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Nitrogen Movement and Leaching in Soil

Lysimeter Experiment

H. E. Jensen
The Royal Veterinary and Agricultural University,
Copenhagen, Denmark

Movement and leaching of residual nitrogen in soil has been studied in some details in a lysimeter experiment. Profile measurements of soil water and of nitrogen concentration in addition to measurements of amount and composition of the drainage water were carried out.

The leaching process could be described by an equation of Day. For a flow rate of approximately 1 cm/day, a dispersion coefficient of 11.5 cm^2/day was obtained independent of the concentration level. Using this value, the equation satisfactorily predicted concentration of nitrogen and leached amount of nitrogen in the drainage water. The equation, although the assumptions inherent in the theory are not completely fulfilled, may therefore be used for predictive purposes under field conditions.

An excess of precipitation, approximately equal to field capacity, is predicted necessary for leaching 50 per cent of an amount of dissolved nitrogen initially localized at the surface of the soil. Consequently, under many soil/climate conditions, the composition of drainage water is influenced by agricultural practices from previous years, which makes difficult interpretation of the results. This has been illustrated by relating some available data on drainage water quality from field experiments to the concentration of nitrogen in the soil water, as predicted by the theory.

Introduction

An ideal objective for land usage for food production is a high production rate of crop of high quality without causing significant permanent damage to environment and natural resources. However, a high production is obtained only by using various tools among which are in particular irrigation and application of relatively high rates of nitrogen fertilizers, which may cause increased leaching of nitrogen. Much effort is paid to investigate the possible contribution from agricultural practices to the pollution load of surface water and ground water resources. Such investigations include studies on nitrogen uptake by plants, nitrogen transformation processes and processes of nitrogen movement. In the present work, movement and leaching of nitrogen in soil has been studied in a lysimeter experiment in order to test a leaching equation under fieldlike conditions with a view to a predictive use of this equation under field conditions.

Materials and Methods

The lysimeter installations and loam soil used in the present work have been described in details by Kristensen and Aslyng (1971). An experiment with ryegrass using high rates of nitrogen application at different rates of water application was carried out in 1973/74 (Jensen, 1974). For the present purpose, two levels of nitrogen application (B and C) - approximately 700 and 1050 kg N/ha - combined with irrigation (1, 2, and 3) at 20, 40, and 60 mm of soil water deficit, respectively, are considered.

The nitrogen was applied to the soil surface as nitrates dissolved in the irrigation water which was applied by at trickle irrigation system. After the last cut, 29th August, the lysimeter installations were left uncovered, and the soil subjected to natural precipitation which - if necessary - was weekly supplied with irrigation in order to get an excess of precipitation over evapotranspiration of an average of about 3 mm/day.

In the growth period and in the subsequent leaching period, measurements of soil water were carried out in depths of 10, 30, 50, 70, and 90 cm, using a neutron probe (Kristensen, 1971). In corresponding depths, samples of soil water were taken, using tensiometer cells under vacuum, and analysed for nitrogen. In the leaching period, the amounts and the quality of drainage water were determined weekly.

Theoretical Considerations

Leaching of nitrogen from soil is a consequence of (a) the presence of nitrogen dissolved in the soil water and (b) downward movement of soil water after excess of precipitation. The two main processes involved in movement of nitrogen in soil are, (1) convection of dissolved nitrogen due to mass flow of soil water, and (2) molecular diffusion of dissolved nitrogen due to concentration gradients.

The extent of movement by convection is determined by the concentration of nitrogen in the soil water and the rate of movement of soil water. The mean velocity of soil water is determined by the rate of excess of precipitation, divided by the fraction of the soil occupied by water-filled pores, while the pattern of microscopic velocities of soil water is determined by the geometry of this pore volume. The extent of movement by diffusion is determined by the concentration gradient and the effective diffusion coefficient, the latter of which is dependent on the geometry of the water-filled pore volume. Both processes can occur simultaneously in the same or in the opposite direction.

$$\frac{\partial c}{\partial t} \equiv D^{*}\frac{\partial^2 c}{\partial z^2} - \frac{\partial (vc)}{\partial z} \qquad (1)$$

