Use of the APSIM wheat model to predict yield, drainage, and NO3- leaching for a deep sand

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Nitrogen and water flows under pasture–wheat and lupin–wheat rotations in deep sands in Western Australia
2.* Drainage and nitrate leaching

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Abstract. Quantification of nitrate (NO_3^-) leaching is fundamental to understanding the efficiency with which plants use soil-derived nitrogen (N). A deep sand located in the northern wheatbelt of Western Australia was maintained under a lupin (*Lupinus angustifolius*)–wheat (*Triticum aestivum*) and a subterranean clover (*Trifolium subterraneum*) based annual pasture–wheat rotation from 1994 to 1996. Fluxes of water and NO_3^- through, and beyond, the root-zone were examined. Drainage was calculated on a daily basis from measurements of rainfall, evapotranspiration, and the change in soil water content to a depth of 1·5 m. Evapotranspiration was estimated from Bowen ratio measurements, and soil water content was determined by time domain reflectometry. Soil was sampled in layers to 1·5 m at the onset of winter rains and analysed for NO_3^-. Ceramic suction cups were installed at 0·25, 0·4, 0·6, 0·8, 1·0, 1·2, and 1·4 m to sample soil solution from June to mid August. The NO_3^- leached from each layer was computed by multiplying the daily drainage through each layer by the estimated concentration of NO_3^- within the layer. The estimated concentration of NO_3^- in a layer was calculated by taking into account NO_3^- either entering that layer through mineralisation and leaching or leaving the layer through plant uptake. Mineral N was added to the surface 0·2 m in accordance with measured rates of net N mineralisation, and daily N uptake was calculated from the measured above-ground plant N derived from soil N. Root sampling was undertaken to determine root length density under pastures, lupin, and wheat.

Cumulative drainage below 1·5 m was similar under wheat and lupin, and accounted for 214 mm from 11 May to 15 August 1995 and 114 mm from 2 July to 15 September 1996. The cumulative evapotranspiration (E_a) over these periods was 169 mm from a wheat crop in 1995, and 178 mm from a lupin crop in 1996. The amount of NO_3^- in soil at the start of the growing season was affected by previous crop, with a lower range following wheat (31–68 kg N/ha) than following legumes (40–106 kg N/ha). These large quantities of NO_3^- in the soil at the break of the season contributed substantially to NO_3^- leaching. Leaching of NO_3^- below 1·5 m in wheat crops accounted for 40–59 kg N/ha where these followed either lupin or pasture. In contrast, less NO_3^- was found to leach below 1·5 m in pastures (17–28 kg N/ha). Greater N uptake by capeweed (*Arctotheca calendula* L.) than by either wheat or lupin was the main reason for the lower amount of NO_3^- leached in pastures.

Additional keywords: N loss, efficiency N use, ‘spared’ N, subterranean clover, capeweed, time domain reflectometry.

Introduction

Legume-based cropping systems are widely used in southern Australian agriculture. The contributions of legumes to soil fertility have been largely measured in terms of long-term changes in soil organic matter (Greenland 1971; Grace *et al.* 1995) and in equivalents of fertiliser nitrogen (N) used by subsequent crops (Rowland *et al.* 1988; McDonald 1989; Mason and

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Rowland 1990). Recent documentation of rising water tables, secondary salinisation (George *et al.* 1997), the spread of soil acidity (Dolling and Porter 1994; Dolling 1995), and the decline in soil fertility (Hamblin and Kyneur 1993) has focused attention on the sustainability of legume-based rotations in Western Australia.

Approximately 2 million ha of deep sands are cropped, mainly with a 2-year lupin–cereal rotation (Perry 1989). The problem of low water retention capacity of this soil type is compounded by the concentration of rainfall during winter (60–80% of annual rainfall occurs between May and October) when the growth of crops and pastures is slow due to cool winter temperatures and low radiation levels. There are no concurrent measurements of drainage and NO_3^- leaching for legume-based rotations, which are commonly grown on deep sands in this region. This lack of information has hindered attempts to establish accurately the efficiency with which plants utilise soil-derived N in these systems. Moreover, it has not been possible to validate models which simulate water and nutrient flows through the soil–crop system. Such models have the potential to examine the interactions between soil properties, climate, crop species, drainage, and N losses beyond that which is possible by field studies.

The sparing effect of legumes on soil inorganic N has often been cited as a mechanism for conserving N for subsequent cereal crop (Jensen and Haahr 1990; Evans *et al.* 1991; Chalk *et al.* 1993). The role of 'spared' NO_3^- in the subsequent nutrition of cereals has not been established for Western Australian rotations. It could be argued that the asynchrony in supply and use of NO_3^- in cropping systems, which arises when NO_3^- accumulates during periods of slow or no plant growth, and its subsequent loss by leaching is the major reason for the rapid development of soil acidity in soils prone to drainage (Dolling and Porter 1994; Dolling 1995). Non-legume pasture species, including capeweed and annual grasses, are important components of annual pastures in southern Australia. The accumulation of NO_3^- by capeweed (Unkovich *et al.* 1998) would suggest that this species may play an important role in reducing the quantities of NO_3^- leached, and hence rates of soil acidification, in the Mediterranean climatic zone.

In this paper we aimed to determine the extent of both drainage and NO_3^- leaching below 1·5 m of soil in lupin–wheat and annual pasture–wheat rotations, which are used on deep sands in Western Australia. Budgets of N are constructed for both of these rotations to determine the efficiency of utilisation of soil inorganic N by wheat, lupin, and pasture.

Materials and methods

The measurements of soil water, evapotranspiration (E_a), and inorganic N contents in soil were conducted on a rotation experiment, 14 km west of Moora, Western Australia, which was initiated in 1994. The area experiences a Mediterranean-type climate, with rainfall concentrated from May–June to October and hot, dry conditions over summer. In this environment annual pastures germinate after late autumn or early winter rainfall, and crops are sown when May–June rainfall has wet the top 0·2 m of soil. The growing season typically extends from May to October but the start and finish are strongly season-dependent.

The experimental design, treatments, and schedule of field operations are described in detail by Anderson *et al.* (1998). The treatment coding is as follows: AP refers to the annual pasture phase, W to the wheat phase, and L to the lupin phase; the prefix number (1 or 2) refers to the number of years of the pasture phase, and the subscript (93, 94, 95, or 96) refers to the year of rotation phase. For example, W_{95}–$1AP_{94}$ refers to wheat in 1995 which was preceded by 1 year of annual pasture in 1994. Measurements were conducted at the same site for 3 consecutive years, enabling the effects of each rotation on water use, and selected N transformations, to be followed over time and across phases.

Soil water content

The soil water content (% v/v) was measured using time domain reflectrometry (TDR) during the 1995 and 1996 growing seasons. Details of the TDR unit and computer program used are given in Gregory *et al.* (1995). A multiplexer unit enabled 16 TDR probes to be connected to a cable tester and a notebook computer. TDR probes (0·4 m in length) were placed horizontally in soil at depths of 0·2, 0·3, 0·5, 0·7, 0·9, 1·2, and 1·5 m under 1 replication of the lupin and wheat phases of the L–W rotation. The surface probe was positioned horizontally at 0·1 m in 1995, and in 1996 this probe was installed obliquely to provide measurements of soil water (SW) between 0·02 and 0·1 m. The SW content was measured at midnight of each day. The SW content of each layer was calculated by assuming that each probe measured SW content of the surrounding 0·05 m of soil. Outside this measured zone, SW content within a particular soil layer was calculated as the average of the 2 probes that defined the outer edge of the soil layer. The soil layers were then defined as 0–0·125 m (L1), 0·125–0·225 m (L2), 0·225–0·3 m (L3), 0·3–0·5 m (L4), 0·5–0·7 m (L5), 0·7–0·9 m (L6), 0·9–1·2 m (L7), and 1·2–1·5 m (L8). These soil layers were the same in 1996 except for L1, which was 0–0·1 m, and L2, which was 0·1–0·225 m. The profile soil water content to 1·5 m ($SW_{1\cdot5}$) was the sum of the water content of layers L1–L8.

The TDR unit was installed on 29 April 1995 but a faulty power supply or multiplexer resulted in only limited data being collected before 9 June 1995 and during August–September 1995. Over these periods a daily water balance was calculated by assuming a drainage upper limit for the soil profile of 162 mm (Asseng *et al.* 1998). Neutron access wells to 2 m were installed near the TDR probes, and within all plots sampled in 1995. Neutron probe readings were taken fortnightly from 15 June to 8 September 1995 and on 23 October 1995 at depths of 0·15, 0·25, 0·4, 0·6, 0·8, 1·0, 1·2, and 1·4 m. TDR measurements of SW content (% v/v) on these dates were used to calibrate the neutron probe. The total SW content of the soil profile was computed (as used for the TDR) for each sampled plot, and the percentage coefficient of variation (CV) of total soil water across the site determined.

Evapotranspiration

Daily actual evapotranspiration (E_a) was measured using the Bowen ratio technique (Dunin *et al.* 1989). A single Bowen ratio unit was placed in an adjacent wheat field from 26 July to 16 October 1995, and in the same paddock in lupin from 12 July to 30 September 1996. E_a was calculated from Penman estimates of evapotranspiration (E_p) either when the Bowen ratio unit was not in place (10 May–26 July 1995 and 2 July–12 July 1996) or during short periods of malfunction. The ratio of E_a to E_p in the periods immediately before and after malfunction were used to calculate E_a from E_p. E_a was set at 75% of E_p for the periods 10 May–26 July 1995, and 2 July–12 July 1996.

