NO_3^-$ | TIN | $NH_4^+$ | $NO_3^-$ | TIN |
| 0–5 | 2·4 | 5·5 | 6·2 | 1·0 | 7·6 | 6·8 |
| 5–10 | 1·6 | 7·5 | 7·6 | 1·0 | 5·7 | 5·6 |
| 10–20 | 0·9 | 7·2 | 13·5 | 0·5 | 4·0 | 7·5 |
| 20–30 | 0·3 | 3·6 | 7·0 | 0·4 | 2·4 | 5·0 |
| 30–50 | 0·3 | 2·7 | 11·2 | 0·3 | 1·6 | 7·0 |
| 50–70 | 0·1 | 0·6 | 2·8 | 0·3 | 1·1 | 5·0 |
| 70–90 | 0·1 | 0·7 | 2·7 | 0·2 | 1·3 | 5·4 |
| 90–120 | 0·1 | 0·4 | 2·8 | 0·1 | 1·5 | 8·6 |
| 120–150 | 0·2 | 0·0 | 0·9 | 0·2 | 1·7 | 10·3 |
| Total | | | 54·7 | | | 61·3 |

[A]Measured on 30 May 1994.
[B]Measured on 18 May 1995.

solutions were collected, *in situ*, using ceramic suction cup samplers and analysed for $NO_3^-$ (Anderson *et al.* 1998*b*). The profile soil water and soil inorganic N contents used to initialise the model for the comparison with field data are shown in Tables 2 and 3.

Wheat (var. Spear) was sown on 31 May 1994 [day of year (DOY) 151], at a depth of 3 cm, and at a row spacing of 18 cm (115 plants/m$^2$). The early break to the season in 1995 enabled wheat (var. Dagger) to be sown on 11 May (DOY 131). In this case, wheat was sown at a depth of 2 cm with a row spacing of 18 cm. Seedling establishment was similar to that recorded for 1994. Rainfall in 1994 from April to October was 238 mm (<2% probability to be below this rainfall amount based on rainfall from 1910 to 1990) and rainfall during the same period in 1995 was 522 mm (7% probability to be above this rainfall amount based on rainfall in the period from 1910 to 1990). Average rainfall for the period from April to October is 389 mm.

All simulations were compared with the mean of replicated measurements and s.e.m., when available, was used to show the variability of the measurements.

*Parameter changes to the model*

Preliminary comparisons between simulated and measured N mineralisation rates in the top layer of soil (depth 0–20 cm) at Moora in 1995 highlighted that mineralisation parameters supplied with the APSIM model, which were derived from N mineralisation studies in a Vertisol at Warra in south-east Queensland and Alfisols at Katherine in the Northern Territory (Probert *et al.* 1998), substantially underestimated mineralisation in the sand. Rates of mineralisation of N, expressed in terms of microbial biomass, have been shown to be higher in sandy soils than fine-textured soils (Van Veen *et al.* 1985; Ladd *et al.* 1992; Hassink *et al.* 1993; Hassink 1994*a*, 1994*b*) partly due to the higher physical protection of organic components in clay soils compared with sands (Hassink and Whitmore 1997). On average, carbon (C) and N mineralisation rates per microbial biomass are 2–3-fold higher in sandy soils than clay soils and N mineralisation rates can be up to 7 times higher in sand than a loam (Hassink 1994*a*). Daily potential decomposition rates for the soil biomass pool were set at 3·24%, compared to a value of 0·81% used by Probert *et al.* (1998) to account for the higher rates of N mineralisation per unit of microbial biomass.

Recent studies in Western Australia have shown that N mineralisation in sandy soil can occur at soil water potential lower than −1500 kPa (D. V. Murphy pers. comm.). In order to account for this, mineralisation and nitrification were set at 5% of their potential rate at the lower limit for plant-available water. Mineralisation and nitrification were set at 100% of the potential rate when soil water content was equivalent to at least 30% of plant available water. Mineralisation and nitrification routines used in the APSIM model are described in detail by Probert *et al.* (1998).

*Weather data, 1994 and 1995*

Solar radiation, maximum and minimum temperatures, and rainfall were recorded using an automatic meteorological station adjacent to the experiment. Malfunction of this equipment between July and October 1994 resulted in data being collected on only 45 days in this period. These gaps in the weather files were corrected as follows. Lost daily rainfall was estimated from a manually operated rainfall gauge, located at the experimental site. This rain gauge was emptied infrequently, and rainfall

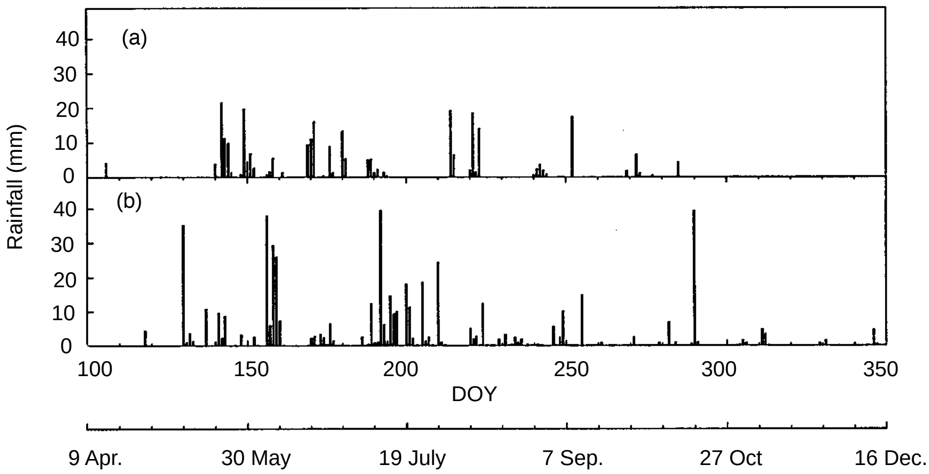


**Fig. 1.** Rainfall distribution for Moora, Western Australia, in (*a*) 1994 and (*b*) 1995. DOY, day of year.

events in Moora town (Bureau of Meteorology, 10 km north-east of the Moora field site) were used to distribute rainfall for the periods in question. Lost temperature data were calculated with regression functions established between records at the Moora site and Moora township. Comparisons between calculated and measured temperature showed a good correlation [$r^2(1:1) = 0{\cdot}86$ ($T_{max}$), $r^2(1:1) = 0{\cdot}75$ ($T_{min}$)]. Lost radiation data were calculated from extraterrestrial solar radiation, and rainfall days using procedures of Bristow and Campbell (1984). Radiation was computed for the 2 years of the experiment and measured data were compared with calculated values to check the accuracy of the procedures [$r^2(1:1) = 0{\cdot}86$]. Rainfall distributions for 1994 and 1995 from April to November are shown in Fig. 1.

