A SIMPLE MODEL FOR PREDICTING THE EFFECTS OF LEACHING OF FERTILIZER NITRATE DURING THE GROWING SEASON ON THE NITROGEN FERTILIZER NEED OF CROPS

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Summary

The model is based on the concept that there is an effective rooting depth above which all the inorganic N in the soil is equally available and below which all N is totally unavailable. The extent to which nitrate is leached below this depth is calculated from the excess rainfall over evapotranspiration and the water holding capacity of the soil.

The model was tested against the results of N fertilizer experiments with lettuce, French beans and overwintered onions which had been carried out in at least 2 years (and often more) on adjacent sites of the same field. The yields from all of the experiments with each crop were plotted against the level of fertilizer applied and against the difference between that applied and that lost by leaching. Comparison of these graphs showed that correcting for leaching in this way greatly reduced the variability between the response curves. The model was also tested against the results of similar experiments with Brussels sprouts grown on different sites with different combinations of base and top dressing. The results showed that the poor response to top dressing could be explained by the relatively small amounts of N in the base dressing which were leached from the rooting zone of this crop.

It appears that the model will enable worthwhile adjustments in N fertilizer dressings to be made for differences in rainfall, provided that leaching occurs during the early stages of crop growth when uptake is small.

Introduction

YEAR-TO-YEAR variation in response of crops to N fertilizer on a given soil is often considerable. Part of this variation may result from differences in the amount of nitrate leached from the rooting zone during the growing season (Fisher, 1925; Hagan *et al*., 1959). A recent examination of the influence of the spatial distribution of nitrate in the soil on N uptake has suggested a simple method for calculating the extent to which leaching can affect the availability of N to crops (Burns, 1980). By selecting simple chromatographic equations for incorporating in the method, it may be used to provide a practical tool for assessing whether N fertilizer practice needs to be adjusted for differences in leaching on individual sites.

The method is based on three main premises :

(a) An effective rooting depth can be defined for each crop such that any N in the zone above it is equally available (irrespective of the spatial distribution) and any N below it is completely unavailable.

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(b) Leaching occurs before significant uptake by the crop.
(c) The effect of leaching on growth is the same whenever it occurs.

If these assumptions are correct, the variability in yield *vs* N fertilizer level between years on the same site should be greater than the variability in the corresponding data after the N levels had been adjusted for leaching (by subtracting the amounts lost from the amounts applied). The object of this paper is to describe the model and to test its validity against the results of published N fertilizer experiments that had been carried out with four different crops. Each aspect of the model has deliberately been kept simple to facilitate its use for predictive purposes.

Methods

The method comprises four separate steps :

1. Calculation of the effective rooting depth at harvest.
2. Calculation of the total amount of fertilizer nitrate plus that nitrified from fertilizer ammonium by the time leaching occurs.
3. Calculation of the amount of nitrate displaced from the rooting zone assuming that it is initially present at the surface and that most leaching occurs before significant uptake.
4. Calculation of how much N remains available to the crop from the amount applied and the amount leached.

Details of the calculations are given below.

1. Effective rooting depth

The effective rooting depth (h cm) of each of the crops was calculated from the equation (Burns, 1980) :

$$h = 6.082\,W + 1.52 \times 10^{-5}\,\rho + (1.81 \times 10^{-3}/a^2) - 2.1 \qquad (1)$$

where W is thé dry weight of the aerial part of the crop (t ha^{-1}), ρ is its population density (plant ha^{-1}) and a is the average radius of its roots (cm). Only one value of h was calculated for each crop as it approached maturity, irrespective of the year or site of the experiment. This value was assumed to correspond to the depth at which nitrate became unavailable to that crop.

2. Nitrate present at the onset of leaching

This is the sum of the nitrate applied in the fertilizer and the amount released from fertilizer ammonium before leaching occurred. All of the ammonium was assumed to have been converted to nitrate unless most of the drainage occurred within six weeks of fertilizer application, in which case only 50 per cent of the ammonium was considered to have been nitrified. In order to keep the model as simple as possible, no attempt was made to include nitrate released from the organic matter by mineralization.