Drainage

Drainage (mm) below a soil layer (D_z where z is soil layers L1–L8) was calculated from measured daily precipitation (P, mm), E_a (mm), and the daily change in cumulative soil water content of the layers from L1 to L8 (ΔSW_z, mm) (Eqn 1).

$$D_z = P - E_a - \Delta SW_z \qquad (1)$$

Deep drainage ($D_{1\cdot5}$) was defined as drainage below the soil layer 1·2–1·5 m (L8).

Soil nitrate measurements

The quantities of NO_3^- in the soil profiles were measured by soil sampling and the use of ceramic suction cups. Soil samples to 1·5 m were collected on 19 March, 14 June, 21 July, 26 September, and 29 November 1994; 12 April, 18 May, and 27 November 1995; and 18 June and 5 December 1996. Ceramic suction cup samples were collected on 11 and 27 July and 15 August 1995, and 26 July and 2, 8, and 15 August 1996.

The procedures used to collect, subsample, and analyse the soil samples for NO_3^- are given by Anderson *et al.* (1998). The exception was in 1994 when soil samples collected above 0·2 m were dried at 40°C in a forced-draft oven before being mixed and subsampled. In 1995 and 1996 soil to a depth of 0·2 m was collected as part of measurements of net mineralisation (Anderson *et al.* 1998). These soil samples were kept at field water content during processing and extraction phases to minimise post-sampling mineralisation and were used to supplement measurements of NO_3^- obtained from ceramic suction cups for all sampling times except 27 July 1995 and 2 and 8 August 1996.

The ceramic suction cup system used here to extract soil solution was similar to that described by Poss *et al.* (1995*a*). Ceramic cups [40 mm outside diameter (o.d.)] were cemented to lengths of PVC pipe (40 mm o.d.). PVC end caps, with ports to facilitate the evacuation of air and the sampling of soil solution, were used to close the end of each pipe. Black polyethylene tubing (6 mm o.d.) was attached to the inside of the suction cup with the tip adjacent to the ceramic wall on the designated lower side to ensure the collection of all of the solution. This tube was extended through a port (6 mm o.d.) in the end cap and a 1-way nylon stop-cock was attached to seal the tube and to facilitate the withdrawal of soil solution using a 50-mL disposable syringe. Threaded irrigation connectors were inserted into another port in the end cap and a length of tubing (6 mm o.d.) was attached to facilitate connection to a vacuum pump. Connections between the PVC pipe and the 6-mm tubing, and between the 6-mm tubing and irrigation fittings, were sealed using a rapid drying adhesive.

Suction cups were placed at 0·25, 0·4, 0·6, 0·8, 1·0, 1·2, and 1·4 m depths in the soil profile. Large access wells (2 m long and 1 m diameter) were excavated along the edge of plots at a randomly chosen point. These wells were lined with heavy duty (1·27 profile) Riblok plastic liners to prevent the collapse of soil. Holes were cut in the plastic liner to enable the insertion of suction cups. Channels were excavated on a downward angle (approximately 5°) using steel pipes of the same external diameter as the PVC pipe. The final 0·06 m of the channel was excavated using a steel pipe (0·03 m o.d.) to ensure a tight fit between the soil and the ceramic cup. Suction cup–PVC pipe assemblies (0·9, 1·2, or 1·4 m in length) were inserted along excavated channels and pushed firmly into the soil. The 1 m diameter of the access wells restricted the initial length of the ceramic cup assemblies to 0·9 m. Additional lengths of pipe and PVC joiners were used to extend units to either 1·2 or 1·4 m. PVC adhesive was used to seal these joints. Pairs of cups for each depth were placed within each well; suction cups were positioned to minimise interference between sampling points in each profile. Black polyethylene tubing (6 mm o.d.) was used to connect all of the inlet ports of the suction cups to a single outlet to facilitate evacuation of air. (A photograph showing the arrangement of ceramic cups is shown on the cover of *Plant and Soil*, Vol. 184, No. 1.) At each sampling, suction to 650 mm Hg was applied in the afternoon and each suction cup unit was then sealed. The solution that suffused overnight was collected the following morning after air pressure was restored. Soil solution samples were frozen until analysed for NO_3^- using a TRAACS 800 continuous flow auto-analyser (Bran and Luebbe 1990).

Nitrate leaching

In 1994, the quantity of NO_3^- leached below 1 m was measured using an anion exchange resin trap installed at the bottom of intact soil columns. Resin traps (0·03 m deep by 0·24 m diameter) constructed using fine nylon were filled with 800 g of Amberlite anion exchange resin (IRA-400) which had been primed for anion exchange by treatment with 1 M HCl. Intact soil columns [1·05 m long by 0·24 m internal diameter (i.d.)] were collected using a Proline auger and a drilling rig. Soil columns were lifted from the ground to remove the bottom 0·03 m soil layer and to install the resin bag. A PVC liner (0·25 m i.d.) was placed into the drill hole and the soil column was then inserted into the PVC liner. Duplicate columns were placed in 2 replicates of the W_{94}–L_{93}, L_{94}–W_{93}, and $1AP_{94}$–W_{93} treatments. The resin traps were first installed on 21 June. These were replaced on 21 July, and the second resin traps were sampled on 26 September. The resin was recovered from each trap, rinsed with deionised water, and mixed, and a 4-g wet subsample was shaken with 100 mL of 3M KCl for 1 h to recover NO_3^-. KCl extracts were filtered through Whatman No. 1 paper and NO_3^- was measured on a TRAACS 800 (Bran and Luebbe 1990).

In 1995 and 1996, the quantity of NO_3^- leached below 1·5 m was calculated from the daily concentration of NO_3^- in L8 and daily drainage from L8 for the periods 12 April–15 August 1995, and 18 June–15 August 1996. Transport of NO_3^- into L8 was based on the daily concentrations of NO_3^- in soil solution for L1–L7, and drainage from these layers. The concentration of NO_3^- in each layer was interpolated from measured NO_3^- concentrations in soil or in soil solution. Inorganic N was added to the surface layer in accordance with measured rates of net N mineralisation, and daily N uptake was calculated from the measured above-ground plant N derived from soil N (Anderson *et al.* 1998). Uptake from the soil was in proportion to root length density and distribution. Leaching of NO_3^- from the surface soil layer was set at zero when evapotranspiration was greater than rainfall. Calculations were undertaken on an Excel spreadsheet. The amount of NO_3^- leached (kg N/ha) from each soil layer (N_z) was computed using Eqn 2

$$N_z = [(N_i + N_a - N_u)/(W_i + W_a)] \times D_z \qquad (2)$$

where N_i is the initial NO_3^- content (kg N/ha) within each soil layer, N_a is the amount of N mineralisation (kg N/ha) for soil layer L1 or the amount of NO_3^- leached from the preceding soil layer for layers L2–L8 over the current day; N_u is N uptake by plant (kg N/ha) from each soil layer over the current day; W_i is the initial amount of water (mm) within each soil layer; W_a is daily rainfall (mm) for L1 or daily drainage (mm) from the preceding soil layer for layers L2–L8 over the current day; and D_z is the current day drainage (mm) through each soil layer.

The calculations of daily NO_3^-, initiated from KCl extracts of soil NO_3^- (18 May 1995 and 18 June 1996), and calculated fluxes of soil water between layers were unable to reproduce soil solution NO_3^- profiles obtained using suction cup extraction. Sampling of soil NO_3^- by solution extraction (suction cups) and KCl extraction of soil collected on the day of solution extraction showed the quantity of NO_3^- determined from soil solution extraction to be 0·8 of KCl extraction (data not presented). Since ceramic suction cup extraction is more likely to remove solution from soil pores which are subject to drainage, KCL extraction measures of the total soil NO_3^- were corrected by a factor of 0·8. Subsequent soil solution NO_3^- analyses were used to check the accuracy of computed NO_3^- profiles. The decrease in soil profile NO_3^- below 0·5 m between 12 April and 18 May 1995 was assumed to be due to NO_3^- leaching.

Root length distribution

The methods used to sample roots and separate root material from soil were described in full by Anderson *et al.* (1998). Root lengths of the collected root subsamples (excluding lupin tap-root) were obtained by scanning for root length using an edge discrimination procedure with a desktop scanner (Pan and Bolton 1991). For better contrast during the scanning process, roots were stained with methylene blue dissolved in ethanol. Root length densities were calculated using the length : mass ratios of the scanned root subsamples, which for wheat were 150 mm/mg for the top 0·1 m depth and 230 mm/mg below 0·1 m, and for pasture and lupin were 120 mm/mg for all depths.

Nitrogen budgets

Nitrogen budgets for each rotation treatment were constructed for the 1995 and 1996 growing seasons. The change in mineral N to 1·5 m, between prescribed sampling times, was assessed in terms of net mineralisation, plant uptake of soil-derived N, and potential recycling of N during grazing. Estimates of net mineralisation and plant uptake of soil-derived N were taken from Anderson *et al.* (1998). It was assumed that 90% of N removed during grazing was excreted by the mature sheep (Hume and Purser 1975) and that 80% of excreted N was in urine (Hume and Purser 1975; White *et al.* 1997). Faecal N was deemed to mineralise slowly and was not included in recycled N (Thompson and Fillery 1997). Deficits in inorganic N were recorded as N unaccounted for.

