Nitrate Leaching under Wheat Crops in the Mediterranean-type Environment of Western Australia

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Abstract: A quarter of the agricultural land in the Mediterranean-type environment of Western Australia is sown to wheat with the potential for large amounts of water draining below the root zone each year. Nitrogen from soil mineralisation in the form of NO_3^- readily moves with draining water and the amounts can be substantial, but also highly variable in such an environment. Leached NO_3^- can be a major loss of a valuable resource, causes soil degradation through soil acidification and contributes to environmental problems by nitrifying wetland and river systems. A crop simulation model (APSIM) was used to evaluate the amounts and variability of NO_3^- leaching below the root zone of wheat crops in Western Australia. APSIM calculates crop development, growth and yield, water and nitrogen dynamics in the soil, as well as uptake of water and N by the crop. Nitrate leaching below the root zone was simulated for five major soil types at a location in the medium rainfall zone (350-450 mm average annual rainfall) of Western Australia with dominant winter rainfall. Soil profiles were assumed to either contain 50 or 100 kg NO_3^- N in the autumn with the NO_3^- distributed in either the 0-30 cm or 30-60 cm soil layers. Simulations were carried out with 90 years of historical weather records from Wongan Hills (390 mm annual average rainfall) with annual rainfall ranging from 161 to 675 mm. Simulated values for NO_3^- leaching ranged from 0 to 163 kg N/ha, with wide variation in respect to season, soil type and initial content and distribution of NO_3^- in soil. Based on the simulations undertaken, a framework was derived for a simple approximation of potential NO_3^- leaching based on soil type, initial NO_3^- in soil and annual rainfall.

Keywords: APSIM-Nwheat; Modelling; Nitrogen; Simulation

1. INTRODUCTION

About one quarter (5 million ha) of the agricultural land in the Mediterranean-type climate of Western Australia is sown to spring wheat (*Triticum aestivum* L.) each year [Anon, 2000]. Crops are typically sown on the first major rainfall from mid May through to the end of June. Seventy five percent of the annual rainfall is received between May and October, resulting in a high potential for water loss from deep drainage especially in winter when vegetative growth and N uptake is slow due to low temperatures and low solar radiation [Asseng et al., 2001a]. Increasing temperatures and radiation in spring (September-October) allow high growth rates, but declining rainfall and high temperatures often restrict the growing season in spring and early summer [Regan et al., 1992].

Large quantities of inorganic N, chiefly NO_3^-, can accumulate in soil during the summer-autumn period in the annual legume-based ley systems of southern Australia [Fillery, 2001]. The amount of inorganic N in the soil after legume phases is dependent on the amount of rainfall in the period between the legume and the subsequent crop phase, and previous legume history. Leaching of NO_3^- that accumulates in the soil before periods of drainage in ley farming systems can be a major mechanism of N loss. For example, 40 - 60 kg NO_3^- N/ha leached below 1.5 m in deep sands during wheat phases following either subterranean clover/capeweed pastures or lupin crops and without N fertiliser additions [Anderson et al., 1998]. Smaller amounts of NO_3^- leaching would be expected on fine-textured soils that have inherently larger water-holding capacities and hence lower rates of drainage than sandy soils for similar rainfall conditions [Fillery, 1999]. Smith et al. [1998] reported that only 4 kg NO_3^- N was leached below 0.9 m when a wheat crop was grown on a clay near Wagga Wagga in a season with 97 mm of drainage below 0.9 m.

Leaching of NO_3^- mineralized from organic sources is one of the major causes of soil acidification in Western Australia [Helyar and Porter, 1989]. Plant growth and yield are reduced significantly on acid soils (pH measured in calcium chloride < 4.8) due to the toxic effects of aluminum on root growth [Dolling et al., 1991]. Nearly 25% of Western Australia's cropping soils have a pH below 4.8 [P.J. Dolling, unpublished]. Widespread applications of neutralizing agents such as lime are required to ameliorate these soils. A total of 3.6 kg of $CaCO_3$/ha is required to neutralize the acidity when 1 kg/ha of NO_3^- is leached, with nitrate resulting from an organic or urea source [Helyar and Porter, 1989].