The approach was based on the experimental finding that the average half life of ammonium under field conditions was *ca* 3 weeks for much of the year (Anderson and Purvis, 1955; Tyler *et al.*, 1959; Low and Piper, 1970; Page, 1975; Burns, 1977). Assuming there are no losses of N from the soil, the release of nitrate for this half life loosely approximates to a step function in which half of the ammonium is present as nitrate for the first 6 weeks after application, and all thereafter. The use of this function enables the main effects of the slow release of nitrate and the distribution of rainfall on the leaching of nitrified N to be considered without a detailed analysis of all the interactions involved.

3. Nitrate displacement from the root zone

The amount of nitrate displaced (L kg N ha^{-1}) was estimated by a simple chromatographic equation (Burns, 1975) :

$$L = A\left(\frac{P}{P + \theta_m}\right)^h \quad (2)$$

where h is the effective rooting depth in cm (see Section 1), A is the amount of nitrate present in kg N ha^{-1} when leaching occurs (see Section 2), P is the accumulated drainage in cm, (*i.e.* the total amount of rain or irrigation water percolating through the soil) and θ_m is the field capacity of the soil (cm^3 cm^{-3}). Equation 2 gives similar predictions to other leaching equations (Pandey and Gupta, 1978), and has been shown to give satisfactory estimates of nitrate displacement provided that the soils are not prone to excessive swelling and cracking (Burns, 1975; Addiscott and Cox, 1976).

Accumulated drainage was estimated from the difference between rainfall and evapotranspiration up to and including the time of the last significant rainfall.

The quantity of water draining through the soil (P_j) during an interval j and the soil water deficit (D_j) at the end of the interval can be calculated from simple water balance equations :

$$\left.\begin{aligned} D_j &= D_{j-1} + E_j - R_j \\ P_j &= 0 \end{aligned}\right\} \text{ if } R_j < (E_j + D_{j-1})$$

$$\left.\begin{aligned} D_j &= 0 \\ P_j &= R_j - E_j - D_{j-1} \end{aligned}\right\} \text{ if } R_j \geqslant (E_j + D_{j-1})$$

where R_j and E_j are the interval totals of rainfall and evapotranspiration and D_{j-1} is the water deficit at the end of the previous interval. The total drainage (P) over a prolonged period of n successive intervals is given by the summation :

$$P = \sum_{j=1}^{n} P_j = \sum_{j=1}^{m} (R_j - E_j) - D_o \quad (3)$$

in which D_o is the soil water deficit at the start of the first interval and m is the number of the last interval for which $(R_j - E_j) \geqslant D_{j-1}$, where $m \leqslant n$. Equation 3 was used to estimate P using an interval size of 1 week. D_o normally corresponded to the water deficit in the seedbed and, as this was normally kept fairly moist, $D_o \simeq 0$.

As accurate estimation of m is impractical over long periods, drainage is often assumed to be equal to the excess rainfall ($m = n$). However, experience has shown that this assumption results in considerable underestimation of drainage when a prolonged dry spell follows intervals of heavy rainfall. A modified method was, therefore, devised in which m

TABLE 1

Estimated evapotranspiration (cm week⁻¹)

Month	For crop cover <25% (i.e. fallow soil)	For crop cover ⩾25% (i.e. established crop)
January–March	0	0
April	0.5	0.9
May	0.7	1.3
June	0.7	1.3
July	0.7	1.3
August	0.5	1.1
September	0.5	0.7
October–December	0	0

was assumed to correspond to the number of the last interval for which rain exceeds evapotranspiration (*i.e.* when $(R_j - E_j) > 0$).