*Long-term simulation experiments*

*Simulation experiment: initial soil profiles*

The soil water characteristics for the long-term simulation experiments were the same as those for the 1994 and 1995 simulations (Table 2). Initial soil water and inorganic soil N profiles are shown in Table 4. Four combinations of inorganic N and soil water were used during each season simulation: (*A*) 'low inorganic soil N' and 'low soil water'; (*B*) 'high inorganic soil N' and 'low soil water'; (*C*) 'low inorganic soil N' and 'high soil water'; and (*D*) 'high inorganic soil N' and 'high soil water' content. High soil water contents were based on measurements made on 12 April 1995, after lupin, and the low soil water contents are the lower limit of plant-available soil water. Concentrations of $NH_4^+$ and $NO_3^-$ in soil below a depth of 20 cm in the high N treatments were based on measurements made at Moora on 27 November 1995 ($NH_4^+$) and 5 January 1996 ($NO_3^-$) after lupin. Concentrations of $NH_4^+$ and $NO_3^-$ in the top layer of soil (depth, 0–20 cm) were estimated. The inorganic N concentrations in this top layer of soil, used in the 'low inorganic soil N' treatments, were measured on 12 April 1995, after lupin. Concentrations for soil layers at a depth of 20–150 cm were set to 0·1 mg N/kg to simulate low summer N mineralisation. A possible reduction of residue N due to summer rainfall was not considered in the initial 'high soil water' and 'high inorganic soil N' combinations.

Residue parameters used to initialise the model during the simulation experiments were the same as those used in the 1995 simulation after a lupin crop (Table 1). Sowing time was

**Table 4. Soil parameters for simulation experiments for initial 'high' and 'low' water and N content in the soil profile: concentrations (mg N/kg) of ammonium ($NH_4^+$) and nitrate ($NO_3^-$), total inorganic nitrogen (TIN, kg N/ha), and soil water content (v/v) at various soil depths (cm)**

| Depth | 'High' water and N content | | | | 'Low' water and N content | | | |
|---|---|---|---|---|---|---|---|---|
| | Water | $NH_4^+$ | $NO_3^-$ | TIN | Water | $NH_4^+$ | $NO_3^-$ | TIN |
| 0–5 | 0·03 | 7·5 | 22·3 | 23·5 | 0·03 | 6·0 | 8·0 | 11·1 |
| 5–10 | 0·03 | 3·9 | 15·3 | 16·1 | 0·03 | 2·0 | 5·0 | 5·9 |
| 10–20 | 0·08 | 2·4 | 6·5 | 14·9 | 0·06 | 0·1 | 4·0 | 6·8 |
| 20–30 | 0·08 | 0·3 | 3·3 | 6·4 | 0·06 | 0·1 | 0·1 | 0·4 |
| 30–50 | 0·10 | 0·6 | 2·2 | 10·4 | 0·06 | 0·1 | 0·1 | 0·7 |
| 50–70 | 0·10 | 0·3 | 1·7 | 7·2 | 0·07 | 0·1 | 0·1 | 0·7 |
| 70–90 | 0·10 | 0·2 | 0·9 | 4·0 | 0·08 | 0·1 | 0·1 | 0·7 |
| 90–120 | 0·11 | 0·2 | 0·7 | 4·9 | 0·09 | 0·1 | 0·1 | 1·1 |
| 120–150 | 0·12 | 0·2 | 0·2 | 2·2 | 0·11 | 0·1 | 0·1 | 1·1 |
| Total | 146 mm | | | 89·5 | 117 mm | | | 28·5 |

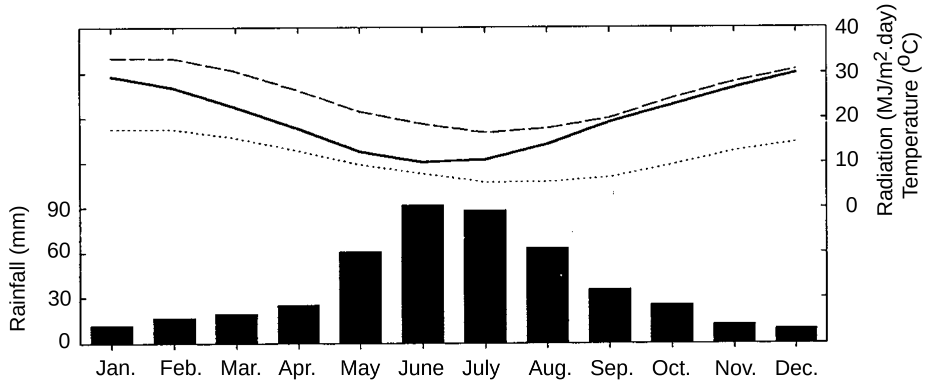


**Fig. 2.** Average monthly solar radiation (——), maximum (– – – –) and minimum (......) temperatures, and rainfall (bars) for Moora, Western Australia.

set between 1 May (DOY 121) and 30 June (DOY 181), but did not occur before at least 25 mm of rain fell within 10 days. Soil water in the layer at a depth of 5–10 cm also had to exceed 50% of available soil water holding capacity. The variety Dagger (late maturing) was sown in May, otherwise the variety Kulin (early maturing) was used. Sowing depth was set to 2 cm and plant density to 100 plants/m$^2$. Each simulation run commenced on 15 April (DOY 105). Accumulation of drainage and $NO_3^-$ leaching below a soil depth of 150 cm commenced on this day. Water was assumed to infiltrate uniformly through the soil profile thus avoiding the complication of preferential soil water flow induced by water repellency in surface soil. The only variables between simulation runs were the initial profile inorganic N and soil water contents, described above, and weather based on historic weather records. The model was reset to initial soil and crop parameters after each simulation.

*Simulation experiment: management of N fertiliser*

The probability, based on historic weather data, of an increase in grain yield and leaching of $NO_3^-$ with the application of urea fertiliser was determined with the model. The 'low inorganic soil N' and 'high soil water' profile (profile C) was used to initialise the model. Urea (50 kg N/ha) was applied as a single application at sowing; alternatively, half was applied at the time of sowing and the other half 40 days after sowing.

*Source of long-term weather data*

Long-term weather data (1910–1990) were supplied by the Agricultural Production Systems Research Unit (APSRU) and included measured daily rainfall (81 years) and maximum and minimum temperature data (about 30 years) from the town of Moora (Bureau of Meteorology). Maximum and minimum temperatures that were not available from the Bureau of Meteorology and all radiation data were calculated by APSRU as described by Meinke *et al.* (1995). The 81-year monthly average for solar radiation, maximum and minimum temperatures, and rainfall are shown in Fig. 2.

## Results

### *Evaluation of the model*

#### *Season 1994*

Observed and simulated yields for the N0 and N50 treatments in 1994 are shown in Table 5. The observed N response was reproduced with the model, but yields and grain N were underestimated in both treatments (Table 5).