By combining equations for movement by convection and for movement by diffusion, Eq. (1) is obtained (Glueckauf, 1949; Lapidus and Amundson, 1952; Gardner, 1965). In addition to diffusion, the heterogeneous velocities of soil water within single pores, and the variation of mean velocity of soil water between pores of different diameters, not to mention blind or dead end pores, result in a mixing process, which in literature has been termed: hydrodynamic dispersion. This process can enhance diffusion and at sufficiently high velocities of soil water completely obscure it. The coefficient, D^*, in equation (1), therefore, should be considered a dispersion coefficient rather than a diffusion coefficient, and not only does it depend on pore geometry but also on the mean velocity of soil water.

$$c = \frac{c_o z_o}{\sqrt{4\pi D^* t}} \exp - \frac{(z-vt)^2}{4D^* t} \qquad (2)$$

$$c_m = \frac{c_o z_o}{\sqrt{2\pi \beta z_m}} \qquad (3)$$

Assuming viscosity, mass density, content, and mean velocity of soil water to be position and time invariable, and the initial nitrogen concentration in the soil water to be c_o down to a small depth, z_o, Eq. (2) is obtained (Day, 1956; Gardner, 1965). An implicit assumption is, that the mean velocity of water and nitrate ions are identical, which may not be the case - especially at low ion concentrations - in soils with high cation exchange capacity (Krupp et al., 1972; Smith, 1972). The maximum concentration is given as a function of depth by Eq. (3) from which the dispersion index, $\beta = 2D^*/v$, and the dispersion coefficient may be calculated, when $c_o z_o$, c_m, z_m, and v are known.

According to Eq. (2) the depth of the maximum concentration, z_m, is displaced downward with a constant velocity. As the downward movement proceeds, the initial narrow band of nitrate - due to diffusion and hydrodynamic dispersion - will extend over a greater part of the profile, so that the nitrate concentrations tend to reach a Gaussian distribution with a standard deviation (dispersion) of $\sqrt{2D^* t}$. As t is increased, the dispersion will extend, and consequently the concentration gradients will decrease.