Statistical analysis

The methods used to analyse variance in NO_3^- content in soil profiles for prescribed sampling times, and levels of significance of rotation treatment, soil depth, and treatment×depth interactions are described in detail in Anderson *et al.* (1998).

Results

Rainfall and evapotranspiration

The cumulative rainfall and E_a between 11 May and 15 August 1995 are shown in Fig. 1*a*, and between 2 July and 15 September 1996 in Fig. 1*b*. Over these periods cumulative rainfall was 419 mm in 1995 and 278 mm in 1996, while cumulative E_a was 169 mm from a wheat crop in 1995 and 178 mm from a lupin crop in 1996. Weekly rates of E_a ranged between 10 and 13 mm in July and August in both years for both wheat and lupin, and from 18 to 27 mm in September 1996 for lupin.

Soil water

The $SW_{1\cdot5}$ under arable crops was reduced at grain harvest to 118 mm in 1995 and 110 mm in 1996 (Fig. 1). Late season rainfall (38 mm) in December 1995 raised $SW_{1\cdot5}$ post harvest, but this soil water had evaporated before the onset of the next growing season. March 1995 rainfall (112 mm) resulted in an $SW_{1\cdot5}$ value of 129 mm at the start of the growing season in 1995, which was higher than measured in 1996 after a long period without rainfall. The upper value for $SW_{1\cdot5}$ approached 200 mm in 1995 and 180 mm in 1996 (Fig. 1).

Across the experimental site, $SW_{1\cdot5}$ as measured by neutron probe showed little variation (CV 6–8%), and there were no treatment differences over the period June–October 1995 (data not presented). It was therefore assumed that the daily TDR measurements, undertaken in 1 replicate of the L–W treatment, were representative of the changes in $SW_{1\cdot5}$ across all treatments of the experimental site. The ability to account fully for rainfall in terms of stored soil water and E_a, after individual rain events, confirmed the accuracy of all of the measurements used to calculate drainage.

Autumn rainfall in 1995 recharged $SW_{1\cdot5}$ and a single rainfall event of 35 mm on 11 May 1995 was sufficient to trigger a drainage event below 1·5 m. In 1996, $SW_{1\cdot5}$ was recharged between 16 June and 1 July when the first drainage event occurred (Fig. 1*b*).

Drainage

$D_{1\cdot5}$ in 1995, derived from Eqn 1 for lupin, was 214 mm over the period 11 May–15 August (Fig. 1*a*). Less $D_{1\cdot5}$ occurred in 1996 (114 mm) primarily due to lower rainfall and a shorter period of drainage than in

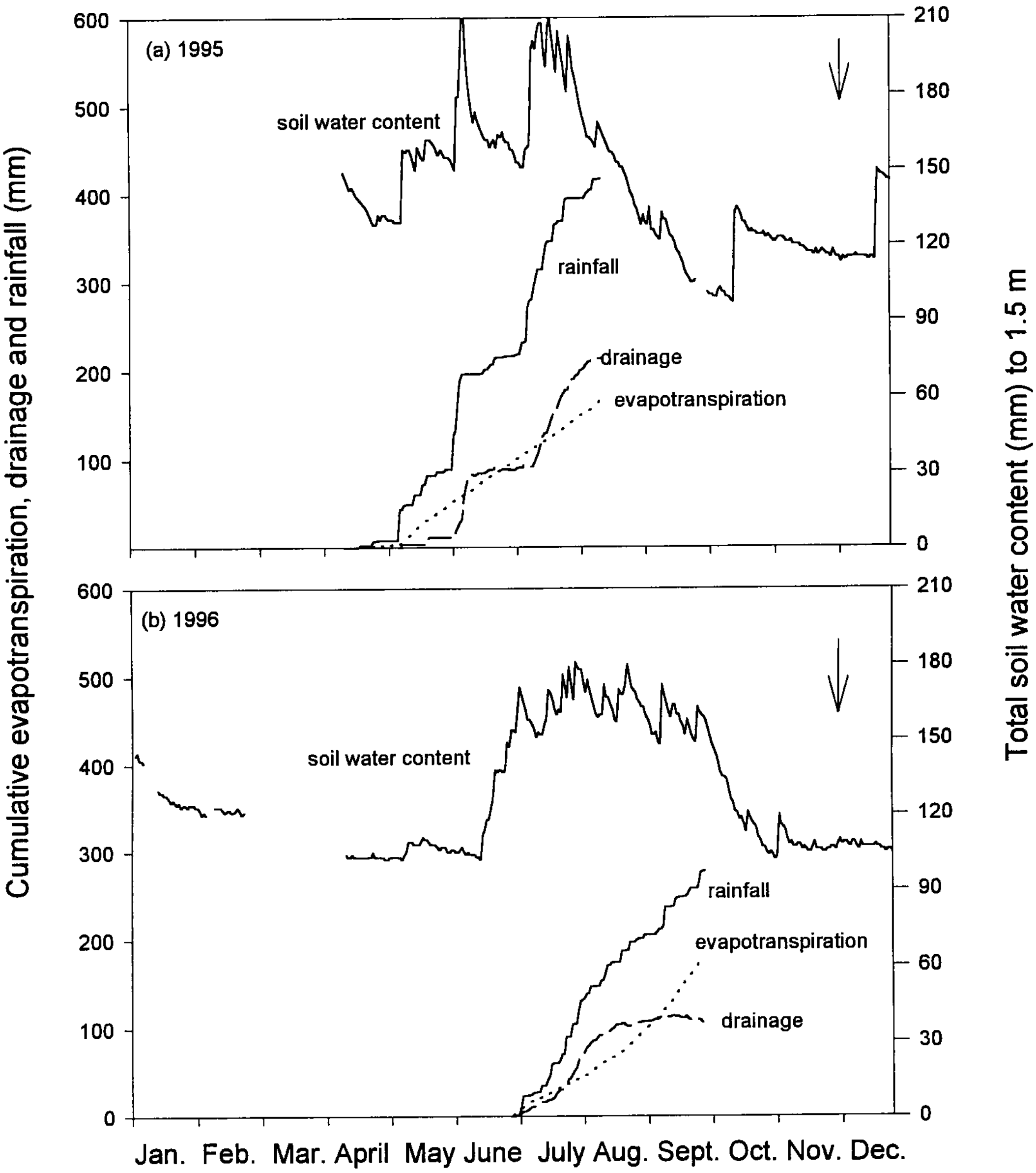

Fig. 1. Total soil water content (mm) to 1·5 m over the whole season and cumulative daily rainfall, evapotranspiration (from wheat in 1995 and lupin in 1996), and drainage (from under lupin in 1995 and an average derived from under both wheat and lupin in 1996) over the periods 11 May–15 August 1995 and 1 July–16 September 1996 at the Moora field site for (*a*) 1995 and (*b*) 1996. Arrows indicate harvest dates of crops.

1995. In 1996, drainage occurred between 1 July and 16 September (Fig. 1*b*) with similar values calculated under wheat and lupin in 1996 (data not presented).

The major drainage events in 1995 occurred between 6 and 12 June when 71 mm was computed to have drained below 1·5 m after 107 mm of rainfall, and between 6 July and 15 August 1995 when 122 mm drained after 199 mm rainfall. The period 1 July–17 August 1996 accounted for 100 mm drainage from 175 mm of rainfall.

Soil nitrate profiles

At the start of the experiment (19 March 1994) soil profiles to depth of 1·5 m contained 62–73 kg NO_3^--N/ha, with 71% of this within the top 0·3 m (Fig. 2*a*). Movement of NO_3^- from the 0–0·1 m soil layers to lower soil layers was evident by 13 June (Fig. 2*b*), and by 21 July (Fig. 2*c*) the peak concentrations of NO_3^- were between 0·9 and 1·2 m. Larger quantities of NO_3^- below 0·5 m were found under L_{94}–W_{93} than