The measured and simulated soil $NH_4^+$ and $NO_3^-$ concentrations for the N0 treatment in 1994 are shown in Fig. 3 and Fig. 4*a*,*b*. The simulated $NH_4^+$ concentrations in the soil layer at a depth of 0–10 cm were consistently lower than the observed values by about 1–2 mg N/kg. Only small changes in inorganic N content occurred in deeper layers, a feature which was predicted by the model. Changes in $NO_3^-$ concentrations in individual soil layers were well predicted. The predicted value for $NO_3^-$ leached at 1 m was similar to the measured quantity (Table 5).

**Table 5. Model performance for grain yield (t/ha), specific grain weight (mg), grain number/m$^2$ grain N (kg N/ha), and nitrate ($NO_3^-$) leached (kg N/ha) on a deep sandy soil at Moora, Western Australia**

N0, 0 kg N/ha; N50, 50 kg N/ha; N90, 90 kg N/ha
Values in parentheses are s.e.m.

| Treatment | Attribute | Observed | Predicted |
|---|---|---|---|
| | *1994* | | |
| N0 | Yield | 1·6 (0·1) | 1·2 |
| | Grain N | 30 (3) | 19 |
| | $NO_3^-$ leached[A] | 24 (3) | 24 |
| N50 | Yield | 2·2 (0·1) | 1·9 |
| | Grain N | 45 (3) | 35 |
| | *1995* | | |
| N0 | Yield[B] | 1·6 (0·1) | 2·0 |
| | Grain weight | 38·5 (0·3) | 44·4 |
| | Grain number/m$^2$ | 4204 (153) | 4583 |
| | Grain N | 27 (1) | 23 |
| | $NO_3^-$ leached[C] | 59 | 55 |
| N90 | Yield[B] | 2·1 (0·1) | 2·5 |
| | Grain weight | 32·1 (0·5) | 36 |
| | Grain number/m$^2$ | 6619 (247) | 6918 |
| | Grain N | 39 (2) | 49 |

[A]$NO_3^-$ leached below 100 cm (Anderson *et al.* 1998*b*).
[B]Observed yield was affected by *Septoria nodorum*.
[C]$NO_3^-$ leached below 150 cm (Anderson *et al.* 1998*b*).

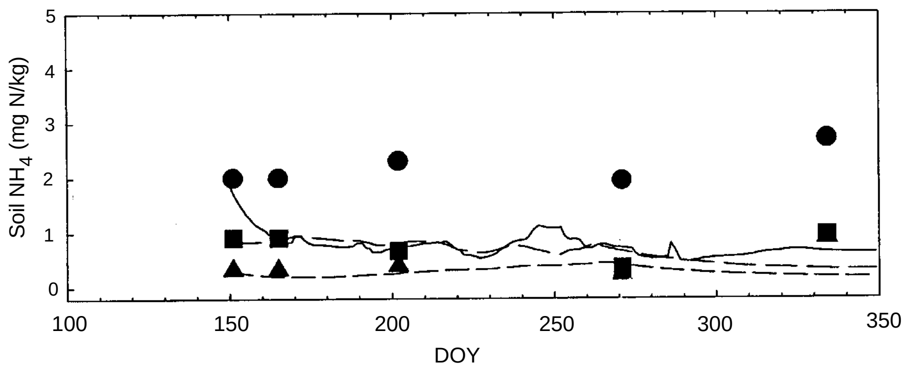


**Fig. 3.** Soil $NH_4^+$ concentrations under wheat in 1994. Observed (symbols) and predicted (lines) soil $NH_4^+$ for soil layers at depths of 0–10 cm (●, ——), 10–20 cm (■, — —), and 20–30 cm (▲, – – –). DOY, day of year.

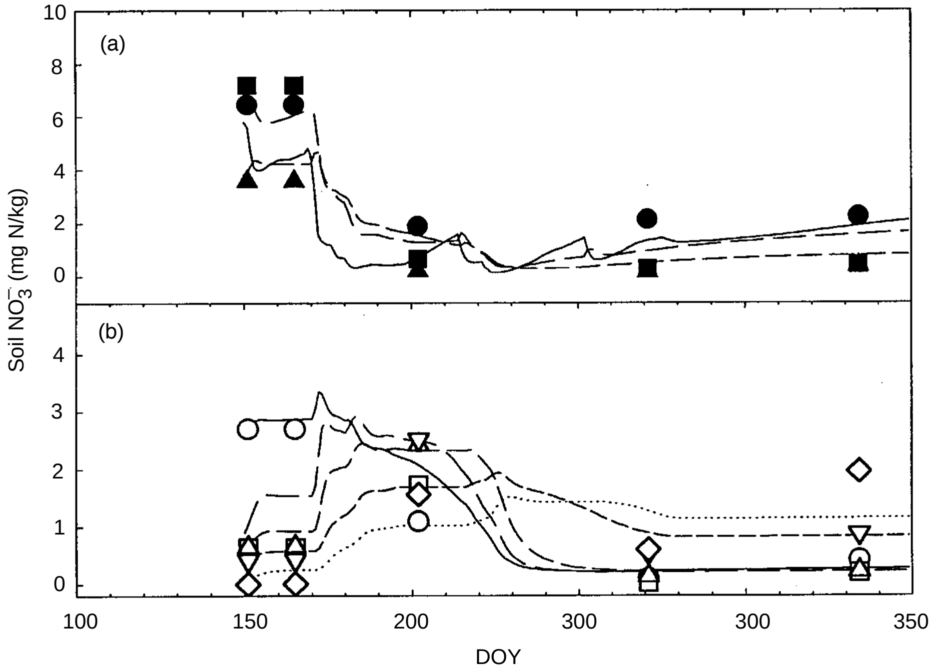


**Fig. 4.** Soil $NO_3^-$ concentrations under wheat in 1994. (*a*) Observed (symbols) and predicted (lines) soil $NO_3^-$ for soil layers at depths of 0–10 cm (●, ——), 10–20 cm (■, — —), and 20–30 cm (▲, – – –). (*b*) Observed (symbols) and predicted (lines) soil $NO_3^-$ for soil layers at depths of 30–50 cm (○, ——), 50–70 cm (□, — —), 70–90 cm (△, – – –), 90–120 cm (▽, - - - -), and 120–150 cm (◇, ......). DOY, day of year.

*Season 1995*

Predicted shoot and root biomass, and shoot N contents were similar to measured values up to anthesis (DOY 263) (Fig. 5). After anthesis, total shoot biomass and grain yield were over-predicted largely as result of a *Septoria nodorum* infection, whereas shoot N content and grain N content were under-predicted. Simulated grain N content in the N90 treatment, however, was 26% higher than measured grain N content (Table 5).

