Study of Nitrate Leaching in a Long-term Experiment - Combination of Field and Simulation Experiments -

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The importance of long-term field experiments has grown due to the increasing dangers of soil and groundwater pollution. When studying a particular problem using an old experiment that was designed for other purposes than the actual question, a lot of past data is missed that cannot be measured in that experiment any more, such as initial moisture, organic matter and plant nutrient concentrations in the soil profile during the period of the experiment. Dynamic parameters, especially, cannot be estimated without a computing tool that is able to consider most of the main natural and technological factors. In order to gain an acceptable estimation of the desired components, back in time, the main processes of the system have to be simulated. Simulation modelling was introduced to agriculture after its excellent performance in army and space technology. Several crop and soil models have been developed since then. The applications soon became known in agricultural production as well as in environmental problem-solving.

Before the execution of an application the model has to be validated to local experimental results. For validation purposes long-term experiments have the advantages of several weather scenarios on the same soil, controlled treatments and measuring technologies and a lot of observed and analyzed data (KOVÁCS et al., 1995, 1996; NÉMETH et al., 1988, 1989; PETŐ et al., 1994). When the crop model simulates most of the processes (i. e. phenology, growth, soil moisture, nitrate accumulation) on an acceptable level, simulation experiments can be run to estimate several parts of the system that cannot be measured. Using these estimations hypothetic relationships can be calculated. These results have to be evaluated carefully and tested in field experiments before conclusions are drawn. Nevertheless important discoveries can be initiated, experimental expenses and time can be reduced significantly by using the technique of combining long-term experiments and simulation modelling. Finally, simulation is a powerful tool of demonstration in education and training, as well as in the forecast of future trends.

Long-term Experiment

The long-term fertilizer experiments used for this study have started in 1967 at the experimental station of our institute (Nagyhörcsök). A twenty-year period (1969-1988) has been selected for validation, during which a rotation of wheat, wheat, maize, maize was applied.

The soil is a loamy calcareous chernozem with loess parent material. The groundwater level is at 13-15 m from the surface. It is important to note that the observed deepest accumulation of nitrates that exceeded the "base" nitrate concentration of a given layer was at 430 cm. (Nitrate concentration measured in the soil profiles of control plots was considered as "base" concentration.) In the split-split-plot experiment with 4 replications nitrogen, phosphorus and potassium fertilizers were applied at different rates. Plots with different nitrogen treatments (such as: 0, 50, 100, 150, 200, and 250 $kg{\cdot}ha^{-1}{\cdot}year^{-1}$) were selected on a uniform level of P and K treatment. Nitrate concentration of soil core samples were analyzed till a depth of measurable nitrate enrichment. According to our earlier results accumulation was never measured deeper than 5 m (NÉMETH et al., 1988, 1989; NÉMETH, 1995, 1996a,b).

Simulation Model

Several models have been developed to simulate soil water balance, however only few have included nitrogen behaviour in the soil and plant (ADDISCOTT & WHITMORE, 1987; FRISSEL & VAN VEEN, 1981; GODWIN & JONES, 1991; FEHÉR et al., 1991; KOVÁCS et al., 1996). CERES models were selected for the present study, which has been supported by the US-Hungarian Joint Fund (J.F. 016/91 and 495/95A) and National Scientific Research Fund (OTKA T 5109 and 17646).

CERES models were designed to describe the system of the crop and its environment (JONES & KINIRY, 1986). One of the emphases of the model developers was to harmonize the scales of the parts of the model. This is why it can be used equally well in estimating nitrate leaching and the grain yield and also transpiration or nitrogen uptake. Despite of this multipurpose capacity, CERES is still a robust model and concentrates only on the most important functional relationships between the main components of the ecosystem to model the production and pollution processes on the field. Some earlier works help in tracing the development of the application of CERES models (RITCHIE, 1989; KOVÁCS et al., 1989, 1994, 1995; PETŐ et al., 1994).

The CERES version used in the present study corresponds to the CERES-Maize and CERES-Wheat included in DSSAT v. 2.1.