Table 1 summarizes the weekly evapotranspiration data used in these calculations. The values for the 6 summer months were adapted from Monteith (1966) and M.A.F.F. (1967), and from average estimates of evaporation at Gleadthorpe EHS (Anon, 1974). Losses for the 6 winter months were assumed to be zero. Although this may cause evapotranspiration to be underestimated slightly, especially in March and October, the overall effects on drainage at this time of year are generally small.

Estimates of accumulated drainage made using this procedure were compared with more accurate predictions from a simulation model (Rowse and Stone, 1978; Rowse *et al*., 1978), which was used to calculate the water losses from a sandy loam soil under a simulated broad bean crop grown over the same period in each of 19 years (1959–77). Although the total drainage estimates from Equation 3 tended to underestimate the predictions of the model (especially when drainage was low), the two sets of data were highly correlated ($r = 0.88^{***}$), with neither the slope (0.919 ± 0.121) nor the intercept (-0.99 ± 0.50) significantly different from unity and zero respectively. Thus, there was good agreement between the predictions of the two methods.

Volumetric field capacity was estimated from the textural class of each soil using average data adapted from *in situ* measurements (Salter and Williams, 1965; Salter, personal communication), and from laboratory measurements of water content at 0.05 bar suction (Thomasson, personal communication; Rijtema, 1969) for a range of different soils.

4. The amount of N remaining available to the crop

This was assumed to equal the difference between the amount of N originally applied and that lost by leaching (calculated by Equation 2). It was assumed that the N which remained in the soil was equally available to the crop no matter how it was distributed within the rooting zone.

Experiments

The experiments with lettuce, French beans and overwintered onions were all carried out on adjacent sites of a sandy loam soil at Wellesbourne which had been cropped continuously with cereals for a minimum of 10 years immediately before each crop was grown. There were 14 experiments with lettuce (between 1966 and 1975) and 7 experiments with French beans (between 1967 and 1974) in which different amounts of ammonium nitrate fertilizer were incorporated in the surface 3 cm of soil immediately before drilling. Details of most of these experiments have been described previously (Greenwood, Cleaver and Niendorf, 1974; Greenwood, Cleaver and Turner, 1974). The results of 5 experiments with overwintered onions carried out over the winters of 1972–73 to 1975–76 (Cleaver and Turner, 1974, 1975; Cleaver *et al*., 1977) in which different amounts of N fertilizer were split between a base and one or more top dressing (applied during the winter or spring) were also used to test the model.

Response data was also taken from 11 transplanted Brussels sprouts crops grown with different combinations of base and top dressing at 4 sites throughout the country (Cleaver *et al*., 1971). The soils ranged from a loamy coarse sand to a very find sandy loam.

Tests of the Method

Final yields were expressed as a percentage of the maximum for each experiment. The combined results for all experiments with each crop were then plotted against both the original and adjusted amounts of fertilizer applied and the two sets of curves compared. The changes in variability between the response curves for each crop before and after adjusting the N fertilizer levels for losses of nitrate were used as a criterion for assessing the accuracy of the model.

The changes in variability in the response data were quantified by a statistical method. This was based on the assumption that all of the data followed a polynomial (cubic) response equation which was fitted separately to both original and adjusted data. The accuracy of the adjustments were then estimated from a comparison of the residual mean squares.

Lettuce and French bean experiments

The model was used to adjust the N levels for any leaching of nitrate which occurred between base dressing and harvest in both sets of experiments.

The combined yield response data from all of the lettuce experiments before and after adjustment are plotted in Fig. 1. This shows a considerable reduction in variability in the data after adjustment, suggesting that the losses of fertilizer N predicted by the model accounted for much of the differences in yield between experiments. This was confirmed by the statistical analysis of the data (see Table 2) which showed that there was an average reduction of *ca* 32 per cent in the residual mean squares after correcting for the losses of nitrate by leaching. However, part of this improvement may also have resulted from the alleviation of salt effects by rainfall at an early stage of growth (Greenwood, Cleaver and Niendorf, 1974).