The quantity of NO_3^- leached depends on soil hydraulic properties, the timing and intensity of rainfall and the amount and timing of N mineralisation. Therefore, measurements of NO_3^- leaching are not easily transferable across seasons, locations and soil types [Fillery, 1999]. Biophysical soil-crop models are useful tools to estimate NO_3^- leaching for a range of soil types, climate (primarily amount and distribution of rainfall) and crop management. A simulation analysis was conducted to quantify the amount and variability of NO_3^- leached below the root zone of wheat crops for different initial soil NO_3^--N profiles, across soil types and a wide range of historical weather scenarios. The data were used to derive a simple approximation of the potential NO_3^- loss based on soil type, initial N profile and annual rainfall for wheat crops grown in the agricultural region of Western Australia. This framework can assist in better targeting of N fertilizer and in budgeting of lime.

2. MATERIALS AND METHODS

2.1 The Simulation Model

The Agricultural Production Systems Simulator [McCown et al., 1996], APSIM-Nwheat[1] (version 1.55s), was used to estimate NO_3^- leaching below the root zone of wheat crops. This model has been rigorously tested against field measurements, in particular soil nitrogen and crop N uptake under a large range of growing conditions [Asseng et al., 1998b; 2000; 2001a; 2001b; Probert et al., 1995; 1998; Turpin et al., 1996] and NO_3^- leaching below the root zone [Asseng et al., 1998a].

APSIM is a simulation model, comprising modules dealing with soil water (using the module SOILWAT which simulates the vertical water movement in a layered soil system using a multi-layer cascading approach), soil nitrogen (SOILN), crop residues (RESIDUE), crop growth and development (Nwheat) and their interactions based on daily calculations. The module APSIM-Nwheat calculates the potential growth of wheat not limited by pests, diseases, weeds and lodging, but limited by temperature, solar radiation, water and nitrogen supply.

APSIM-Nwheat was developed from the CERES family of crop and soil models [Ritchie et al., 1985; Jones and Kiniry, 1986], and the PERFECT model [Littleboy et al., 1992], as modified by Probert et al. [1995; 1998]. The main differences between the APSIM-Nwheat model and the CERES-Wheat model are summarized by Probert et al. [1995] and Asseng et al. [1998b].

2.2 Soil Mineral Nitrogen

Mineralisation and immobilisation of soil N are simulated in the APSIM soil N module [Probert et al., 1995; 1998]. Mineralisation and immobilisation are simulated using a constant C:N ratio of the receiving organic matter pools. Mineral N released from organic material during mineralisation and immobilisation of inorganic N into organic material are both functions of the quantity of surface residues, the size of organic matter pools and their C:N ratio, plus soil temperature and soil moisture. The soil N module also simulates nitrification, denitrification and urea hydrolysis considering NH_4-N, NO_3-N and urea-N concentration, soil temperature, soil moisture, active organic carbon and soil pH [Probert et al., 1995; 1998].

In the model NH_4-N is assumed to be immobile in the soil while NO_3-N and urea-N move with the mobile water according to their concentrations. Nitrate and urea, if the latter is present, are displaced into a lower soil layer by the downward movement of water. Any NO_3-N or urea-N entering a soil layer is included when determining the concentration for displacement into the next layer down. If N fertiliser is applied, the fertiliser is added to the soil urea-N, NH_4-N or NO_3-N pools according to the components of the fertiliser.

[1] Documented model source code in hypertext format can be obtained by writing to Dr B.A. Keating, CSIRO Sustainable Ecosystems / APSRU, Long Pocket Laboratories, 120 Meiers Road, Indooroopilly, Qld 4068, Australia, email: Brian.Keating@cse.csiro.au, or can be viewed at www.apsim-help.tag.csiro.au.

2.3 Simulation Experiment

A simulation experiment was conducted using five major soil types: deep sand, duplex (sand over clay), acid loamy sand, loamy sand and clay soil in Western Australia [Asseng et al., 2001a] with plant available soil water-holding capacities in the potential root zone from 55 to 130 mm. Ninety years (1907-1996) of historical weather records from the medium rainfall zone (350-450 mm annual long-term average rainfall) at Wongan Hills (31.0S 116.7E) were used in the experiment. Over these years the annual rainfall ranged from 161 to 675 mm, giving years with rainfall below the long-term average rainfall of low rainfall locations (300-350 mm) and above the long-term average of high rainfall locations (450-600 mm) in Western Australia.

Table 1. Initial soil N profiles set on 1st April each year.