Discussion

An evaluation of the performance of CERES-Wheat and CERES-Maize models has been published earlier by KOVÁCS et al. (1995) based on the same experiment. In the following two figures are repeated to help in summarizing the evaluation.

Figure 1 shows the CERES yield estimation in comparison to the observed yields. Each number represents one plot in one year. It can be seen that the simulation slightly over-estimated the yield of control plots. The model assumes higher natural soil fertility than was observed. The possible reason for this is that the behaviour of long-term experiments differs from a one year experiment and the model has not been prepared to handle that case yet. The plots fertilized by nitrogen showed an acceptable fit to the 1 to 1 linear function.

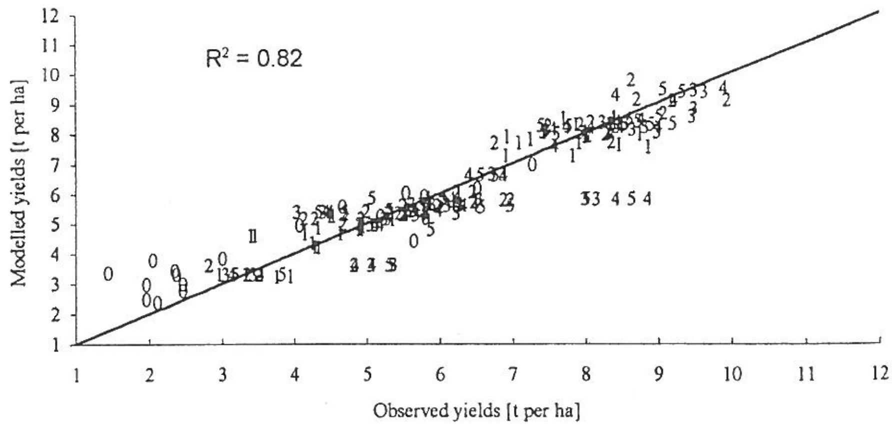

Figure 1
Observed and modelled yields of the Nagyhörcsök experiment between 1969-1988. Numbers represent the yields of plots treated with the following amounts of nitrogen fertilizer yearly: 0: 0; 1: 50; 2: 100; 3: 150; 4: 200; 5: 250 kg N per ha per year

Figure 2 shows the observed and simulated nitrate-N accumulation in the soil profile after 20 years of nitrogen fertilizer application. The modelled values follow the accumulations measured in the field experiment. The ratio of nitrogen accumulation between the root zone and the leaching zone is a bit biased, overestimating the leaching. But in case of the highest fertilizer treatment the estimation is quite satisfactory for the total accumulation and the ratio, too.

The five subfigures (A-E) in Figure 3 show the annual sums of nitrate-N leached to the depth of 170 cm from the surface (A), and four factors of nitrate leaching, such as the yearly sum of precipitation (B), and drainage (C), yearly nitrogen balance (added - uptaken) (D), summed N-balance (added - uptaken - leached till the given year) (E).

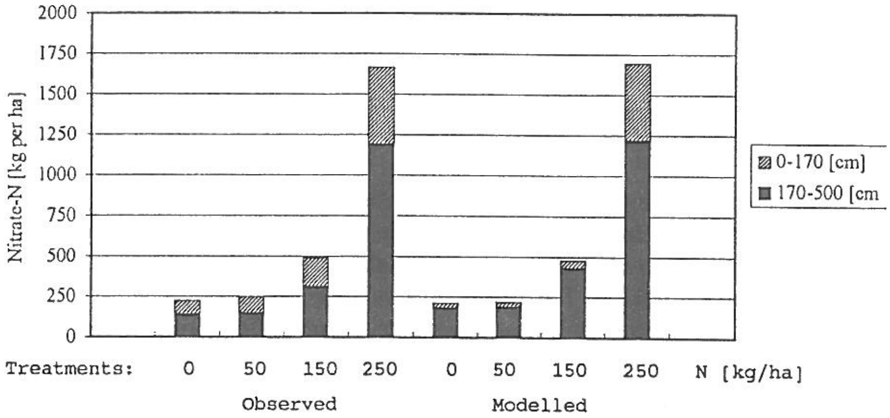

Figure 2
Observed and simulated nitrate-N accumulation and leaching from the root zone (below 170 cm) after 20 years of nitrogen treatments