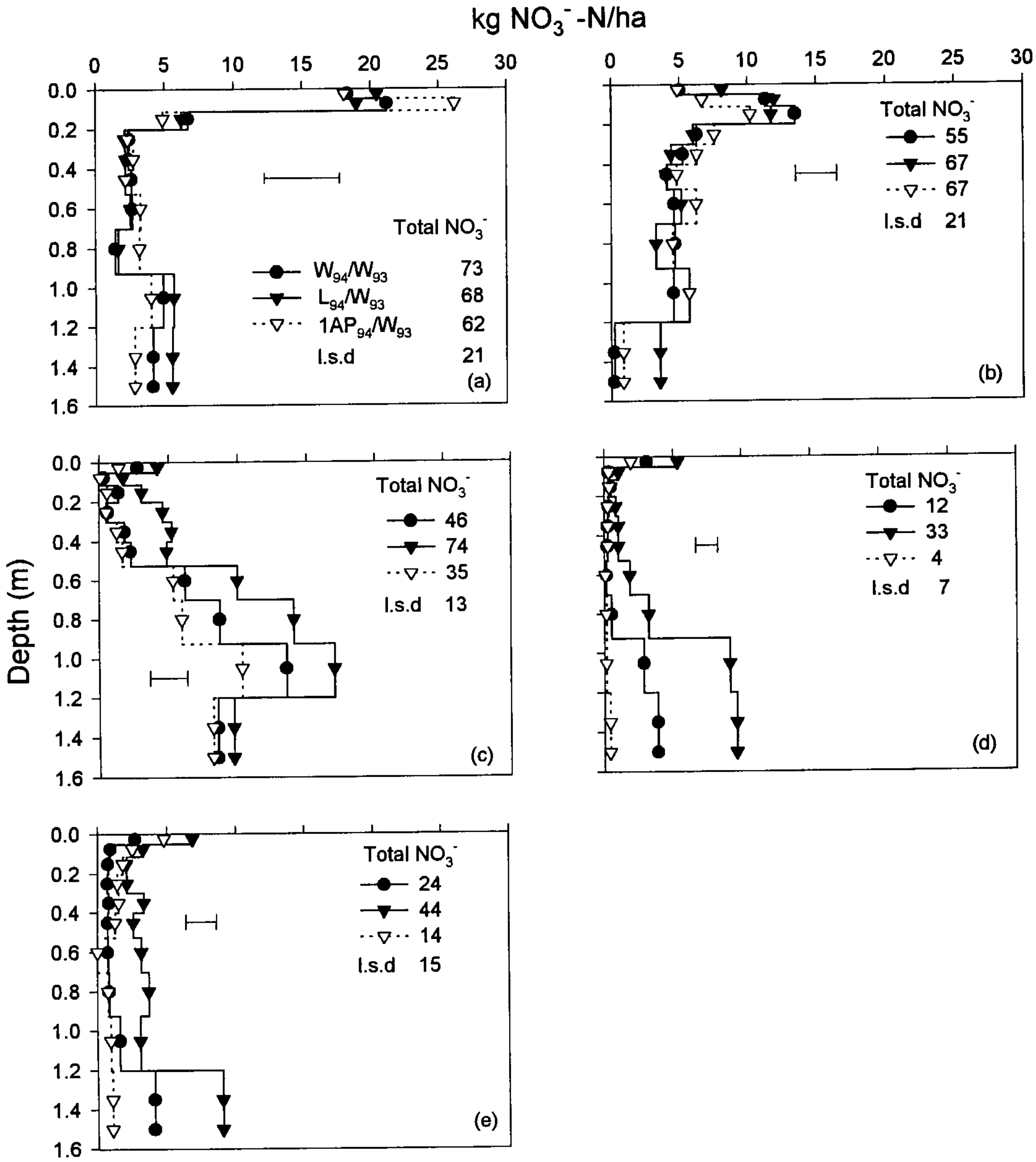

Fig. 2. Measured profile soil NO_3^- (kgN/ha) under $1AP_{94}$–W_{93}, W_{94}–W_{93}, and L_{94}–W_{93} on (*a*) 19.iii.94, (*b*) 13.vi.94, (*c*) 21.vii.94, (*d*) 26.ix.94, and (*e*) 29.xi.94. The horizontal bars represent the l.s.d. for the treatment×depth interaction. Total NO_3^- is the quantity (kg N/ha) to 1·5 m for each treatment and the corresponding l.s.d. value.

either the W_{94}–W_{93} or $1AP_{94}$–W_{93} treatment on 26 September and 29 November (Fig. 2*d*,*e*; significant treatment×depth interaction). The detection of 27 kg N/ha (60% of total soil NO_3^-) in soil below 0·5 m on 29 November under lupin, compared with 4 kg N/ha (25%) for the same soil layers under pasture, highlighted the differences in rates of utilisation of NO_3^- by the grain legume and pasture systems, and the greater potential for future leaching losses of NO_3^- from the lupin–wheat rotation compared with the pasture–wheat rotation.

In April 1995, the W_{95}–L_{94} treatment soil profile contained 70 kg NO_3^--N/ha with 57% of this NO_3^- distributed below 0·5 m whereas both the L_{95}–W_{94} and $2AP_{95}$–$1AP_{94}$ treatments contained less NO_3^- distributed throughout the soil profile (significant treatment×depth interaction) (Fig. 3*a*,*b*). The NO_3^- content in soil below 0·5 m for the W_{95}–L_{94} treatment decreased by 15 kg NO_3^--N/ha over the period 12 April–18 May 1995 (Fig. 3*c*,*d*). In contrast, there was no decrease in the quantities of NO_3^- in the soil below

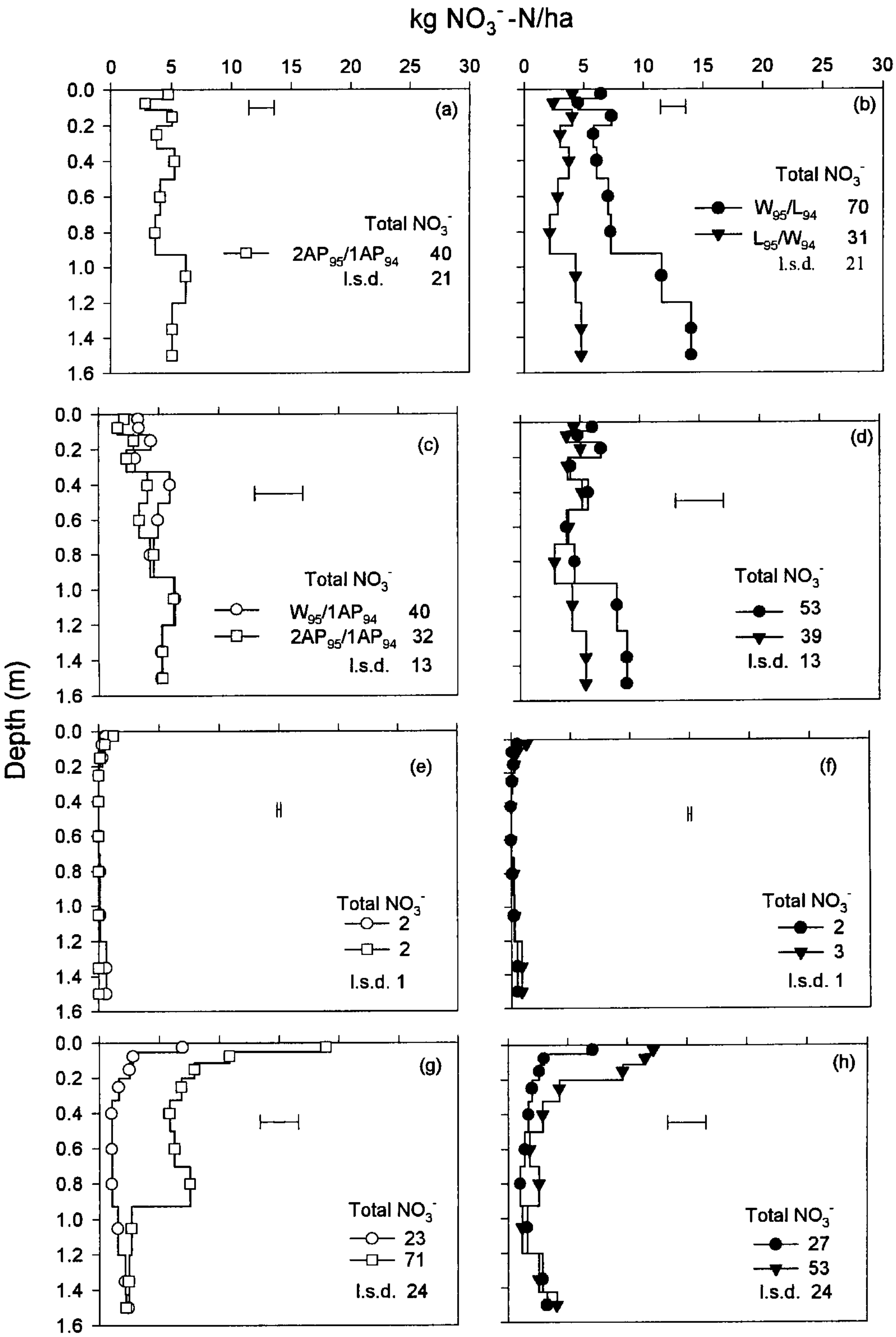

Fig. 3. Measured profile soil NO_3^- (kg N/ha) under W_{95}–$1AP_{94}$ and $2AP_{95}$–$1AP_{94}$ phases of the AP–W rotation (*a*, *c*, *e*, *g*) and W_{95}–L_{94} and L_{95}–W_{94} phases of the L–W rotation (*b*, *d*, *f*, *h*) on (*a*, *b*) 12.iv.95, (*c*, *d*) 28.v.95, (*e*, *f*) 15.viii.95, and (*g*, *h*) 27.xi.95. The horizontal bars represent the l.s.d. for the treatment×depth interaction at each sample time. Total NO_3^- is the quantity (kg N/ha) to 1·5 m for each treatment and the corresponding l.s.d. value.