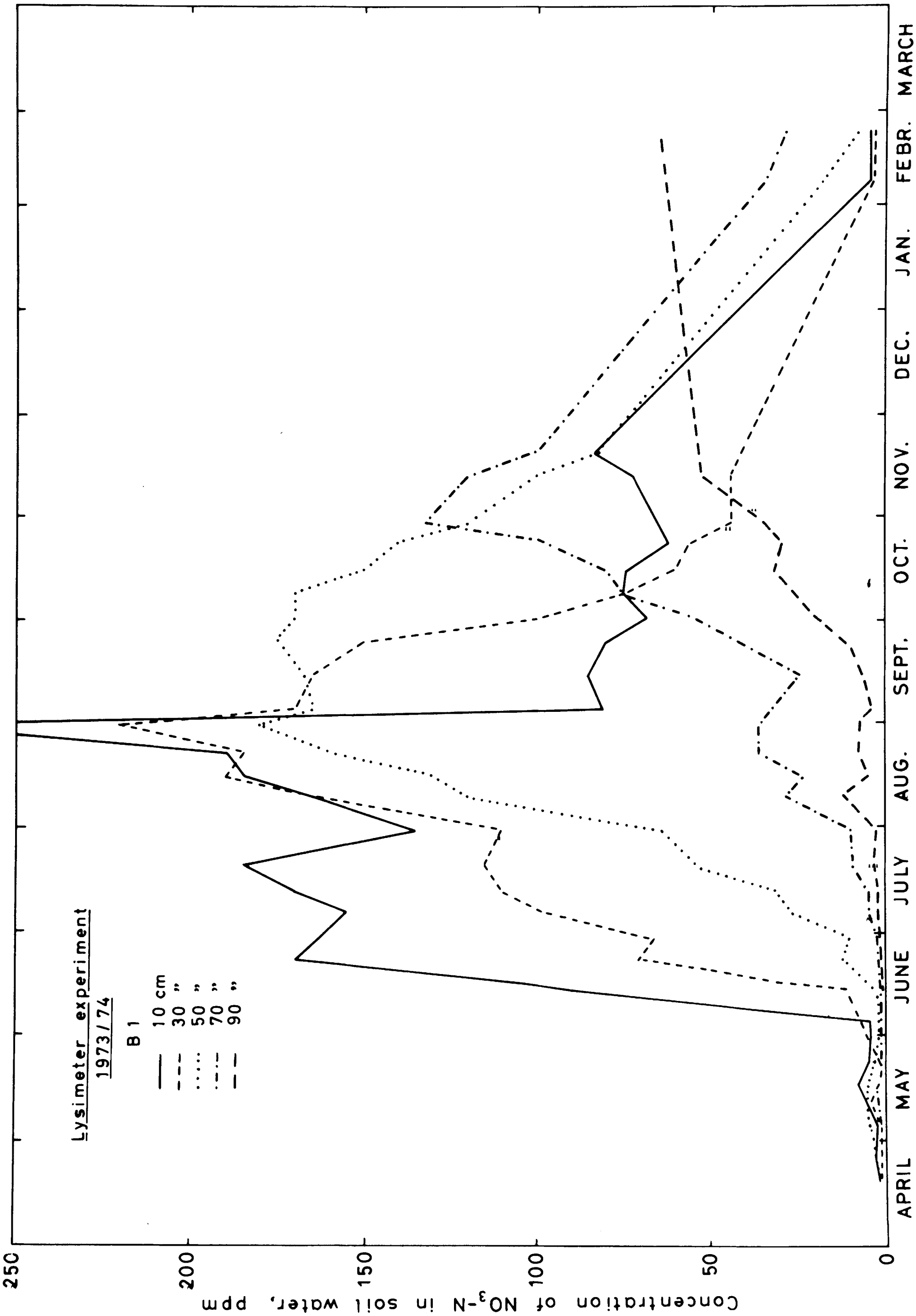

Fig. 1. Concentration of NO_3-N in soil water at five depths, plotted against time.

$$N_1 = \frac{1}{\sqrt{2\pi}} \int_{\alpha}^{\infty} e^{-\frac{\alpha^2}{2}} d\alpha \qquad (4)$$

The fraction of the initial amount of dissolved nitrogen leached from the soil profile may be calculated from Eq. (4), where $\alpha = (z - vt)/\sqrt{2D^*t}$. In order to calculate the relative loss of nitrogen from a soil profile of z cm within a given time, t, the value of the dispersion coefficient, D^*, and the mean flow velocity of soil water, v, must be known. Although the assumptions inherent in this theory are not completely fulfilled, it has been applied to the experimental results obtained in the present work.

Results and Discussion

Results from the soil water analyses for experiment B 1 are shown in Fig. 1. During the growth period, nitrogen was slowly translocated to greater soil depths, partly by diffusion and partly by slow, downward movement of soil water. Similar results were obtained for other fertilizer/irrigation combinations. During the subsequent leaching period, the concentration of nitrogen in the soil water decreased in the upper soil layers, while in the lower layers, the concentration still increased, but eventually also decreased in these layers. The relative high concentration in the top soil layer during the early stage of leaching may be due to microbial activity.

Three nitrate concentration profiles for experiment B 1 are shown in Fig. 2. The concentration profiles represent one day in the growth period, one day in the first part of the leaching period, when approximately 80 mm excess of precipitation had passed the profile, and one day in the last part of the leaching period, when more than 400 mm excess of precipitation had passed the profile, respectively. Similar results were obtained for other fertilizer/irrigation combinations. The form of the obtained relationships is in agreement with that predicted by Eq. (2).

From the amount and location of residual nitrate at the end of the growth period, the maximum concentration of nitrate at 110 cm depth, and the corresponding value of z_m, the value of the dispersion coefficient, D^*, was calculated by Eq. (3). Values for D^* of 11.5 cm^2/day were obtained for experiment B as well as for experiment C. Thus the dispersion coefficient was found to be independent of the concentration level of nitrate in the soil water. Apparently, the influence of differences in viscosity and mass density due to concentration gradients have been of no significance.

The mean velocity of soil water during leaching was 1 cm/day, giving a value for the dispersion index, β, of 23 cm. Gardner (1965) estimated a value for β of 22 cm for a clay soil. Nielsen and Biggar (1967) - in column experiment - found a value for β of 2 cm. Hansen (1974) - in column experiments with continous leaching with different rates of flow - found values for β in the order of 1 cm for a loamy soil. Kolenbrander (1970) using sandy and peat soils estimated an average for β of 3 cm.