The result of simulation is attractive concerning the annual differences of nitrate leaching (3A Figure). The large amplitude can be expected but without the simulation the amounts and distribution between years cannot be figured out. The largest single leaching was suggested for the year 1986 with an amount of 250 $kg.ha^{-1}$. The next largest one was less than 150 $kg.ha^{-1}$ (in 1970) and the following amounts were only around 100 $kg.ha^{-1}$. It is important to note that there were years with no leaching at all or with only few $kg.ha^{-1}.year^{-1}$. This large diversity year by year gives a good opportunity for studying the possible causes of the differences in N-transport.

Relationships between the different factors of leaching (x axes) and the estimated nitrate-N leaching (y axes) can be seen more clearly from Figure 4. The best fit was gained by the product of summed N-balance and drainage (E). The reason of the high correlation between drainage and leaching is obvious, as there is no leaching without water moving through the layers. At the same time, for a significant N-leaching a significant positive N-balance has to occur. A positive balance itself though will never cause leaching in itself (C and D).

The years between 1979 and 1984 were mostly dry years. Cereals could not take up nitrogen in the field experiment, the sum of N-balance was growing each year, but there was not a single year when drainage was able to leach nitrate through a depth of 170 cm or more. And finally, during the years of 1985 and 1986 a sufficient amount of water gathered and entered into the deeper soil horizons to move the accumulated nitrate out of the root zone.

Functions on Figure 4B and 4E could be used to estimate nitrate leaching at the given location without a crop model if the effective factors (drainage and summed N-balance) were easily measurable or estimated.