The model marginally underestimated evapotranspiration over the growing season (Fig. 6*a*). Evapotranspiration measurements were undertaken in a field that received 55 kg N/ha, whereas the simulated evapotranspiration was for experimental plots which did not receive fertiliser N and consequently had poorer biomass yields. Overall, the model predicted changes in soil water content in the different soil layers throughout the growing season (Fig. 6*b*,*c*). The peak soil water content in the layers at a depth of 10–50 cm was overestimated except during

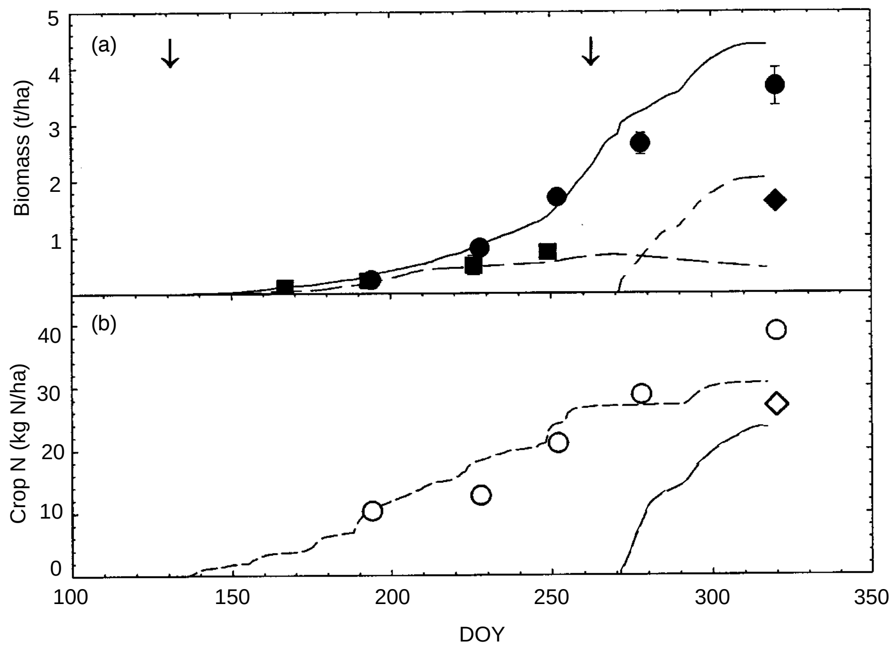


**Fig. 5.** Crop biomass N contained in wheat, Moora 1995. (*a*) Observed (symbols) and predicted (lines) shoot (●, ——), root (■, — — —), and grain (◆, ——) biomass. (*b*) Observed (symbols) and predicted (lines) total shoot N (○, – – – –), and grain N (◇, ——). Arrows indicate sowing and measured date of anthesis. DOY, day of year.

the period from DOY 250 to 270 when the model underestimated soil water content in surface soil following small rainfall events (Fig. 6*b*). There was excellent agreement between measured and predicted drainage (Fig. 6*a*).

**Table 6. Cumulative N mineralisation (kg N/ha) in the top layer of soil (depth, 0–20 cm) at Moora in 1995 for wheat after lupin**

Observed data after Anderson *et al.* (1998*a*)

| Period | N mineralisation | |
|---|---|---|
| | Observed | Predicted |
| 13.vii–10.viii | 11·9 | 12·4 |
| 18.viii–7.ix | 15·2[A] | 8·5 |
| 12.ix–5.x | 18·7[A] | 4·8 |
| 9.x–20.x | 8·4[A] | 5·3 |
| 20.x–27.xi | 7·0 | 6·2 |

[A] Possible overestimation of actual field situation due to severance of roots material and the absence of plant water uptake in mineralisation tubes.

Good agreement was obtained between measured and predicted N mineralisation for the period from 13 July (DOY 194) to 10 August (DOY 222) and from 20 October (DOY 293) to 27 November (DOY 331) when wheat plants were in the early stage of growth or senesced (Table 6). Observed N mineralisation between 18 August (DOY 230) and 20 October (DOY 293) was greater than that predicted by the model. Wheat roots were cut when tubes were inserted in the soil to measure net mineralisation. This detachment of roots would have reduced water loss from the mineralisation tube, ensuring that the water content of this soil was maintained at a higher level following rainfall than would have been the case for soil in contact with live roots. The increased supply of organic substrate from dead roots and the higher soil water contents could also explain the larger measured value for net mineralisation.

The model predicted the temporal changes in $NH_4^+$ and $NO_3^-$ concentrations in the top 30 cm of soil with the exception of the underestimation of the late increase of $NH_4^+$ and $NO_3^-$ in the layer at a depth of 0–10 cm (Figs 7 and 8*a*). Concentrations of $NO_3^-$ in soil layers at depths of 0–10 cm and below 30 cm were slightly overestimated (Fig. 8*b*). The model predicted 55 kg N/ha to be leached as $NO_3^-$, whereas 59 kg N/ha was leached based on measurements of fluxes of water and changes of $NO_3^-$ concentrations in the soil profiles (Table 5).

*Simulation experiment: initial soil profiles*

Probability distributions for grain yield, drainage, and $NO_3^-$ leaching, based on 81 years of historic weather information, for the different combinations of initial soil water content and soil $NO_3^-$ are shown in Table 7. Predicted yields were largely unaffected by the initial profiles of soil water and initial $NO_3^-$ content, with yields ranging from 0·7 to 3·4 t/ha (Table 7).