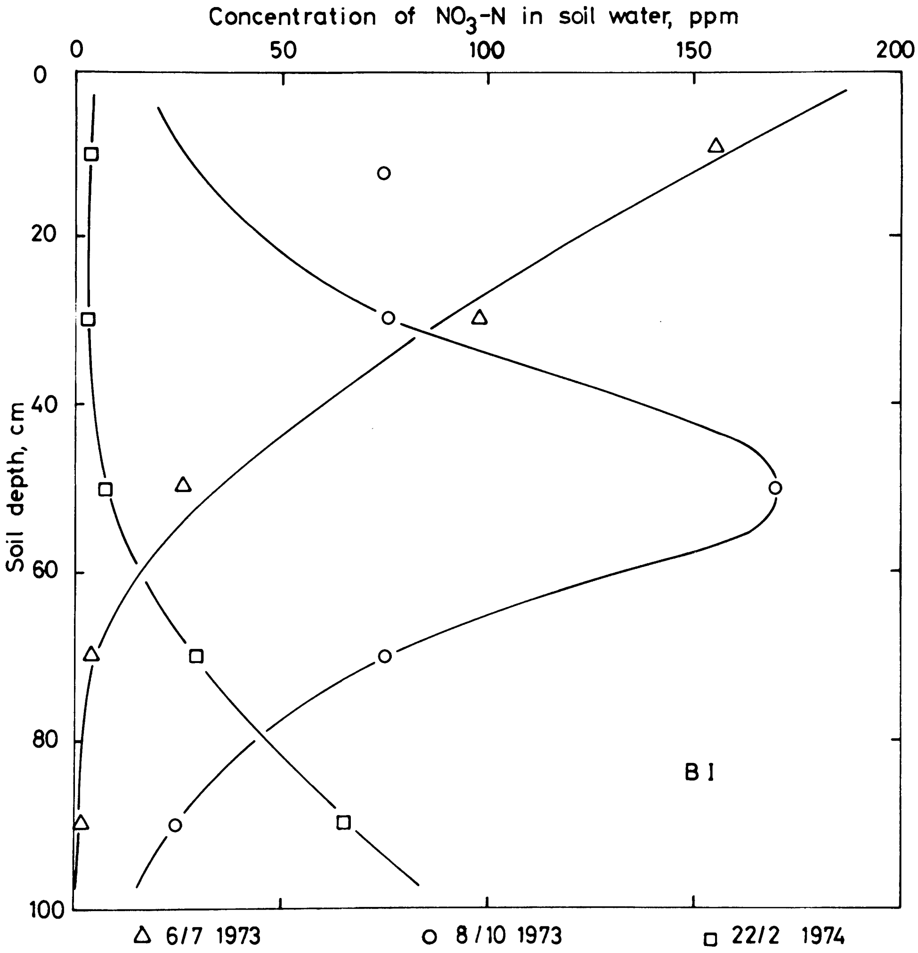

Fig. 2. Nitrogen concentration profiles at three different times.

The difference between β-values obtained in column experiments and those obtained in field experiments with soils of comparable texture must be due to differences between the pore geometry and/or differences between the flow patterns of the different experiments. At flow velocities sufficiently high, the value for β should be independent of flow velocity (Day and Forsythe, 1957). However, Nielsen and Biggar (1963) working with glass beads found β to be dependent on flow velocity. Hansen (1974) working with sandy and loamy soils and glass beads of different diameters found β to be approximately constant within a limited range of velocities. The present value for β obtained in lysimeter experiment corresponds to a small initial dispersion and to intermittent leaching, both of which are prevailing under field conditions.

By use of Eq. (2), the obtained values for β were used to predict the nitrate concentration at a depth of 110 cm as a function of time, which should correspond to the nitrate concentration in the outflow from the lysimeter. Using Eq. (4), the amount of nitrate leached was calculated as percentage of the initial amount of nitrate present in the soil. The calculated and experimentally determined values of the nitrate concentrations as well as the relative amounts of nitrogen leached are compared in Figs. 3 and 4, respectively. In view of the experimental conditions, the agreement between calculated and measured values is satisfactory.