The corresponding data for French beans showed no overall reduction in variability after adjustment (see Table 2). It is possible, however, that the

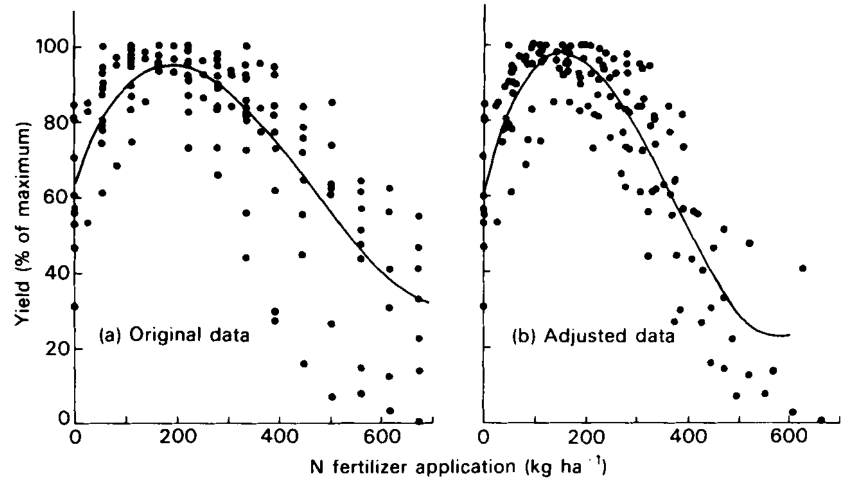

FIG. 1. Yield response of lettuce to added N fertilizer in 14 experiments: (a) before and (b) after adjusting N dressings for losses of nitrate by leaching.

effects were obscured by the large proportion of data from experiments in which relatively little leaching occurred. Thus, comparison of the results for the driest (1967) and the wettest (1968) experiments alone, shown in Fig. 2, gave a reduction of 76 per cent in residual mean squares after leaching losses had been taken into consideration.

Overwintered onion experiments

The wide range of treatment combinations in these experiments enabled the results from each experiment to be analysed separately. However, in

TABLE 2
Statistical analysis of N response data

Crop	*Year*	*% variance accounted for by response equations* — *original data*	*adjusted data*	*Ratio of: (Adjusted RMS[3] / Original RMS[3])*
Lettuce	All	64.9	76.2	0.677
French beans	All	67.3	66.0	1.040
	1967, 1968	82.6	95.9	0.238
Overwintered onions	1972–73	78.7	87.6	0.582
	1973–74	59.5	42.8	1.415
	1974–75[1]	−1.4	23.6	0.754
	1975–76(S1)[2]	31.7	31.1	1.008
	1975–76(S2)[2]	24.2	65.5	0.456
	1975–76(S3)[2]	6.7	38.2	0.662

[1]Results of two experiments (one large and one small) have been combined in this analysis.
[2]S1, S2 and S3 are sowing dates 1, 2 and 3 respectively.
[3]RMS is the residual mean squares after fitting the respective response equations.

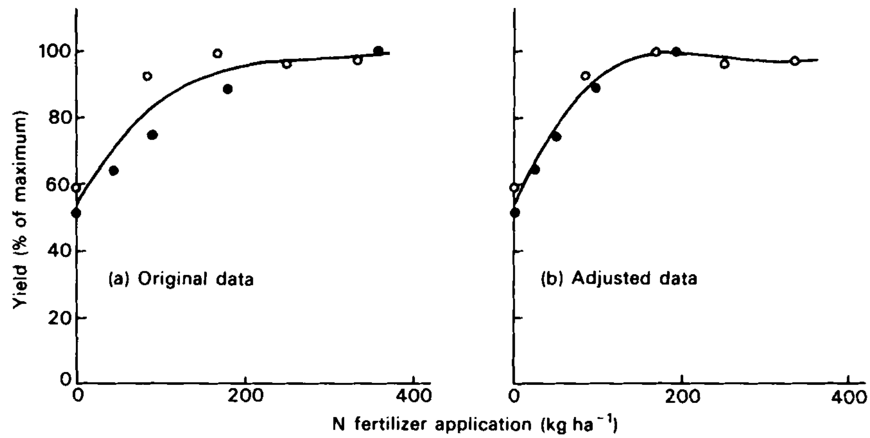

FIG. 2. Yield response of French bean to added N fertilizer in dry (○) and wet (●) conditions: (a) before and (b) after adjusting N dressings for losses of nitrate by leaching.