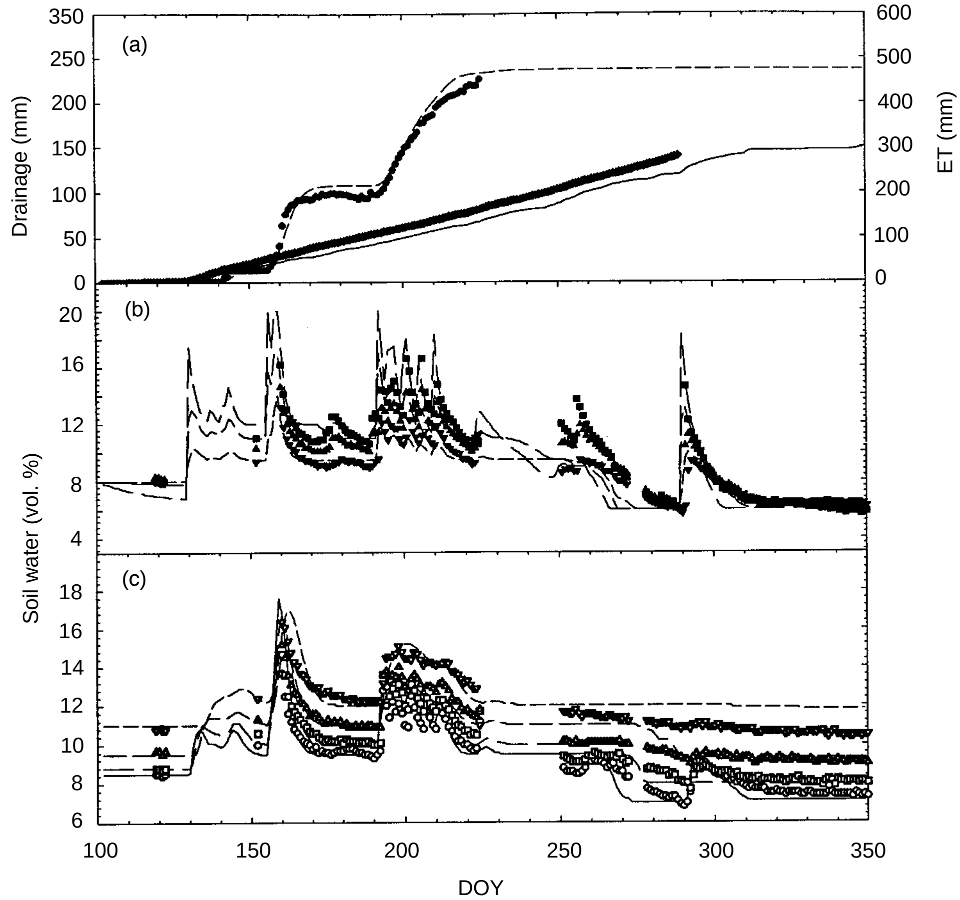


**Fig. 6.** Evapotranspiration, drainage, and changes in soil water content for a deep sand at Moora in 1995. (*a*) Observed (symbols) and predicted (lines) drainage (●, – – – –), and evapotranspiration (◆, ——). (*b*) Observed (symbols) and predicted (lines) soil water content for soil layers at depths of 10–20 cm (■, — —), 20–30 cm (▲, – – –), and 30–50 cm (▼, - - - -). Note that measurements for the soil layer at a depth of 0–10 cm were not available and therefore simulation results for this layer are not shown. (*c*) Observed (symbols) and predicted (lines) soil water content for soil layers at depths of 50–70 cm (○, ——), 70–90 cm (□, — —), 90–120 cm (△, – – –), and 120–150 cm (▽, - - - -). DOY, day of year.

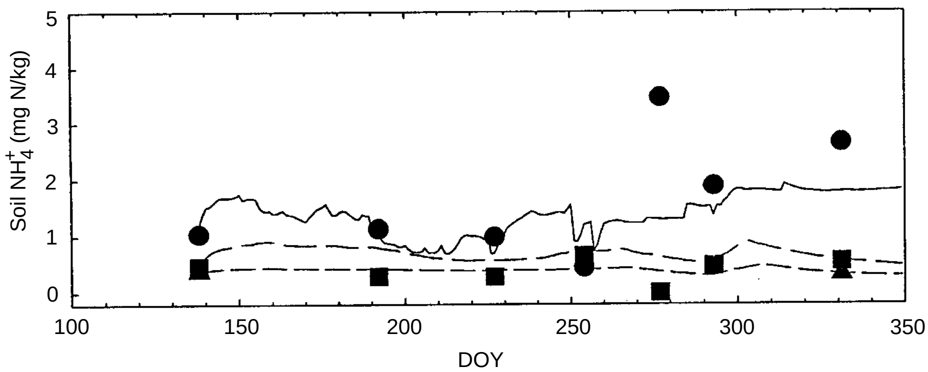


**Fig. 7.** Soil $NH_4^+$ concentrations under wheat at Moora in 1995. Observed (symbols) and predicted (lines) soil $NH_4^+$ for soil layers at depths of 0–10 cm (●, ——), 10–20 cm (■, — —), and 20–30 cm (▲, – – –). DOY, day of year.

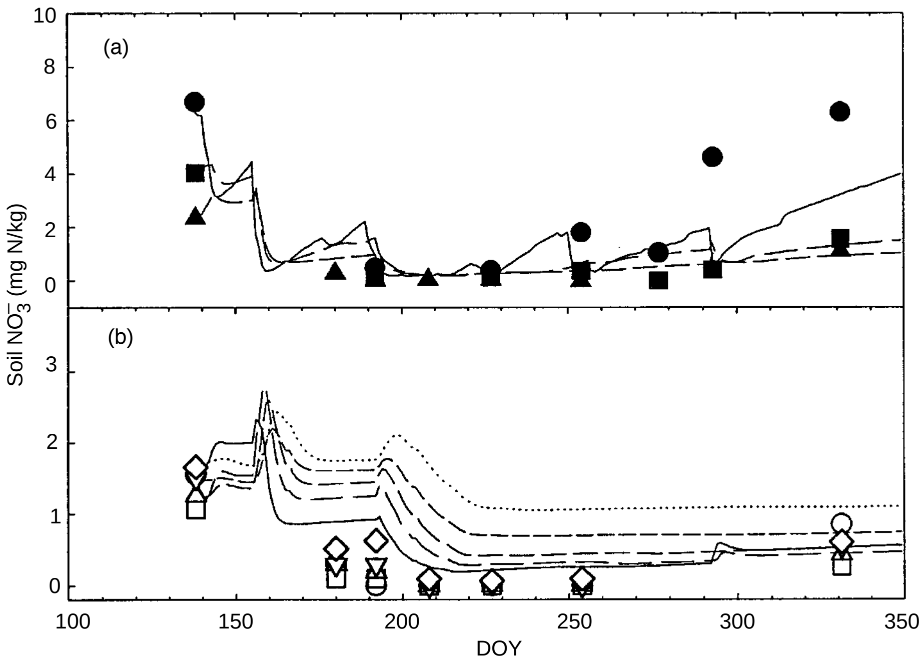


**Fig. 8.** Soil nitrate $NO_3^-$ concentrations under wheat at Moora in 1995. (*a*) Observed (symbols) and predicted (lines) soil $NO_3^-$ for soil layers at depths of 0–10 cm (●, ——), 10–20 cm (■, — —), and 20–30 cm (▲, – – –). (*b*) Observed (symbols) and predicted (lines) soil $NO_3^-$ for soil layers at depths of 30–50 cm (○, ——), 50–70 cm (□, — —), 70–90 cm (△, – – –), 90–120 cm (▽, - - - -), and 120–150 cm (◇, ......). DOY, day of year.

In the case of wheat after lupin, without fertiliser N there was a 20% probability of grain yield ranging from 2·5 t/ha to a maximum of 3·4 t/ha and a 20% probability that grain yield could be lower than 1·4 t/ha, with a minimum yield of 0·7 t/ha. There was also a 50% probability (median) that grain yield could exceed 1·8 t/ha.