From the present results and in accordance with results obtained by Gardner (1965) and Kolenbrander (1970), the conclusion is drawn that the equation of Day (1956) for predictive purposes satisfactorily describes movement and leaching of nitrate from soil under particular field conditions. This equation or numerical solutions of Eq. (1) therefore may be used in simulations of movement and leaching of nitrogen.

During leaching, the water content of the soil was approximately that at field capacity. Under such conditions, the present theory predicts an excess of precipitation approximately equal to the field capacity necessary for leaching 50 per cent of an amount of nitrate initially localized at the soil surface. For a profile of 1 metre of the present soil, this corresponds to 300 mm of excess of precipitation. In order to leach all the nitrate, an excess of precipitation corresponding to more than two times that at field capacity is required. On several localities, the annual excess of precipitation is less than field capacity for a profile of one metre of the soil. In such cases, the depth of the maximum concentration of an annual concentration wave is translocated less than one metre downward within a year. Consequently, annual concentration waves of nitrate will overlap each other resulting in a relatively constant nitrate concentration in deeper soil layers, especially in soils with high field capacity and a high β-value. Under condition of relatively high rates of annual excess of precipitation, annual waves of nitrate will sustain to greater soil depth, especially in soils with low field capacity and a low β-value.

Eq. (2) may under particular conditions offer a means of estimating the concentration of nitrate in the outflow from drainpipes. For instance, if drainpipes are located on an impermeable soil layer in a thin soil layer with a much higher hydraulic conductivity than that of the upper soil layer, the flow in the upper and lower layers may then be considered as parallel vertical and parallel horizontal, respectively, and the nitrate concentration in the outflow from the drainpipes may be approximately estimated as that predicted in the drainage depth by Eq. (2). However, in most cases of subsurface-drained soils, the pattern of flow is not so simple, and a more refined model of nitrate transport to the drains is required. In addition to this, nitrogen transformation processes may occur even in deeper soil layers.