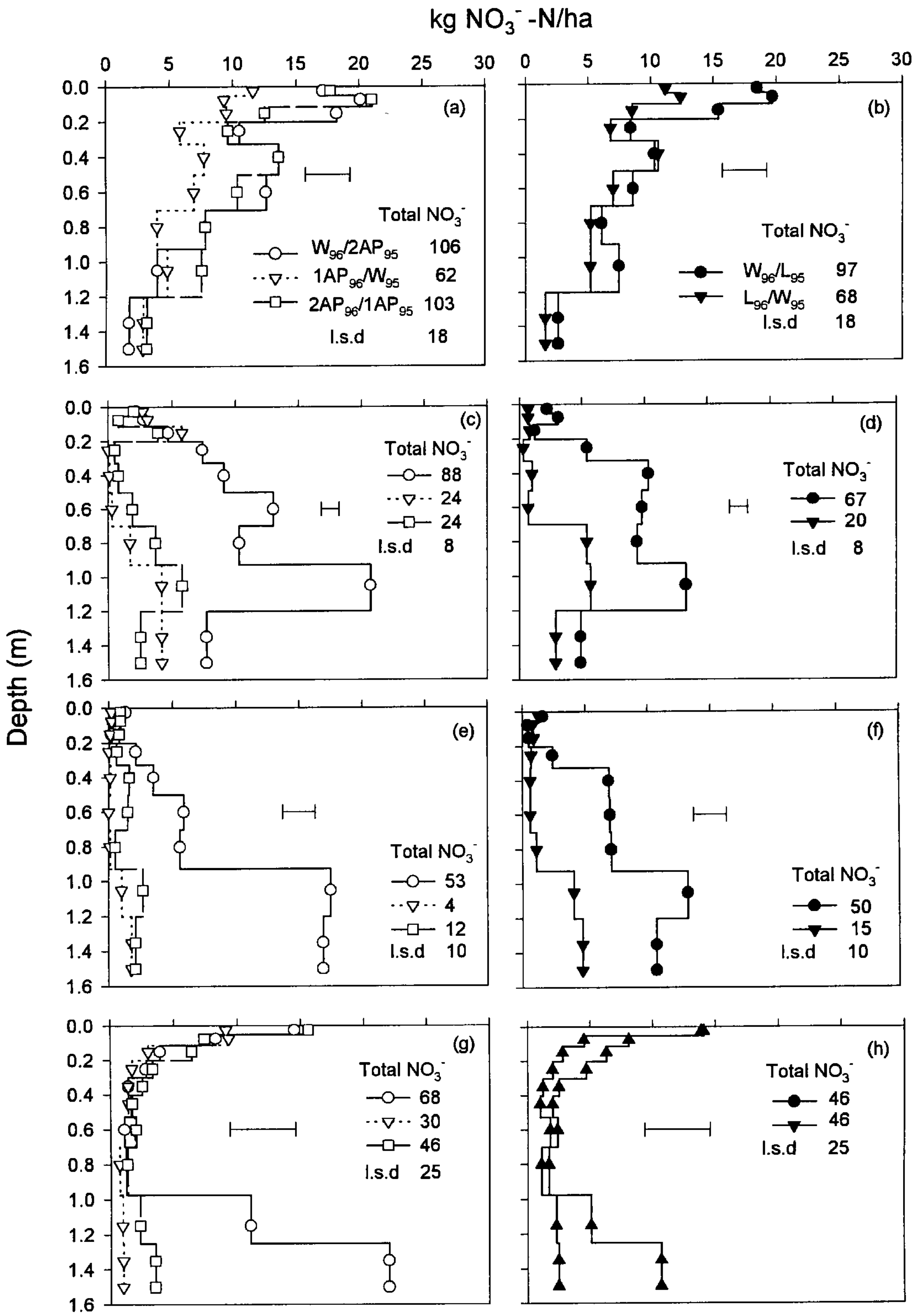

Fig. 4. Measured profile soil NO_3^- (kgN/ha) under W_{96}–$2AP_{95}$, $1AP_{96}$–W_{95}, and $2AP_{96}$–$1AP_{95}$ phases of the AP–W rotation (*a*, *c*, *e*, *g*) and W_{96}–L_{95} and L_{96}–W_{95} phases of the L–W rotation (*b*, *d*, *f*, *h*) at (*a*, *b*) 18.vi.96, (*c*, *d*) 26.vii.96, (*e*, *f*) 15.viii.96, and (*g*, *h*) 5.xii.96 sampling times. The horizontal bars represent the l.s.d. for the treatment×depth interaction at each sample time. Total NO_3^- is the quantity (kg N/ha) to 1·5 m for each treatment and the corresponding l.s.d. value.

$0 \cdot 5$ m for the $2AP_{95}$–$1AP_{94}$ and L_{95}–W_{94} treatments (Fig. 3*a*–*d*). Plant uptake reduced the level of NO_3^- in the surface $0 \cdot 5$ m soil layers by 9 kg N/ha in the $2AP_{95}$–$1AP_{94}$ treatment between 12 April and 18 May 1995 (Fig. 3*a*,*c*). The quantity of NO_3^- within the soil profile to a depth of $1 \cdot 5$ m (53 kg N/ha) on 18 May was significantly greater for W_{95}–L_{94} than the other treatments (Fig. 3*c*,*d*).

The quantities of soil solution NO_3^- were very low at the end of the period of deep drainage (15 August) for all treatments in 1995 (Fig. 3*e*,*f*). At grain harvest in 1995, the level of soil NO_3^- was greater for the $2AP_{95}$–$1AP_{94}$ and L_{95}–W_{94} treatments than both wheat treatments (Fig. 3*g*,*h*).

Large quantities of NO_3^- (97–106 kg N/ha) were found in soil profiles on 18 June 1996 where the previous treatment was lupin, $1AP_{95}$, or $2AP_{95}$, compared with W_{95} (62–68 kg N/ha) (Fig. 4*a*,*b*). At least 70% of the soil profile NO_3^- was detected in the top $0 \cdot 5$ m at this sampling time (significant treatment×depth interaction).

The distributions of this NO_3^- in soil solution are shown in Fig. 4*c*,*d* on July 26 and in Fig. 4*e*,*f* on August 15. Uptake of N by capeweed reduced the amount of NO_3^- in the top $0 \cdot 7$ m of soil in the $2AP_{96}$–$1AP_{95}$, $1AP_{96}$–W_{95}, and L_{96}–W_{95} treatments by 26 July 1996. In the case of the L_{96}–W_{95} treatment, capeweed was present as a weed which was finally removed by hand on 16 August 1996. Significantly larger total quantities of NO_3^- were found in soil solution in wheat than in pasture and lupin treatments by July 26 and August 15, with significantly larger amounts of NO_3^- in the wheat treatments located at depth (76–86% of NO_3^- in soil solution below $0 \cdot 9$ m) on 15 August 1996.

The detection of 19–35 kg N/ha (43–52% of total soil NO_3^-) in soil below $0 \cdot 5$ m for the W_{96}–$2AP_{95}$ and W_{96}–L_{95} treatments on 5 December highlights the low utilisation of NO_3^- by the wheat (Fig. 4*g*,*h*), and the potential for future leaching losses of NO_3^- from these treatments over the next growing season.

Table 1. Nitrate leached (kg N/ha) measured using anion exchange resin traps during 1994

Treatment	21.vi–22.vii	22.vii–26.ix	Total
L_{94}–W_{93}	14	10	24
W_{94}–W_{93}	13	11	24
$1AP_{94}$–W_{93}	1	1	2
l.s.d.	10	13	10

Nitrate leached

The quantities of NO_3^- retained by anion exchange resin placed at 1 m under either L_{94}–W_{93} or W_{94}–W_{93} treatment were equivalent to 24 kg N/ha in 1994 (Table 1). Significantly lower quantities of NO_3^- leached below the $1AP_{94}$–W_{93} treatment than the crop treatments in this season.

Cumulative NO_3^- leached in 1995 from below $1 \cdot 5$ m was calculated to be 59 kg N/ha from W_{95}–L_{94}, 34 kg N/ha from W_{95}–$1AP_{94}$, 35 kg N/ha from L_{95}–W_{94}, and 17 kg N/ha from $2AP_{95}$–$1AP_{94}$ (Fig. 5*a*). Rainfall events on 11 May and 6–12 June were responsible for 68% of the NO_3^- leached from the W_{95}–L_{94} treatment.

The lower drainage in 1996 than in 1995 reduced the potential for NO_3^- leaching (Fig. 5*b*). The lowest cumulative leaching in 1996 occurred from $1AP_{96}$–W_{95} (21 kg N/ha) followed by L_{96}–W_{95} (23 kg N/ha). As was the case in the 1995 season, the highest losses of NO_3^- occurred in wheat following a legume phase (43 kg N/ha for W_{96}–$2AP_{95}$ and 42 kg N/ha for W_{96}–L_{95}). Although pasture establishment was later in 1996, and the quantities of NO_3^- in the soil at the start of the growing season were greater, the amount of NO_3^- leached below $1 \cdot 5$ m for the $2AP_{96}$–$1AP_{95}$ treatment in 1996 (28 kg N/ha) was similar to the amount for the $2AP_{95}$–$1AP_{94}$ treatment in 1995 (17 kg N/ha) (Fig. 5*b*).