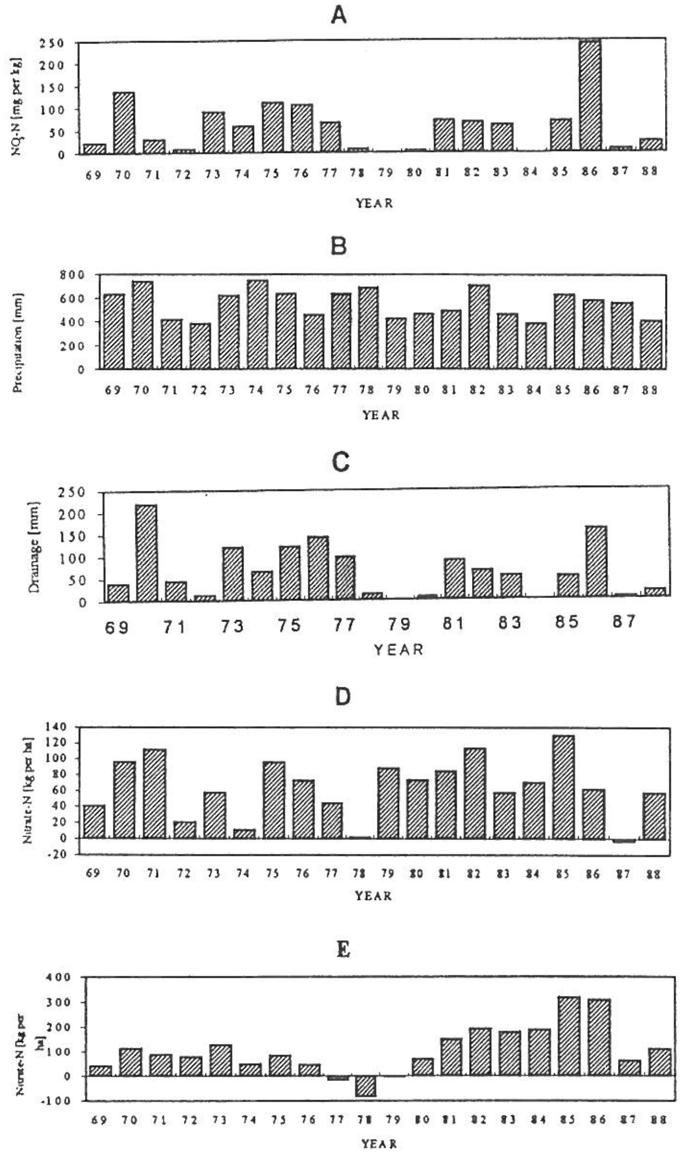

Figure 3

Leaching and some of its possible factors during 20 years of the experiment. A. NO_3-N leached out of root zone. B. Yearly total observed precipitation [mm·year^{-1}]; C. Yearly total simulated drainage [mm·year^{-1}]; D. Yearly nitrogen balance (added-uptake) [kg·ha^{-1}·year^{-1}]; E. Summed balance of N (sum of added-uptake-leached till given year) [kg·ha^{-1}]

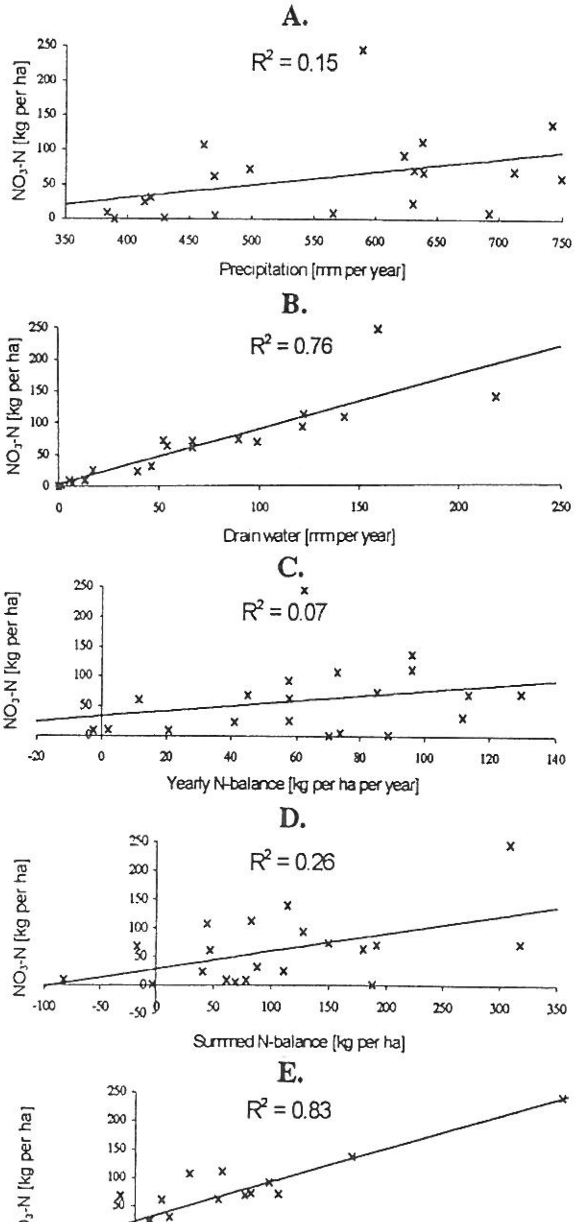

Figure 4

Relationship between NO_3-N leached from root zone (170 cm) and its factors. A. Yearly precipitation; B. yearly drain water; C. yearly N-balance; D: summed N-balance; E. product of drain water and summed N-balance till the year