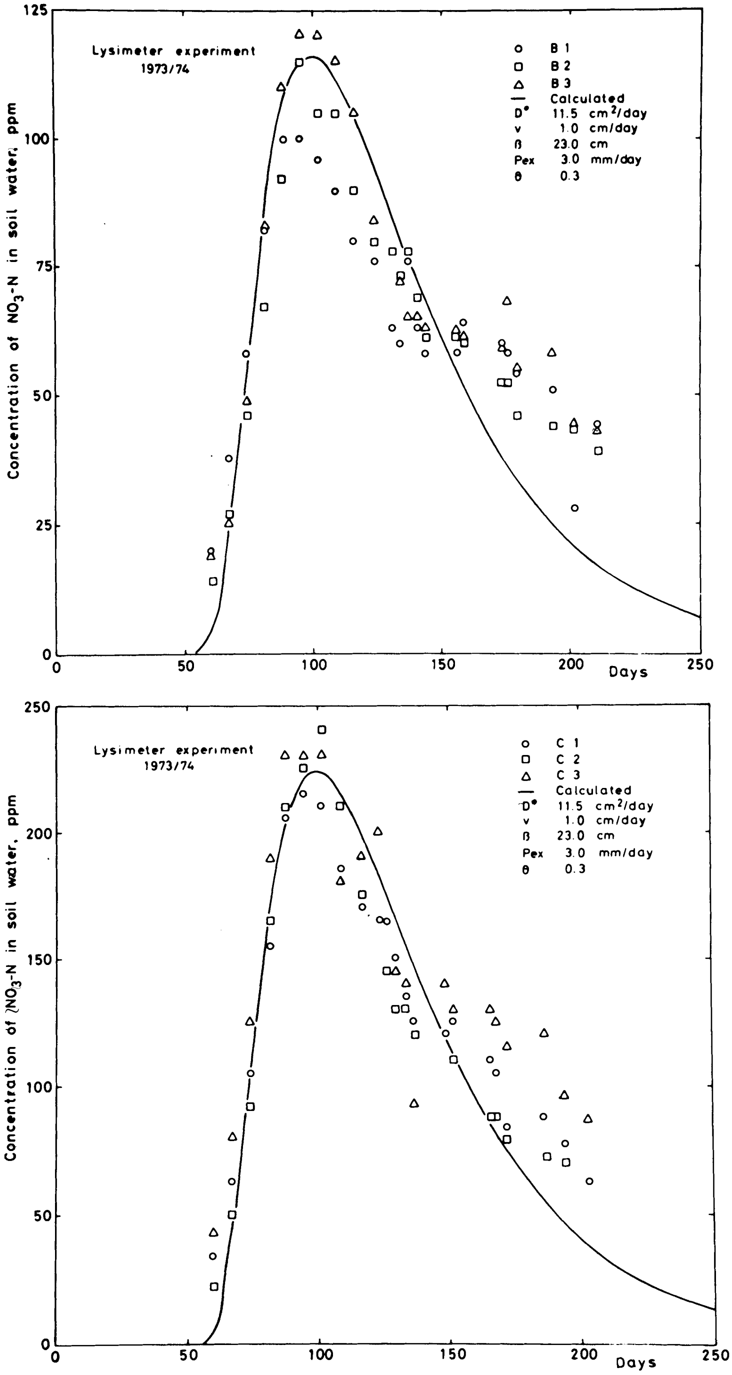

Fig. 3. Calculated and experimentally determined concentrations of NO_3-N in outflow from lysimeter, plotted against time.