In 1995, the calculated values of the total amount of NO_3^- retained in soil profiles were higher (13–15 kg NO_3^--N/ha) than the measured values (2–3 kg NO_3^--N/ha, Fig. 3*e*,*f*). In 1996 the observed amounts of NO_3^- in soil profiles (x) were highly correlated to calculated values ($y = -4 \cdot 1 + 0 \cdot 8x$, $r^2 = 0 \cdot 9$).

Calculations of daily NO_3^- concentrations were unable to describe the loss of NO_3^- from the W_{95}–L_{94} treatment for the period 12 April–18 May 1995 (Fig. 3*e*,*f*), when measurements showed NO_3^- content in soil below $0 \cdot 5$ m declined by 15 kg N/ha yet there was only 4 mm of estimated drainage based on uniform infiltration of rainfall.

Nitrogen budgets

The change in total inorganic N between seeding of annual crops and their harvest in relation to net N mineralisation, computed quantities of recycled N (grazed pastures), and plant N uptake (shoot plus root) for 1995 and 1996 are summarised in Table 2. N unaccounted for was obtained by difference after determination of the changes in stored inorganic N, and totalling N inputs and N exports from each treatment. Estimates for NO_3^- leaching, based on daily drainage and interpolation of daily changes in soil solution NO_3^- are also shown. Except for W_{95}–$1AP_{94}$ and L_{95}–W_{94}, the 2 methods of assessing N loss in crop treatments gave comparable results. N losses determined by difference in pasture treatments were either the same as, or exceeded, estimates of NO_3^- leached. Ammonia volatilisation from urine patches would be expected from grazed pasture but rainfall events during, or soon after, each grazing event kept this loss small.

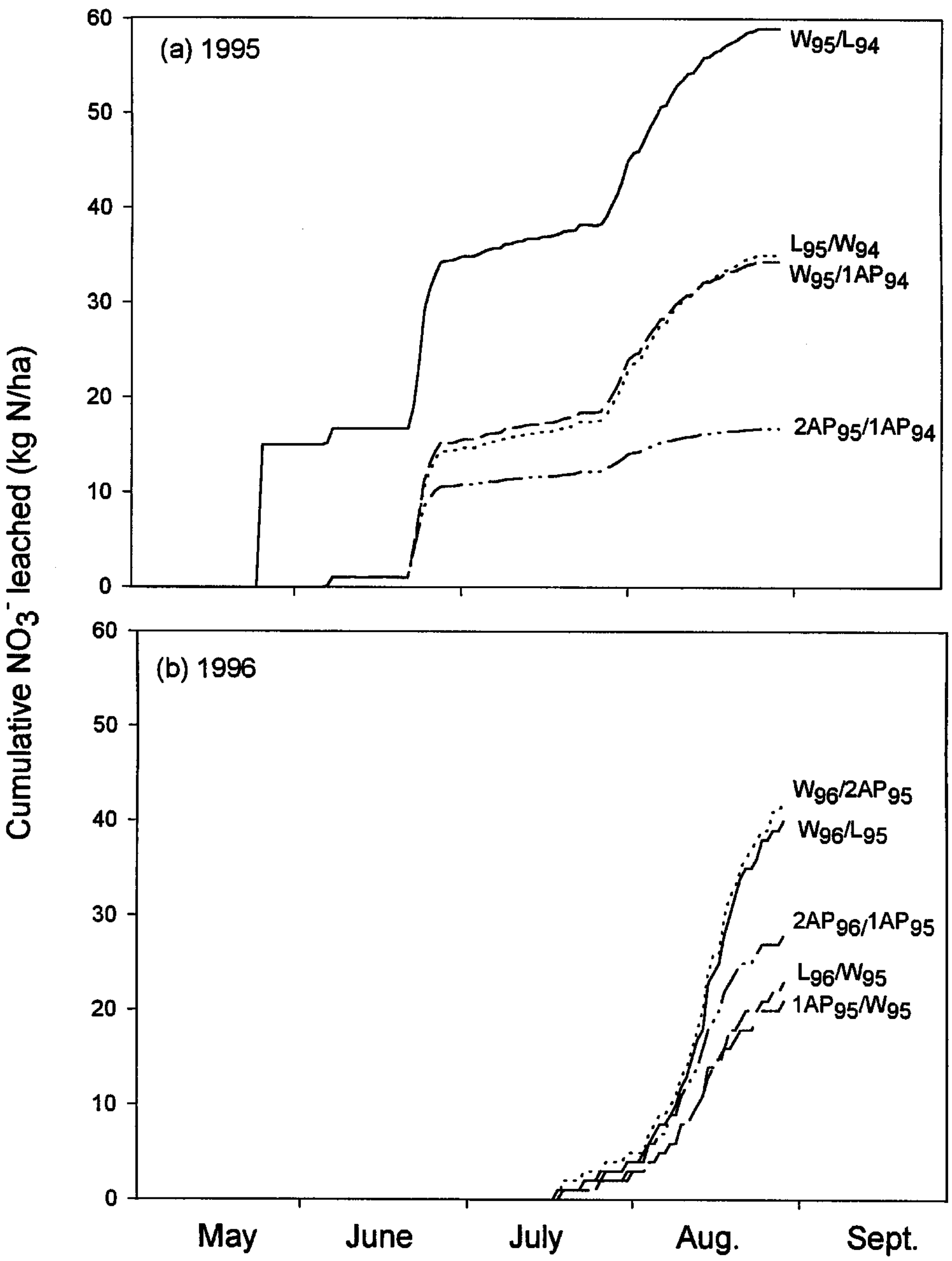

Fig. 5. Cumulative NO_3^- leached (kg N/ha) for each treatment in (*a*) 1995 and (*b*) 1996.

Root growth and water extraction

Root length densities for lupin, wheat, and annual pasture are shown in Fig. 6. In all years roots were detected at 1·5–2 m, although the densities measured below 1 m were small. The surface 0·2 m of soil exhibited the greatest range in root length densities, both temporally and between species. Overall, the lowest root length densities were recorded under lupin (Fig. 6). Nevertheless, lupin had the greater percentage of its roots below 0·5 m. Root extension to depth was greater in 1996 than in 1995, for all crops, with all treatments being deep-ripped in 1996 but not 1995.

The extraction of soil water by lupin and wheat after the cessation of $D_{1 \cdot 5}$ is shown in Fig. 7. Compared to lupin, wheat extracted less water from the soil profile below 1·0 m in 1995.

Table 2. Nitrogen budgets (kg N/ha) for treatments May–November 1995 and June–December 1996
Values in parentheses are NO_3^- leached as calculated from drainage and soil and soil solution NO_3^- measurements

N pool/process	Sampling date			Sampling date		
	18.iv.95		27.xi.95	18.vi.96		5.xii.96
		L$_{95}$–W$_{94}$			**L$_{96}$–W$_{95}$**	
Nitrate	39		53	68		46
Ammonium	13		14	7		14
Lupin uptake[A]		−42			−42	
Capeweed uptake[B]		0			−31	
Mineralisation		69			90	
N unaccounted for		−12 (35)			−32 (23)	
		W$_{95}$–L$_{94}$			**W$_{96}$–L$_{95}$**	
Nitrate	53		27	97		46
Ammonium	14		11	15		17
Wheat uptake[A]		−43			−67	
Mineralisation		72			56	
N unaccounted for		−58 (44[D])			−38 (42)	
		W$_{95}$–1AP$_{94}$			**W$_{96}$–2AP$_{95}$**	
Nitrate	40		23	106		68
Ammonium	17		8	17		15
Wheat uptake[A]		−32			−69	
Grass uptake		0			−10	
Mineralisation		80			90	
N unaccounted for		−74 (34)			−51 (43)	
					1AP$_{96}$–W$_{95}$	
Nitrate				62		30
Ammonium				9		14
Pasture uptake[A]					−115	
Recycled[C]					53	
Mineralisation					53	
N unaccounted for					−18 (21)	
		2AP$_{95}$–1AP$_{94}$			**2AP$_{96}$–1AP$_{95}$**	
Nitrate	32		71	103		46
Ammonium	14		22	22		20
Pasture uptake[A]		−104			−170	
Recycled[C]		106			90	
Mineralisation		72			57	
N unaccounted for		−27 (17)			−36 (28)	

[A] Uptake of soil-derived N by the above-ground plus below-ground biomass.
[B] Capeweed present as a weed in the lupin crop during 1996. [C] Urine deposition from sheep.
[D] For W$_{95}$–L$_{94}$ treatment, 15 kg N/ha was leached between 12.iv.95 and 18.v.95.

Discussion

Drainage

The range in absolute values for deep drainage ($D_{1\cdot5}$, 114–214 mm/year; Fig. 1*a*,*b*) reported here for annual crops grown on deep sands are larger than previous estimates of drainage for annual crops and pastures (44–154 mm/year; Nulsen 1984), which were based on measurements of recharge of watertables made at 2 sites in Western Australia over 2 seasons. However, in terms of growing-season rainfall, our estimates of drainage for deep sand at Moora (42% in 1995 and 30% in 1996) are within the range (31–58%) obtained by Nulsen (1984). Another estimate of drainage near Meckering, Western Australia, which was also based on the recharge of groundwater beneath deep sands, placed drainage at close to 54 mm/year (Williamson 1973). Asseng *et al.* (1998), using historic weather data and the APSIM model (validated using data presented in the paper), predicted deep drainage from deep sands to range from 33 to 355 mm. The yearly deep drainage of 214 mm observed in 1995 could be expected in 20% of seasons, and there was a 50% probability of at least 141 mm of drainage below 1·5 m based on historic weather data (Asseng *et al.* 1998).