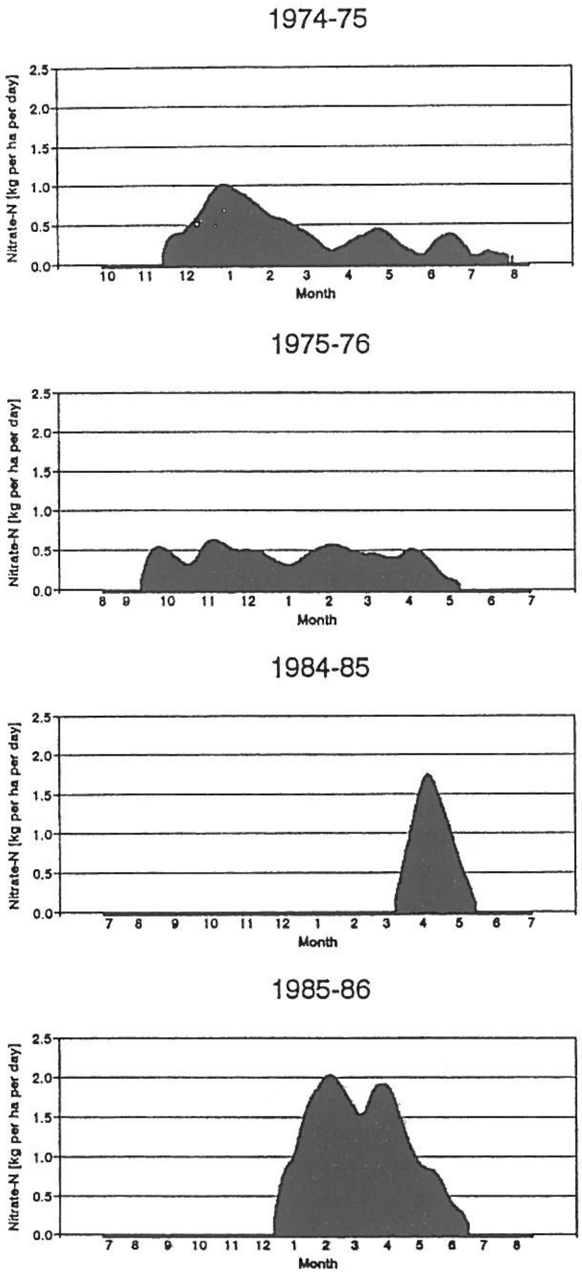

Figure 5
Daily amounts of nitrate-N fluxes at the bottom of the root zone

N-leached [kg.ha^{-1}] = 3.17 + 0.85 * Drained water [mm.ha^{-1}]
(Function of Figure 4B)
N-leached [kg.ha^{-1}] = 22.23 + 4.51 * Drained water * Summed N-balance [mm.ha^{-1}]
(Function of Figure 4E)

This is shown only as an example for generating hypotheses from long-term experiments using simulation models. In most cases these factor variables are not easily estimatable. Consequently, the crop model is still needed for the estimation.

The intensity of nitrate leaching varies not only between years but within years, too. Within year distribution of occurrences of leaching can be as important as the comparison of years. Crop models enable us to study N-transport in the soil by seasons or even in daily steps. Figure 5 shows daily amounts of nitrate-N fluxes at the bottom of the root zone.

The selected four seasons show that winter and spring months have dominance in leaching. There were long and less intensive leaching seasons but in some years the leaching occurred in a short and intensive period. Further investigation is needed to create hypotheses on causal relationships and measurements have to be carried out to prove them.

Conclusions

CERES-Maize and -Wheat models gave good estimates of yields, nitrogen balance (transformation, uptake) and water and nitrogen transport processes running continuously through 20 years as compared to a long-term field experiment. The simulation experiment estimated annual and seasonal nitrate-N amounts leached out of the root zone. Great amplitudes were found in nitrate leaching among years depending on the summed nitrate balance and drainage. Winter and spring months had dominance in leaching.

These data could not be gained by measurements from the field experiment any more. It would be too expensive to carry out the experiment for another 20 years in order to measure that part of the agricultural system. Using this simulation technique those figures can be computed plus hypothetic causal relationships can be calculated. Though these results have to be evaluated carefully and tested in field experiments before conclusions are drawn, nevertheless, important discoveries can be initiated, experimental expenses and time can be reduced significantly by using the technique of combining long-term experiments and simulation modelling.

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