order to reduce the number of drainage calculations the amounts of nitrate lost by leaching were only estimated for the winter period between fertilizer application and the beginning of March, by which time all of the top dressings had been applied. Thereafter, it was assumed that any differences in nitrate leaching between treatments were small.

Graphs of the response curves for the 1974–75 and 1975–76 experiments show a considerable reduction in the degree of variation after the N levels had been adjusted for losses of nitrate, especially for the two later sowing dates in 1975–76 (see, for example, Fig. 3). This is also shown by the statistical data in Table 2, which shows substantial reductions (54

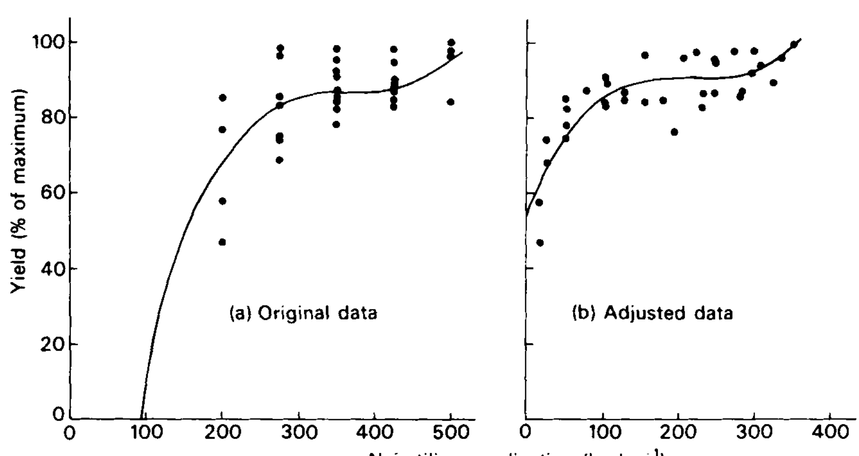

FIG. 3. Yield response of overwintered onions to added N fertilizer for sowing date 2 in the 1975–76 experiment: (a) before and (b) after adjusting N dressings for losses of nitrate by leaching.

per cent and 34 per cent respectively) in variability for this data. However, although the reductions in residual mean squares were apparently smaller for sowing date 1 in 1975–76 and for the 1974–75 experiment (0 and 24 per cent respectively), further examination of the data showed that this was caused by a few isolated results which still deviated considerably (presumably due to random variation) after adjustment for leaching was made. The results for the 1972–73 and 1973–74 experiments, also summarized in Table 2, show a substantial improvement in the data for the first experiment and a small deterioration for the second. However, as there was relatively little response over the range of N levels used in these two experiments, the corresponding values in Table 2 were influenced more by random variations in the data than by any differences in the performance of the model.

Brussels sprout experiments

The model was used to calculate the amounts of nitrate which became unavailable to the crop due to leaching during the period between application of base and top dressing in each of the experiments. The results showed that all losses were relatively small and, consequently, no formal analysis of the variation in the response data (before and after adjustment for leaching) was made.