Measurements undertaken elsewhere in Australia also highlight the potential for drainage under annual crops. Ridley *et al.* (1997) observed yearly drainage below 1·1 m in a red-brown earth to range from 2 to 157 mm with a non significant effect of pasture species. Poss *et al.* (1995*b*) observed 94 mm of drainage below 0·9 m in a red Kandasol soil in New South Wales during

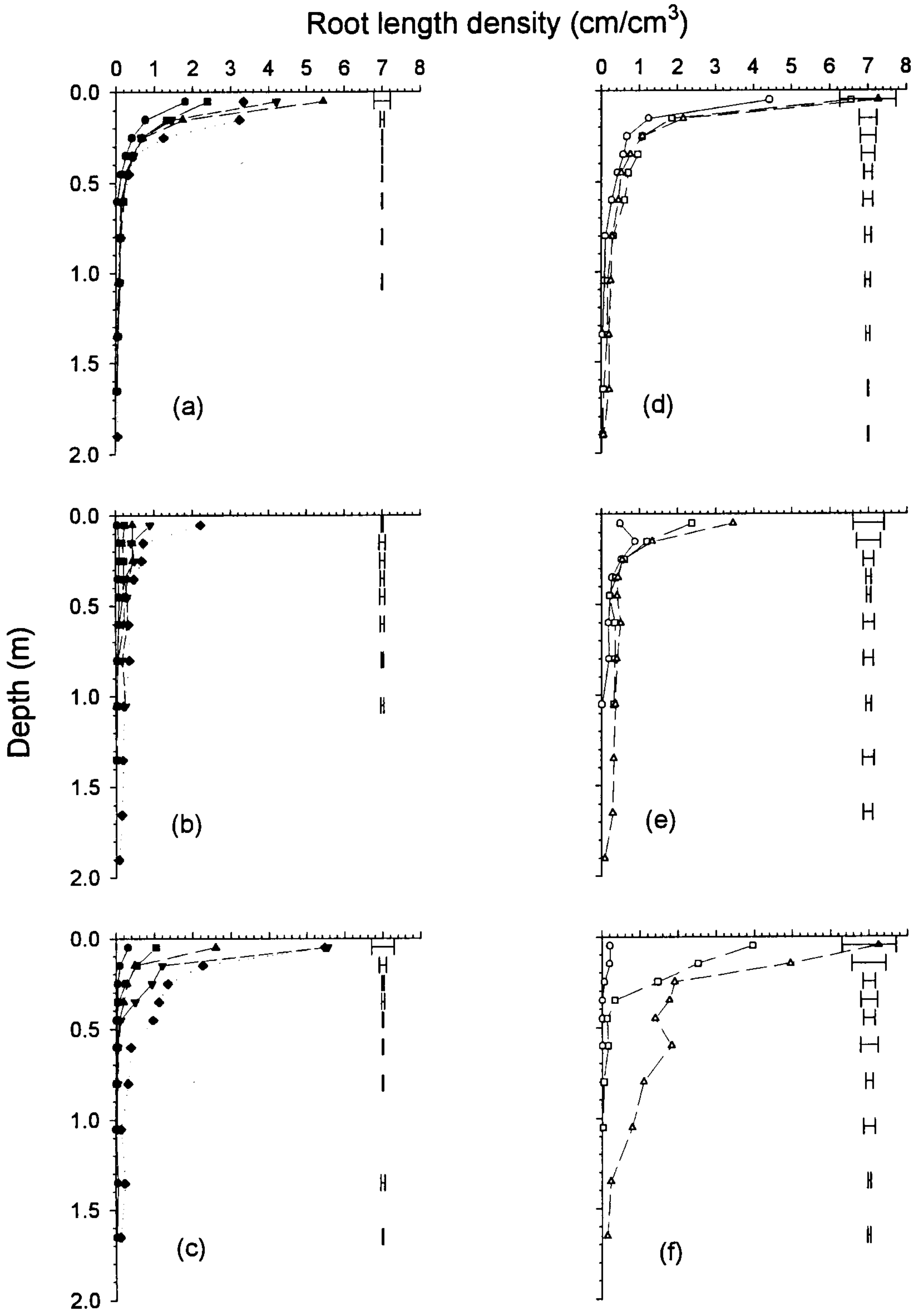

Fig. 6. Root length densities in relation to soil depth for (*a*, *b*, *c*) 1995, and (*d*, *e*, *f*) 1996, for (*a*, *d*) pasture, (*b*, *e*) lupin, and (*c*, *f*) wheat. Roots were sampled on 19 May (●, only pasture), 16 June (■), 12 July (▲), 14 August (▼), and 6 September (◆) in 1995; and on 18 July (○), 16 August (□), and 23 September in pasture and lupin and on 10 October in wheat (△) in 1996. The horizontal bars represent the standard errors (s.e.) of the mean at each depth at the final sampling in each year. Missing s.e. bars represent values below $0{\cdot}2$ cm/cm^3.

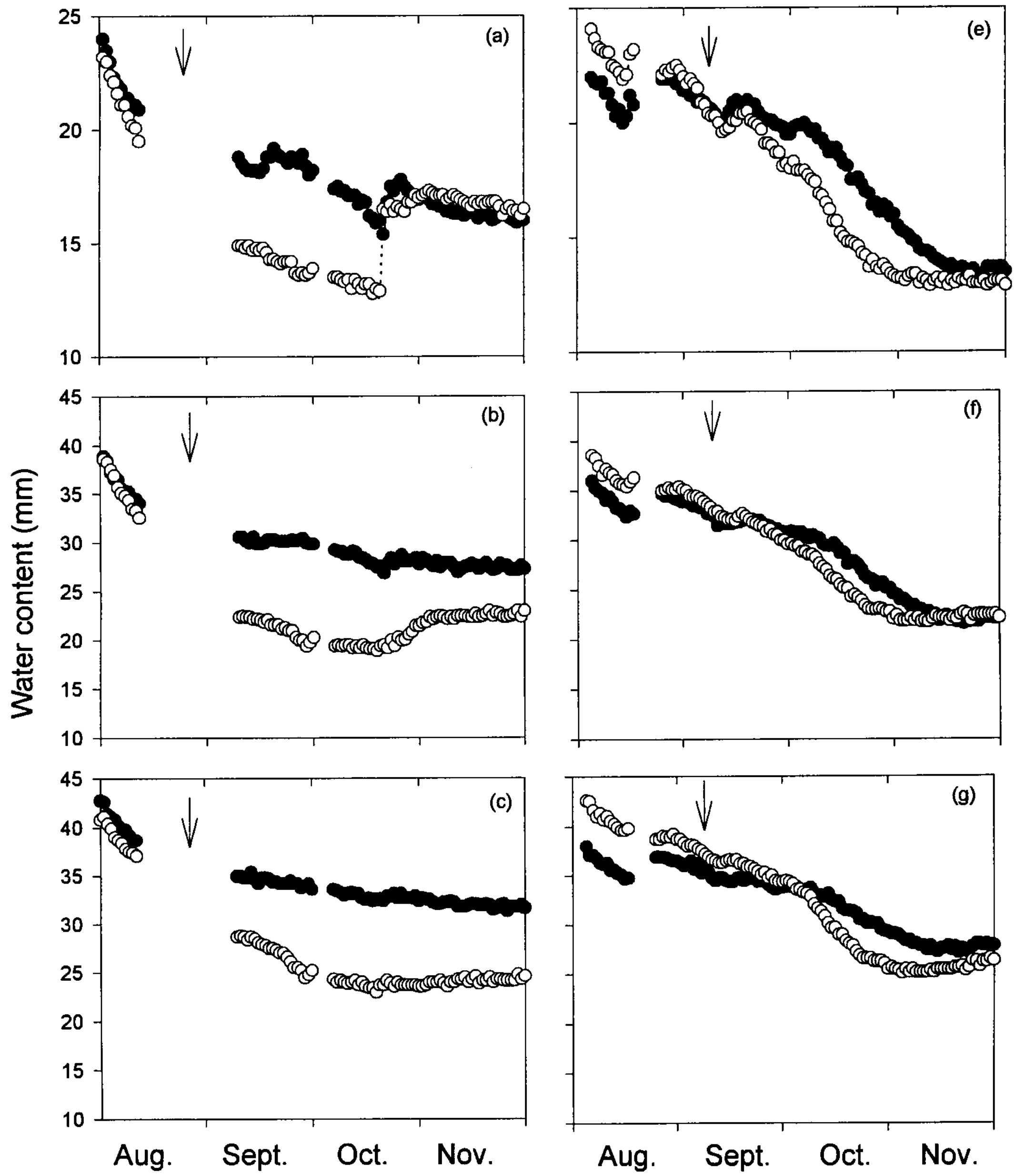

Fig. 7. Amount of soil water (mm) in the wheat (●) and lupin (○) treatments between the soil layers (*a*, *e*) 0·7–0·9 m, (*b*, *f*) 1·0–1·2 m, and (*c*, *g*) 1·2–1·5 m as measured by TDR in (*a*, *b*, *c*) 1995 and (*e*, *f*, *g*) 1996 for the period after deep drainage had ceased (as indicated by the arrows) until crop harvest.