Drainage below 150 cm, where soil water profiles were 'high' on 15 April at the start of the simulation ranged from 32 to 355 mm, with a 50% probability at 141 mm (Table 7). The amount of $NO_3^-$ leached was predicted to be between 0 and 116 kg N/ha, depending on the initial content of $NO_3^-$ in the soil profile (Table 7, Fig. 9). The quantity of water in the soil profile at the start of the simulation did not significantly affect the amount of $NO_3^-$ leached (Table 7, Fig. 9). There was a 50% probability that 53 kg N/ha could be lost by $NO_3^-$ leaching below 150 cm for soil profiles that received summer rainfall and a 20% probability (1 of 5 years) that >84 kg N/ha could be leached during the season for the same summer rainfall conditions.

**Table 7. Range of probability and the 50% probability for drainage (mm), nitrate $NO_3^-$ leached (kg N/ha), and grain yield (t/ha) for four combinations of initial soil profiles and three nitrogen (N) fertiliser applications**

See Table 4 for 'low' and 'high' N and 'low' and 'high' $H_2O$ initial soil profiles

| Treatment | Range | | | 50% probability | | |
|---|---|---|---|---|---|---|
| | Drainage | $NO_3^-$ leached | Grain yield | Drainage | $NO_3^-$ leached | Grain yield |
| A, low N, low $H_2O$ | 2–323 | 0–56 | 0·7–3·3 | 109 | 16 | 1·8 |
| B, high N, low $H_2O$ | 2-323 | 0–115 | 0·7–3·4 | 109 | 46 | 1·8 |
| C, low N, high $H_2O$ | 32–355 | 1–57 | 0·7–3·3 | 141 | 20 | 1·8 |
| D, high N, high $H_2O$ | 32–355 | 4–116 | 0·7–3·4 | 141 | 53 | 1·8 |
| N0 | 32–355 | 1–57 | 0·7–3·3 | 141 | 20 | 1·8 |
| N50 | 32–356 | 1–100 | 0·8–4·3 | 138 | 29 | 1·9 |
| N50 split | 32–358 | 1–92 | 0·8–4·6 | 137 | 26 | 2·2 |

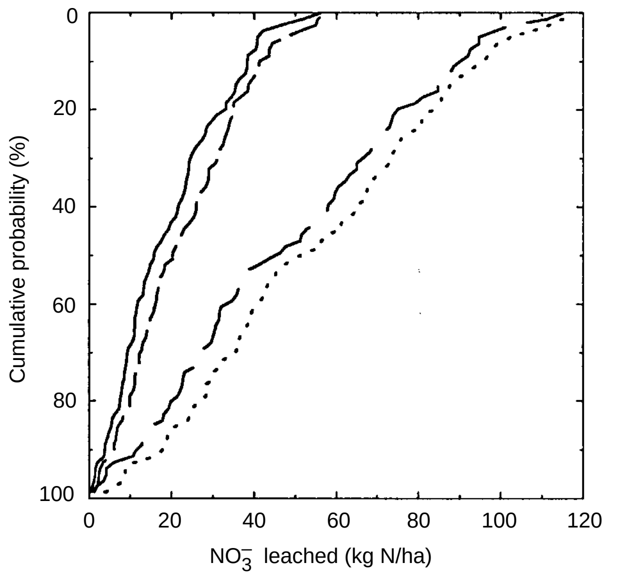


**Fig. 9.** Effect of the content of water and $NO_3^-$ in a deep sand on 15 April on subsequent simulated $NO_3^-$ leaching. The cumulative probability distributions for $NO_3^-$ leaching (below a depth of 150 cm) are for initial soil profiles containing 'low inorganic soil N' and 'low soil water' (—), 'high inorganic soil N' and 'low soil water' (— — —), 'low inorganic soil N' and 'high soil water' (– – – –), and 'high inorganic soil N' and 'high soil water content' (......). The quantities of inorganic N and volumetric soil water contents at various depths for each initial soil profile are given in Table 4.

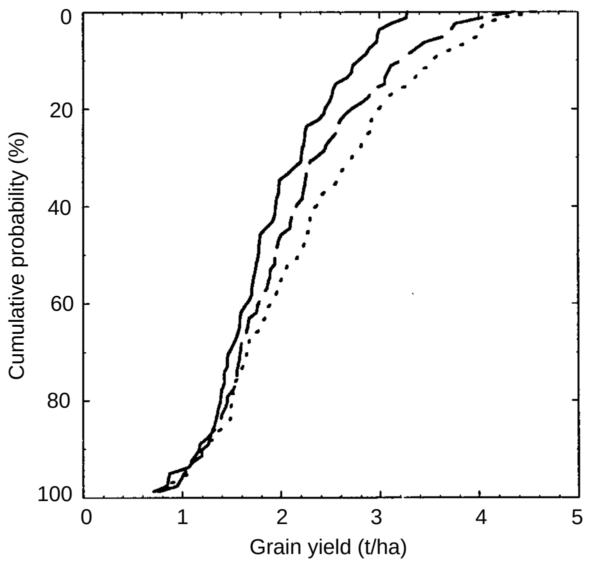


**Fig. 10.** Effect of rate and time of application of N fertiliser on predicted grain yield. Cumulative probability distributions for 0 kg N/ha (—), 50 kg N/ha at sowing (— — —), and 25 kg N/ha at sowing plus 25 kg N/ha 40 days after sowing (......). A 'low inorganic soil N' and 'high soil water profile' (see Table 4) was used to initialise the soil modules at the start of each simulation.

*Simulation experiment: management of fertiliser N*

Model simulations showed that N fertiliser applied at, or after, the time of sowing increased biomass growth and grain yields (Fig. 10), whereas the quantity of soil-derived inorganic N on 15 April at the start of the simulation did not affect wheat yields (Table 7). The 20% probability of achieving a yield >2·4 t/ha (with a maximum of 3·3 t/ha) without fertiliser increased to >2·7 t/ha (with a maximum of 4·3 t/ha) when simulations were run with an input of 50 kg N/ha of fertiliser. Splitting the 50 kg N/ha into 2 equal applications further increased the yield for the 20% probability to >3·0 t/ha (with a maximum of 4·6 t/ha) (Fig. 10). The application of 50 kg/ha of fertiliser N increased the predicted quantity of $NO_3^-$ leached from 20 kg N/ha to 29 kg N/ha when assessed on the basis of a 50% probability, a loss of N equivalent to 18% (9 kg N/ha) of fertiliser N applied. Splitting the N fertiliser into 2 equal applications resulted in a 50% probability that 26 kg N/ha of $NO_3^-$ could be leached below 150 cm, a loss of 6 kg N/ha or 12% of the fertiliser N applied (Table 7).

The relationships between predicted yield for the N0 and N50 split simulations and cumulative rainfall between April and October (growing season rainfall) are shown in Fig. 11. Predicted grain yields were poorly correlated with growing season rainfall and only few yields reached the potential yield line of 20 kg of grain yield increase with each mm of rainfall.

A better fit of the predicted grain yield to the French and Schultz (1984*a*, 1984*b*) potential yield line was achieved by comparing yields against available soil water (rainfall minus estimated drainage), and in several cases (N0 and N50 split treatments) yields exceeded the French and Schultz potential (Fig. 12). The model predicted runoff to be in a range of 0–25 mm with an average of 3 mm/year for the 81 years of historic weather data, thus discounting the requirement to include runoff in the calculation of available soil water.