However, the yields for treatments in which different combinations of base plus top dressing had been applied were compared with those where

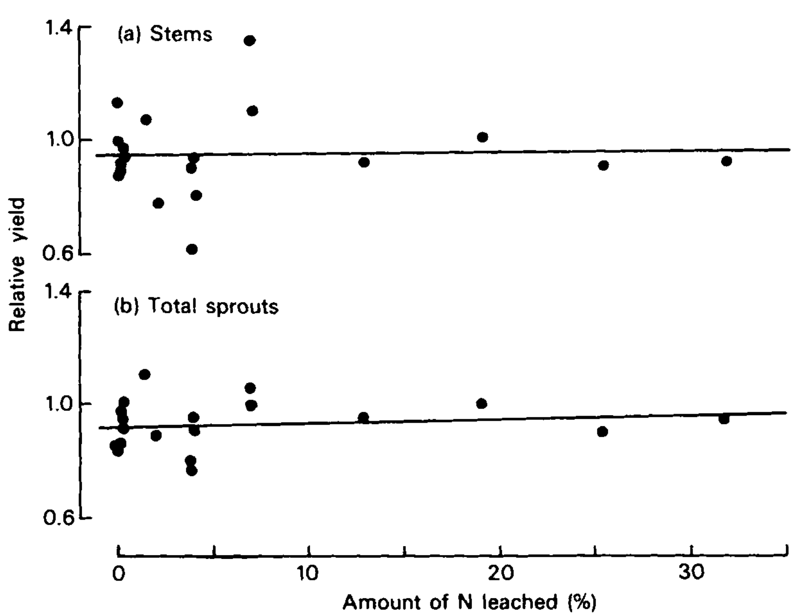

FIG. 4. Plot of relative yield *vs* amount of nitrate leached in 11 experiments with Brussels sprouts: (a) for stems and (b) for total sprouts. Relative yield is the average yield from different combinations of base and top dressings as a fraction of the yield from base dressing alone.

the same amount of N had been restricted to a base dressing alone, and the ratios of the two calculated. The average ratios for both sprouts and stems from each experiment are plotted against the corresponding proportion of N leached in Fig. 4. The results show there was no significant benefit to be obtained from applying part of the N as a top dressing, which is consistent with the predictions.

Discussion

The model is based on the assumption that most of the leaching occurs before there is significant uptake by the crop. This assumption is probably sound for many situations, because the risk of leaching tends to diminish as the crop grows (and the soil dries out), and because crop recoveries of fertilizer N often do not exceed 50 per cent even at harvest (Widdowson *et al.*, 1967; Greenwood, Cleaver and Turner, 1974; Johnston, 1976). There was, nevertheless, a tendency for the predictions to overestimate the losses of nitrate when leaching occurred late in the life of a crop. This was manifested in the results of the Brussels sprouts experiments and, to a greater extent, in an unpublished analysis of response data for transplanted winter-hardy cauliflower crops grown at Kirton (Whitwell, 1970, 1971, 1972), for which there was strong early growth.

Mineralization of organic N also affected the accuracy of the predictions, especially when small dressings of fertilizer were applied. The total amount of nitrate released from the organic matter throughout the profile during the summer depends largely on previous cropping practices. However, the proportion of this N actually available to an individual crop varies with the length and time of growth (*i.e.* with its sowing and harvest dates), and with its rooting depth. The situation is further complicated when leaching occurs, because the slow release of mineralized nitrate and the differences between the distributions of mineralized and freshly-applied fertilizer N affect the rate at which nitrate from the two sources is lost. Consequently these effects can only be satisfactorily accounted for by a more complicated dynamic model beyond the scope of this paper. Because no attempt was made to allow for mineralization in the model, there was a tendency to underestimate the total losses of nitrate from the soil. The effects of this were most noticeable at low fertilizer levels (see Figs. 1 to 3) where, because the mineralized N represented an important fraction of the total available N, the response curves appeared to show that insufficient adjustments for the leaching of fertilizer N had been made.

Despite these reservations, the predictions of the model were generally consistent with the observed data regardless of whether the leaching occurred during the winter or summer. This suggests that the assumptions on which the model was based are broadly correct. The model should, therefore, be helpful in determining whether losses of nitrate by leaching early in crop growth are sufficient to warrant additional applications of N.

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