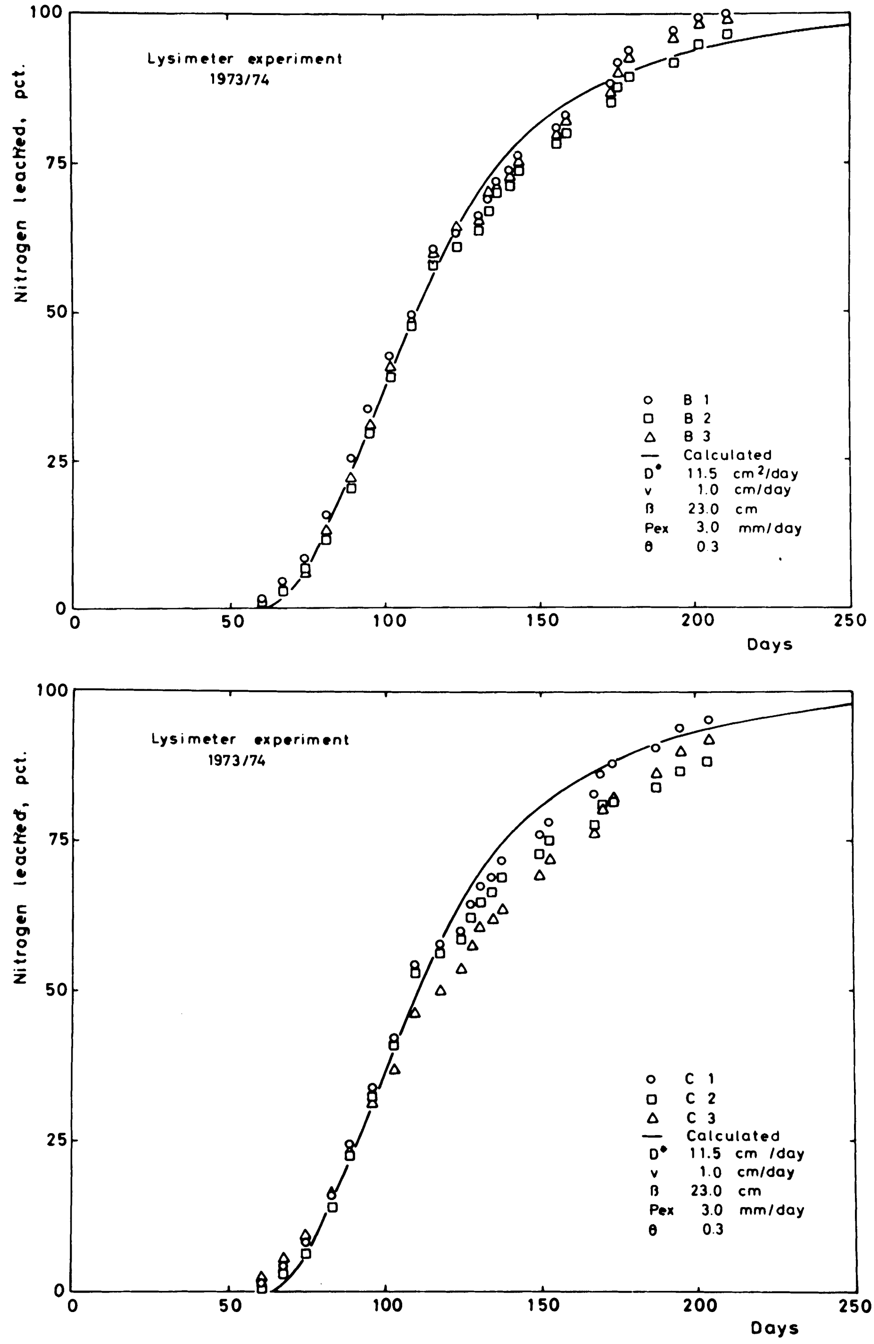

Fig. 4. Calculated and experimentally determined relative amount of nitrogen leached from lysimeter, plotted against time.

Using Eq. (2) assuming β and θ to be 23 cm and 0.3, respectively, and that 32 kg N/ha/year are leached and that the average daily excess of precipitation is 0.9 mm in a period of 36 weeks per year, the concentration of nitrate in the soil water at one metre soil depth has been calculated. In Fig. 5, the broken lines represent the individual annual concentration waves, while the solid line represents a superposition of the individual annual waves. It appears that at least three individual concentration waves contribute to the resulting curve, and that the resulting concentration wave has an amplitude much less than the amplitude of the individual annual concentration waves. In investigations on the quality of drainage water under similar conditions as those used in this calculation, concentrations and annual concentration wave with an amplitude of the same order of magnitude as those calculated has been found (Hansen, 1972). Some of the results are plotted in Fig. 5.

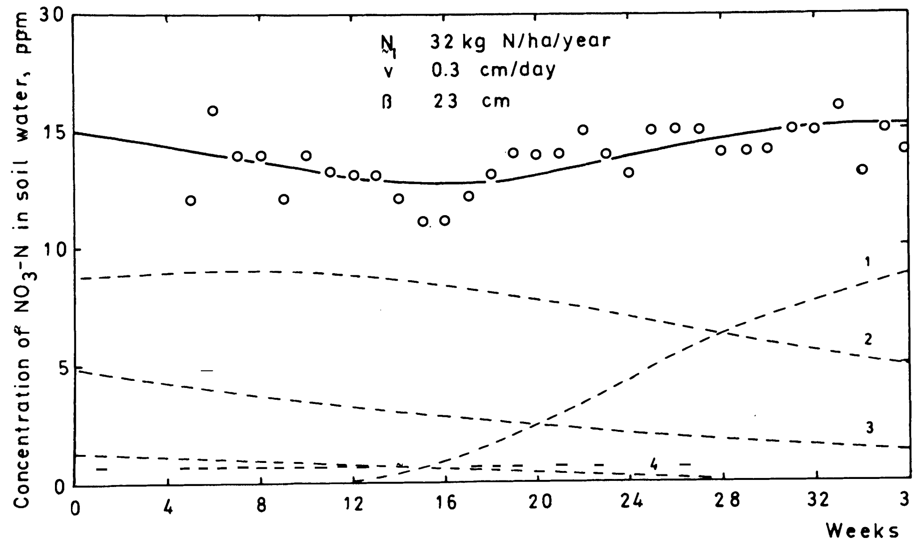

Fig. 5. Individual and superimposed annual concentration waves (broken and solid line, respectively) at one metre depth, calculated from Eq. (2), in relation to some data on drainage water quality.

From these considerations it follows that investigations on drainage water quality should be carried out over a period of years in order to identify and quantitatively estimate the possible influence of various agricultural practices on the pollution load of surface water and ground water resources.

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Notation

D^*	Dispersion coefficient
N_l	Nitrogen leached
Pex	Excess of precipitation
c	Concentration of nitrogen in soil water
c_0	Initial concentration of nitrogen in soil water
c_m	Maximum concentration of nitrogen in soil water
t	Time
v	Mean velocity of soil water
z	Position variable, soil depth
z_0	Initial depth of nitrogen in soil water
z_m	Depth of max concentration of nitrogen in soil water
α	Dimensionless parameter
β	Dispersion index
θ	Volumetric soil water content

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Address:
Hydrotechnical Laboratory,
Bülowsvej 23,
DK-1870, Copenhagen V,
Denmark