## Discussion

*Evaluation of the model*

The APSIM model predicted soil water content, deep drainage, inorganic soil N, $NO_3^-$ leaching, crop growth, and grain yield reasonably well in rainfall seasons that are both below average (1994) and above average (1995). Others have also obtained good predictions of wheat soil systems with the APSIM wheat model (Asseng *et al.* 1995, 1998; Keating *et al.* 1995; Probert *et al.* 1995, 1996, 1998; Meinke *et al.* 1997).

In our study, discrepancies between simulated and observed data can largely be attributed to processes

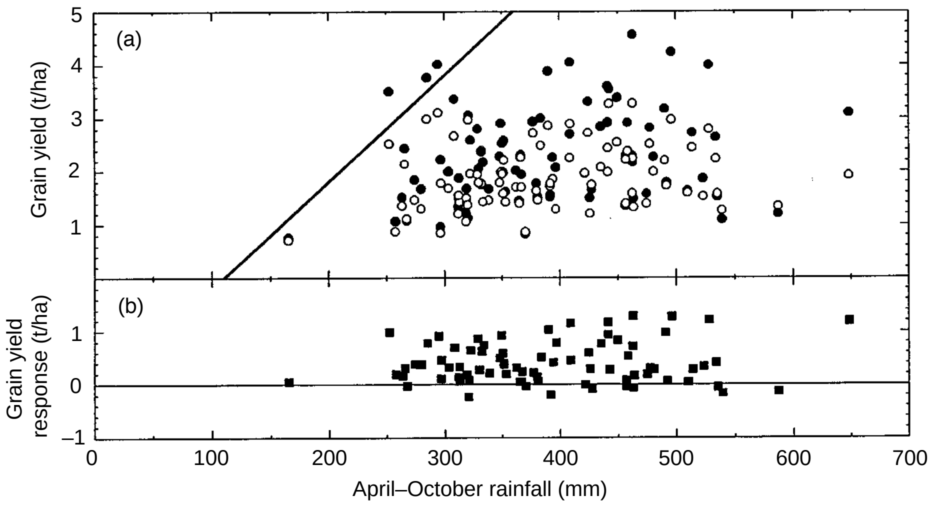


**Fig. 11.** Model predictions of (*a*) wheat grain yields and (*b*) the difference in wheat yield between 0 kg N/ha (N0), and 50 kg N/ha of fertiliser N applied at sowing and 40 days after sowing (N50 split) in relation to cumulative rainfall for a deep sand at Moora. Predictions were based on 81 years of historic weather records with either N0 (○) or N50 split (●). The solid line in (*a*) shows the 20 kg/ha increase in grain yield per mm of rainfall above 110 mm (French and Schultz 1984*a*, 1984*b*).

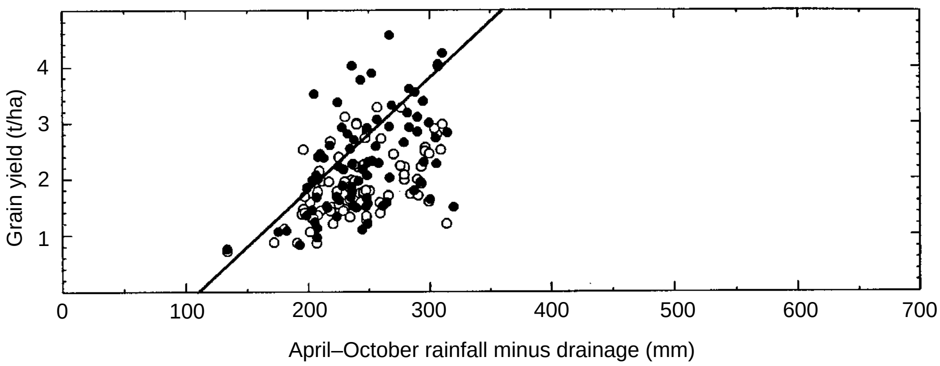


**Fig. 12.** Model predictions of wheat grain yields in relation to cumulative rainfall for a deep sand at Moora. Predictions were based on 81 years of historic weather records with either nil N (○) or split application (50 kg N/ha, ●) of fertiliser N. The solid line shows the 20 kg/ha increase in grain yield per mm of rainfall above 110 mm (French and Schultz 1984*a*, 1984*b*).

which are not currently included in the model. For example, the current APSIM crop model assumes a disease-free crop and discrepancies between predicted and measured yields will arise where a disease is present as was the case in the 1995 wheat crop which was infected with *Septoria nodorum*.

The underestimation of crop N uptake, particularly late in the growing season, and the poor simulation of grain N could be a result of an underestimation of crop N demand with increasing leaf senescence, or an underestimation of mineral N supply in the soil. Although the potential mineralisation rates used to test the model for sandy soil were increased from those developed for finer textured soils, it is possible that the 4-fold increase in the rate of decomposition of the microbial biomass pool was still too small for the sandy soil used here. The model also underpredicted the soil water content in the surface layer between DOY 250 and DOY 270, presumably as a result of rapid removal of water by the wheat crop. This faster rate of depletion of surface soil water may have lead to lower quantities of predicted mineralisation for the period concerned and reduced availability of N for uptake by wheat. Experimentation with simulated residue inputs showed that the predicted N mineralisation was sensitive to the quantity, and to the C : N ratio of above- and below-ground residues. Measurements of above- and below-ground residues, before the break of season, are needed to ensure that the model is initialised correctly.

*Probability of drainage and $NO_3^-$ leaching in deep sands*

The 50% probability that drainage could exceed 141 mm in the deep sandy soil at Moora confirmed the high rate, and frequency, of recharge under annual crops for this soil type (with only 50·5 mm soil water between the drained upper limit of water and the lower limit of plant available water for the 0–150 cm soil profile) in the high rainfall zone of Western Australia. The observed drainage of 214 mm in 1995 under annual crops (Anderson *et al*. 1998*b*) corresponded to a 16% probability of recharge, and the 84 mm simulated drainage in 1994 corresponded to an 84% probability. Nulsen (1984) estimated drainage at 2 sites in the Western Australian wheatbelt to be 44–154 mm/year for a range of crops. Similar quantities of deep drainage (50–270 mm) have been reported by Allison and Hughes (1978) for a range of soils located in the high rainfall zone (700 mm) of South Australia. Dunin *et al*. (1994) have reported a 5% probability of 100 mm drainage below a depth of 90 cm during a growing season on a red Kandasol soil at Wagga Wagga, New South Wales (525 mm rainfall).