1993, a season in which June–October rainfall was equivalent to the wettest 6% of years recorded. Allison and Hughes (1978) estimated annual recharge, using isotope methods, to be 50–270 mm/year for different soil groups in the Mt Gambier region of South Australia (annual rainfall of 704 mm). These quantities of drainage under crops and annual pastures are thought to be responsible for the rise in watertables in many agricultural catchments in southern Australia in the time since clearance of native perennial vegetation. In many catchments the elevation of the watertable has brought saline water within the rooting zone of crops and pastures, a process which threatens the sustainability of traditional agricultural systems (George *et al.* 1997). Reduced recharge of watertables would appear to be needed to slow the spread of salinity in these environments.

Changes to agronomic practices to increase dry matter production of existing annual crops and pastures have been suggested as a means to decrease drainage and groundwater recharge (George *et al.* 1997). However, this strategy is unlikely to change annual recharge appreciably because drainage occurs soon after the start of the growing season when either crops are not present or pasture and crop growth is slow. Our data reinforce the need for the introduction to rotations of crop and pasture species that are able to extend water use into the early summer or use water during summer and autumn (George *et al.* 1997). Alternatively, where groundwater is not saline this water resource could be used to irrigate summer crops.

Nitrate leaching

The drainage of soil water soon after the start of the winter rainfall, when the content of NO_3^- within soil profiles was large, resulted in NO_3^- leaching being an important pathway of N loss in this deep sand. Nevertheless, the range in quantities of NO_3^- leached beneath the 3 rotations studied offers some optimism that changes in agronomic management could result in lower losses of NO_3^- (Fig. 5*a*,*b*). Overall, the wheat phase of both rotation management systems was the most prone to leaching, due to the combined effects of relatively high NO_3^- within the soil profile at the break of the season following legumes (Figs. 3*a*,*b*; 4*a*,*b*) and the low utilisation of this soil NO_3^- by the wheat crop (Anderson *et al.* 1998). Clover–capeweed pasture was less prone to NO_3^- leaching than both cropping phases, primarily because capeweed has a large capacity to take up soil inorganic N (Anderson *et al.* 1998). The amount taken up by capeweed appeared to be related to the quantity of NO_3^- within the soil profile at the break of the season and we conclude that this species is an important sink for NO_3^- in annual pastures, as has been noted elsewhere (Unkovich *et al.* 1998). The potential for NO_3^- leaching under a lupin–wheat cropping system appears to be greater than for an annual clover based pasture–wheat rotation. This is due to the more frequent occurrence of a wheat phase after lupin and the greater utilisation of soil-derived N by the pasture phase than the lupin phase. Our work suggests that the selective removal from pastures of capeweed and grasses, which possess the capacity to use larger quantities of NO_3^- than legumes, may result in increased NO_3^- leaching and faster rates of soil acidification under a pasture–wheat cropping system.

In general, the downward movement of NO_3^- followed classical piston flow. However, displacement of NO_3^- to depth appeared to be greater after autumn rainfall than could be accounted for by assuming uniform infiltration of rainfall (Fig. 3*c*,*d*). Surface soil exhibited non wetting properties when dry, and it is assumed that infiltration was not uniform over the soil surface during autumn rainfall, as has been observed previously in water-repellent soils (Dekker and Ritsema 1996; de Rooij and de Vries 1996).

There are few detailed estimates of NO_3^- leaching for Australian legume-based rotations, and no other studies on sandy soils in this continent. Smith *et al.* (1998) reported that only 4·2 kg N/ha was leached from a red earth (red Kandasol) sown to wheat in a season when 94 mm of drainage occurred below 0·90 m. In contrast, 112 mm of drainage for the same soil under lucerne, in 1995, resulted in 12 kg N/ha of NO_3^- leached beyond 0·9 m. The much lower estimates of NO_3^- leaching for red earths than for the deep sand is attributed to the finer texture and the different temporal patterns of drainage in relation to N mineralisation and N uptake from those observed in this study. Alluvial soils near Lincoln, New Zealand (660 mm annual rainfall), studied by Adams and Pattinson (1985), have physical properties that are closer to the sands than the red earths. These workers put annual NO_3^- leaching at 10 kg N/ha for a lightly grazed white clover pasture grown for seed, 90 kg N/ha in the winter following a summer pea crop, 60 kg N/ha for spring wheat following a summer pea crop and a previous clover pasture, and 35 kg N/ha for the second year of wheat with undersown clover, which are all within the range of estimates of NO_3^- leaching determined in our study.

Value of 'spared' nitrate and summer-derived mineral N

The large quantities of NO_3^- in soil at the start of growing season rainfall contributed substantially to the NO_3^- leaching in these studies (Figs 2*a*; 3*a*,*b*; 4*a*,*b*). This NO_3^- can be traced to N mineralisation in the previous legume phase (Evans *et al.* 1991; Anderson *et al.* 1998) or N mineralised from plant residues and soil organic matter between growing seasons (Anderson *et al.* 1998).

The low utilisation of soil NO_3^-, or sparing of NO_3^- by lupin, has been documented in the review of Unkovich *et al.* (1997). This conservation of inorganic N is considered to be a factor in the production of high grain protein in wheat crops in south-eastern Australia by ensuring a supply of NO_3^- at depth in soil for utilisation late in the growth of cereals (Angus 1992). However, based on the W_{95}–L_{94} observations, 'spared' NO_3^- cannot be considered a reliable source of inorganic N for subsequent crops in soils prone to drainage; rather, it contributes to N leaching.

Nitrogen calculators (Bowden and Diggle 1996) have become popular methods to assist with the determination of fertiliser N requirements for cereals or oilseeds.

Some have the provision to increase the supply of soil-derived inorganic N based on the occurrence of summer rainfall. Although this facility is useful in the computation of N availability, blanket assumptions that this N is retained in soil could lead to serious overestimates of the capacity of soil to supply inorganic N. The availability of inorganic N produced over the summer and autumn to a cereal crop would be determined mainly by the amount and intensity of deep drainage over the subsequent growing season (Fig. 5*a*,*b*).

Root distribution and exploitation of NO_3^- *and water*

The distribution of roots reported here (Fig. 6) is typical for arable crops grown on sandplain soils (Hamblin and Hamblin 1985). The large quantities of NO_3^- that remain below 1·2 m in soil profiles at the harvest of wheat and lupin (Anderson *et al*. 1998), and the poor utilisation of soil water below this depth by wheat in particular (Fig. 7*c*), highlight the inability of these crops to extract these resources. The higher root length density at depth of wheat in 1996 than in 1995 is attributed to deep-ripping, which reduces soil compaction that is often observed in deep sands (Jarvis 1986).

Abrupt cessation of deep soil water extraction was observed in both 1995 and 1996 following leaf drop in lupin (Fig. 7). Genetic modification of lupin is needed to overcome premature leaf drop response to soil water deficits in spring to help improve late season water use in this crop.

It is notable that capeweed was a more effective user of soil NO_3^- than wheat, lupin, and clover, even when germination occurred at about the same time as cereals (i.e. 1996 season). Nevertheless, root length measurements under pasture did not show pasture roots to be longer at depth than those of either lupin or wheat. Little is known about the dynamics of root growth and nutrient uptake by capeweed. Our observations, and those of Unkovich *et al*. (1998), suggest that capeweed is well adapted to the sandy soils of the Mediterranean climatic zone, and therefore may be a useful model of an annual plant for this region.

Future management to reduce nitrate leaching

The long period over summer without growing plants contributed to the build-up of soil NO_3^- prior to periods of drainage. 'Catch' crops have been advocated to minimise NO_3^- leaching between traditional crop phases in temperate production systems where rainfall distribution and temperature permit growth (Wagger and Mengel 1988; Martinez and Guiraud 1990; Francis *et al*. 1995). The low probability of summer and autumn rainfall in the Moora region, coupled with high ambient temperatures, preclude the regular use of short-season 'catch' crops. However, short-season 'catch' crops may be beneficial in seasons with early summer rainfall to reduce the quantities of soil water and mineralised N in soils before the break of the next season. Use of perennial pasture species in preference to annuals may also help to reduce NO_3^- loss if these are efficient users of soil NO_3^- over summer and autumn. Minimum tillage compared with conventional cultivation should reduce the amounts of NO_3^- leached by shortening the period between the onset of growing season rainfall and germination of crops.

The larger loss of NO_3^- through leaching under lupin, compared with first year pasture after wheat (Table 1; Fig. 5*b*), illustrates the potential for greater leaching under legume monocultures. The uptake of 31 kg N/ha by volunteer capeweed in the early stages of lupin growth in the 1996 season highlights the possible beneficial effect of the inclusion of low densities of a NO_3^- scavenging species in lupin crops to reduce NO_3^- leaching. The use of nitrophilic species as short-term intercrops with lupin warrants further examination. Canola has been recently introduced into the farming system on deep sands in Western Australia and may reduce NO_3^- leaching compared with wheat. The ability of canola to utilise soil-derived N, compared with wheat, should be examined over a range of seasonal conditions. N budgets are also required for each rotation phase from which efficient management of N fertiliser inputs can be developed.

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