Soil depth (cm)	Nitrate in soil profile (kg N/ha)			
	A1	A2	B1	B2
0 - 30	50	100	0	0
30 - 60	0	0	50	100
>60	0	0	0	0

The soil water was re-set on 1st January each year to the lower limit (LL) to avoid any carry-over effects between years. Sowing time was controlled by the following rule: it occurred between 5th May and 31st July, but did not occur before 5th June unless at least 25 mm of rainfall had accumulated within the previous 10 days or after 5th June until at least 10 mm of rainfall had accumulated.

Four soil NO_3-N profiles were initialized on 1st April each year with 50 and 100 kg N/ha evenly distributed between 0-30 cm and 30-60 cm layers, respectively (Table 1). These NO_3^- profiles represent possible scenarios of soil N resulting from mineralisation of previous cereal and legume residues [Fillery, 2001] and movement of NO_3^- due to summer rainfall. Zero and 50 kg N/ha was applied as urea at sowing as an additional treatment to analyze the effect of fertilizer N.

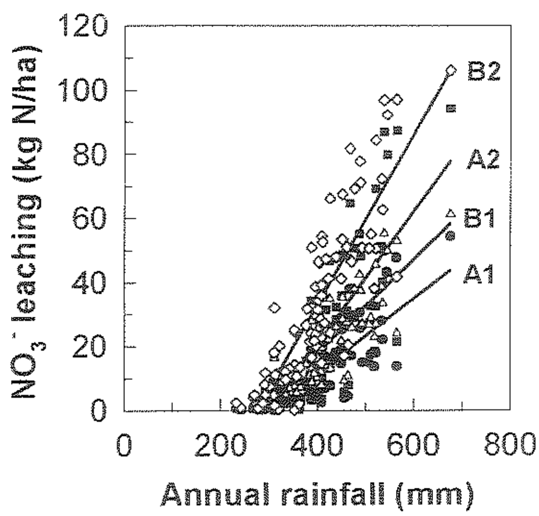

Figure 1. Simulated NO_3^- leaching below the potential root depth of 150 cm in an acid loamy sand with initial soil N profiles: A1 (●), A2 (■), B1 (△) and B2 (◊). No fertilizer N was applied to the crop. Lines show linear regression for each initial soil N profile (r^2 = 0.80-0.86).

Table 2. Average (±s.d.) threshold rainfall needed to start NO_3^- leaching below the potential rooting depth in a soil (average of years, for all soil NO_3^- profiles, and zero and 50 kg N/ha fertilizer N).

	Soil type				
	Sand	Duplex	Acid loamy sand	Loamy sand	Clay
Potential root depth (cm)	150	70	150	230	130
Plant available soil water-holding capacity (mm)	55	81	90	130	109
Required annual rainfall to commence NO_3^- leaching (mm)	314 ±17	296 ±28	334 ±17	408 ±8	434 ±11

3. RESULTS

The amount of NO_3^- leached below the potential root depth of wheat crops varied from 0 to 163 kg N/ha with a percentage standard deviation ranging from 43 to 206%. The amount of NO_3^- leached depended on the annual rainfall, seasonal rainfall distribution, soil type and initial soil N. However, despite large variations in NO_3^- leaching for any given annual rainfall, the intercepts of the linear regression (or the commencement of NO_3^- leaching) for each initial NO_3^- soil profile was similar (Figure 1). This is illustrated for an acid loamy sand, but the same response occurred for the other soils, although the rainfall needed before NO_3^- leaching was initiated varied with soil type.

For all soil types the threshold rainfall needed for NO_3^- leaching was only 7% lower when NO_3^- was distributed in the 30-60 cm soil layer compared to the 0-30 cm soil layer. Application of N fertilizer changed the threshold rainfall needed to initiate NO_3^- leaching by 5% on average for all soil types (r^2 for each individual regression ranged from 0.59 to 0.87, data not shown). Hence, the overall average rainfall required to start NO_3^- leaching in the treatments examined differed by less than 10% compared to average values for each soil type (except for two treatments in the duplex soil with <13% of the duplex soil average).

This finding implies that a single threshold rainfall value could be used as a simple first approximation to initiate NO_3^- leaching based on soil type and annual rainfall (Table 2).

In addition to the large effect of soil type on the commencement of NO_3^- leaching (Table 2), soil type also affected the slope of the regression (amount of N leached per mm of rainfall) as shown for the 100 kg/ha initial N in 0-30 cm treatment (A2) in Figure 2. Furthermore, the initial soil N profiles had a large effect on this slope, particularly in the low water holding sandy soils (Fig 2 and Table 3). Application of 50 kg N/ha of fertilizer N at sowing of wheat crops increased the slope of the regression by 18 to 26% for a clay and a sandy soil, respectively (data not shown).