Simulated drainage in the deep sand transported 0–116 kg N/ha below a depth of 150 cm, depending on the seasonal rainfall and the initial quantity of $NO_3^-$ in the soil. The probabilities of $NO_3^-$ leached of the order observed in field experimentation (46% for 59 kg N/ha in 1995 and 84% for 24 kg N/ha in 1994) highlight the likely high frequency of loss of N from deep sands, particularly when cereals are planted after lupin (Anderson *et al*. 1998*b*). Mason *et al*. (1972) also found significant $NO_3^-$ movement through deep sandy soils after rainfall events at Lancelin, Western Australia, and inferred large N losses out of the root-zone. By comparison, only 5 kg N/ha of $NO_3^-$ was leached below a depth of 90 cm in a red Kandasol soil, even though drainage below 90 cm accounted for 100 mm of rainfall (Dunin *et al*. 1994). Differences in the temporal pattern of drainage in the Kandasol soil compared with the deep sand studied here, and an increase in crop uptake of $NO_3^-$ from soil as a result of delayed drainage from the Kandasol, account for the differences in the extent of $NO_3^-$ leaching.

Summer rainfall is common at Moora, with an average of 70 mm (50% probability of 50 mm; range 3–315 mm) between November and March (based on Moora township rainfall records between 1910 and 1990). Mineralisation of organic N is increased by summer rainfall (D. V. Murphy pers. comm.), resulting in high concentrations of $NH_4^+$ and $NO_3^-$ in the soil profile before the break of the season. It might be expected that mineralisation of soil organic N would increase the potential for grain yield in subsequent crops. Simulation experiments, using historic weather data, showed that simulated grain yield was not affected by the quantity of inorganic soil N at the break of season. This finding suggests that inorganic N in the soil at the time of seeding of wheat on deep sands is largely lost by $NO_3^-$ leaching.

*Potential wheat yields*

Wheat yields, determined from the model, ranged from 0·7 to 4·6 t/ha for the deep sandy soil at Moora. Moora Shire records show that wheat yielded in the range 0·6–2·1 t/ha over 40 years (Hamblin and Kyneur 1993). Henderson (1989) reported wheat yields of 1·7–2·8 t/ha on a deep sand at Geraldton, Western Australia, while wheat yields of 1·2–4·4 t/ha have been recorded on a loamy sand at Wongan Hills, Western Australia (Delroy and Bowden 1986; Siddique *et al*. 1989; Anderson 1992).

The French and Schultz (1984*a*, 1984*b*) relationship is often used to set target or potential yield using growing season rainfall or soil water use as the determinant of potential yield (Angus *et al*. 1980; French and Schultz 1984*a*, 1984*b*; Perry 1987; Anderson 1992; Gregory *et al*. 1992; Turner and Whan 1995). Assessments of potential yield by the French and Schultz (1984*a*, 1984*b*) method indicate potential yield given that all factors other than water are not limiting. Our results confirm that a better measure of the efficiency of grain production on deep sandy soils will be obtained by using available water after drainage is deducted from seasonal rainfall. When this was undertaken the potential yield line was achieved or exceeded on several occasions, mainly where fertiliser N was applied in a split application, but also with some yields without N application.

A closer examination of the possible constraints to yield, both in terms of the total growing season rainfall and in terms of the distribution of this rainfall, indicated that a more sophisticated predictive tool than the French and Schultz (1984*a*, 1984*b*) relationship may be needed to assess the success of strategies for increasing yields. For example, total seasonal rainfall, or available water, was not always the best indicator of yield potential. In 3 of the 9 years in which the simulated yields reached more than 3·5 t/ha, cumulative seasonal rainfall was below the 81-year average of 389 mm. In contrast, 2 of the 8 seasons with a simulated yield of $<1{\cdot}2$ t/ha occurred in an above-average rainfall season. Drainage in these 2 years accounted for 295 mm and 338 mm of rainfall and the model predicted a leaching loss of 71 kg N/ha and 83 kg N/ha, respectively. The remaining 6 of the

8 simulated yields of <1·2 t/ha occurred when cumulative rainfall was below average. In 2 of these seasons, the harvest index decreased below 0·21 as a result of low available water post-anthesis, whereas the 81-year average determined from the model was 0·40. These findings emphasise the importance of including the distribution of season rainfall in assessments of potential grain yields. Nevertheless, the French and Schultz (1984*a*, 1984*b*) procedure provides a simple and easy-to-use tool to assist producers to assess target yields. The APSIM model may help agronomists determine why yields do not approach the French and Schultz yield potential.

*Management of fertiliser N*

The modelled grain yield response to fertiliser N, from a 50% probability of 1·8 t/ha to 2·2 t/ha, demonstrated that in most years N was the limiting growth factor for the potential yield. In some seasons, yield response to added fertiliser N was predicted for high-yielding crops in the absence of fertiliser N, whereas in other seasons crops did not respond to fertiliser N even though grain yields were low in the absence of fertiliser N. Only in those seasons with terminal drought were yields depressed by the application of 50 kg N/ha, a finding that is consistent with reports that enhanced early biomass growth can result in severe water deficit in crops during grain filling (Fischer 1979; Passioura 1979; Van Herwaarden 1996). The probability of receiving at least a cumulative amount of 30 mm of rainfall per month at Moora decreases rapidly from 55% in September, to 36% in October, and finally to only 10% in November. Hence, the chance of a terminal drought is high in wheat crops where anthesis of wheat usually occurs between mid September and mid October.

The model showed that higher grain yields are to be expected from split application compared with a single application of N fertiliser for deep sandy soils. Numerous fertiliser trials on this soil type have demonstrated the advantage of splitting the application of fertiliser N to reduce leaching of fertiliser N (Mason *et al*. 1972; Mason 1985, 1987). This confirmation of experimental results illustrates that the wheat model is correctly predicting the effect of management practices on wheat production and grain yields.

## Conclusion

Evaluation of model output against observations has shown that the APSIM model can predict the interactions between biomass growth, grain yield, water and N uptake, soil water, soil N, and weather for a wheat crop on a deep sandy soil in Western Australia. Improvements in routines which handle the N demand of crops during senescence, and the allocation of this N to grain N, are required. More research is also needed to identify input parameters for C and N transformation processes with respect to soil type and residue components. Nevertheless, the current model is sufficiently accurate to enable assessments of the effects of soil and crop management on wheat yield, water use, and N losses in the context of present crop rotation systems used on deep sands. Use of soil information relevant to other soil types should enable an analysis of the interactions between crop growth, water use, and N loss processes for other soil and climate regimes.

## Acknowledgments

The authors thank Dr M. Probert for helpful discussions about the soil N module, Drs M. Robertson, D. Tennant, and M. Stapper for valuable comments on the manuscript, Mr I. Foster (Agriculture Western Australia), the Bureau of Meteorology, and Dr H. Meinke from APSRU for weather data. This study was supported by the Grains Research and Development Corporation.

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Manuscript received 17 June 1997, accepted 20 December 1997