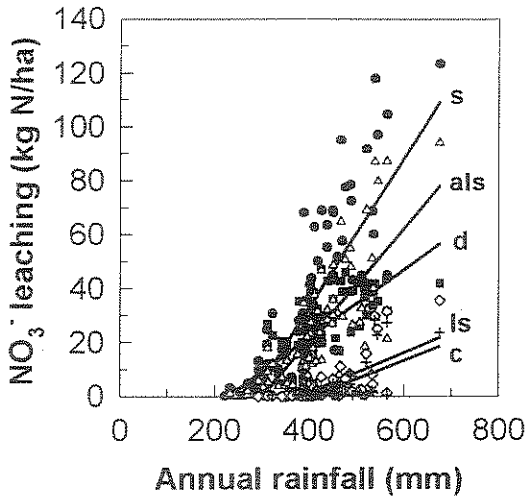

Figure 2. Simulated NO_3^- leaching below the potential root depth (see Table 1) for a deep sand, s (●), duplex, d (■), acid loamy sand, als (△), deep loamy sand, ls (◊) and clay, c (+) soil with A2. No fertilizer N was applied to the crop. Lines show linear regression for each soil type (r^2 = 0.62-0.80).

Table 3. Leached NO_3^- (kg N/ha) below the potential root depth of a soil type per mm annual rainfall received above the required rainfall amount to commence leaching (see Table 2), without N application to the crop.

	Soil type				
Initial soil NO_3^- profile	Sand	Duplex	Acid loamy sand	Loamy sand	Clay
50 kg N/ha in 0 - 30 cm (A1)	0.16	0.07	0.12	0.04	0.04
100 kg N/ha in 0 - 30 cm (A2)	0.28	0.13	0.21	0.07	0.07
50 kg N/ha in 30 - 100 cm (B1)	0.19	0.11	0.15	0.06	0.06
100 kg N/ha in 30 - 100 cm (B2)	0.32	0.21	0.26	0.11	0.11
Mean	0.24	0.13	0.18	0.07	0.07

4. DISCUSSION AND CONCLUSIONS

The values of NO_3^- leaching predicted using the APSIM-Nwheat model varied with annual rainfall, physical properties of soil types (mainly plant available soil water-holding capacity) and initial soil NO_3^- in the soil profile. Measured values of NO_3^- leaching, although also variable, generally differ less widely for a given soil type [Anderson et al., 1998; Dunin et al., 1999]. This is indicative of the limitations of site and season specific measurements as representations of a highly variable system. A simulation model can be used to overcome this limitation by taking into account the variability associated with rainfall, soil types and initial soil NO_3^- profiles. In addition, the large amount of output data created by the simulation model allows a comprehensive analysis of the system and the search for simple approximations that can account for most of the treatment differences.

The simple framework of threshold rainfall and NO_3^- leaching rate derived here can be used as a first approximation of NO_3^- leaching below the potential root depth of wheat crops grown in the agricultural areas of Western Australia. Knowledge of the plant available water-holding capacity of a soil is sufficient to estimate the commencement of potential NO_3^- leaching, since the threshold for commencing NO_3^- leaching was not effected by initial soil mineral N in the profile nor by the fertilizer N application significantly. In addition, above the annual rainfall threshold the rate of NO_3^- leaching mainly varied with soil type and initial mineral N in the profile, but less with fertilizer application rates. For example, for an average rainfall year at Wongan Hills (390 mm), using Table 2 and 3 with no additional fertilizer N applied, zero kg N/ha NO_3^- leaching is estimated for the deep loamy sand and the clay soil, and 6 to 29 kg N/ha are predicted for the deep sand, duplex and acid loamy sand, depending on the initial soil NO_3^- profile.

These estimates of the amount of NO_3^- leaching can be useful in order to determine the loss of the valuable resource nitrogen from the cropping system with possible negative effects on groundwater, wetland and river systems. The information can be used to estimate acidification rates for given projected or historical rainfall and to assist with budgeting lime requirements. Additional runs of the model could be performed to expand the estimates to take account of a wider range of initial soil NO_3^- profiles and N fertilizer application rates or other factors as e.g. initial stored soil water.

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