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# Valuing the Environment in Crop Profitability: A Case Study of the Kempen, Belgium

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## Abstract

The limits for NO3-N concentrations in groundwater and surface waters are still under discussion, but it is likely that they will become stricter. The process of denitrification is important in preventing high agriculture-source nitrate loads from entering and polluting rivers. The aim of the research was to examine if the $NO_3$-N concentration in drain water of agricultural fields can be kept below the EU limit of 11.3 mg $l^{-1}$ by controlling the denitrification process through management of the water table level. As such the research focused on the determination of the exact denitrification amount to achieve both, limitation of the $NO_3$-N leaching and optimisation of the nitrogen-nitrate uptake by the crop. The method used in this study is based on the nitrogen version of DRAINMOD model. This model was used to simulate the performance of the drainage system using two drainage strategies (conventional and controlled) at the Hooibeekhoeve experiment, situated in the sandy region of the Kempen (Belgium), and this for a 14-year (1985-1998) period. In the analysis a continuous cropping with maize was assumed. Daily $NO_3$-N losses were predicted for a range of drain spacings. The study illustrated that the denitrification process has a very strong impact on the amount of nitrate that can be leached to ground and surface waters. Simulated results indicated that $NO_3$-N losses to the environment could be substantially reduced by reducing the drainage density below the level required for maximum profits based on grain sales. The results have also shown that if the water table elevation is properly controlled, one should be able to strike the delicate balance between our need for maximum yield production and a minimum hazard to our environment. The study concluded that, if the environmental objective is of equal or greater importance than profits, the drainage systems can be designed and managed to reduce $NO_3$-N losses while still providing an acceptable profit.

Keywords: Conventional and Controlled Drainage, Drainmod-N, Denitrification, Plant Uptake, Environment

# Introduction

Nitrogen has a very strong covalent bond that can only be broken by certain bacteria, volcanic action, and lightning. After the bond breaks, the nitrogen enters the food chain of plant and soil microorganisms. Nitrogen becomes either fixed on the soil matrix or is assimilated by plants. All of the compounds, ammonium, nitrite and nitrate are sensitive to leaching and runoff. Nitrogen could be lost by the process of denitrification. During this process, bacteria convert nitrate or nitrite to $N_2$ and some nitrous oxide ($N_2O$). Human activities affect the nitrogen cycle through the application of fertilisers and wastes , and by gas emission from cars and industry. Nitrogen based fertilisers and fossil fuels release pollutants that increase soil acidity. This affects the root absorption of magnesium, calcium, and potassium ions. As a result, the nitrogen cycle becomes less efficient as the losses of nitrogen increases.

The process of nitrogen loss through leaching can be of serious environmental concern, particularly in areas where the leached pollutants can reach the groundwater aquifers. Leaching of nitrogen also reduces the efficiency of fertiliser use since nitrogen will no longer be available for plant uptake. Leaching of nitrogen usually occurs when nitrogen is in the nitrate ($NO_3^-$) form since nitrate can not be adsorbed on the soil matrix. This research studied for farming conditions:

(i) the effect of subsurface drainage density on nitrate losses and
(ii) the economics of nitrate losses, using the nitrogen version of DRAINMOD-N.

The objective of the research was to examine if through management of the water table level the denitrification process could contribute to a reduction of the nitrate-nitrogen leaching to the subsurface drains, to a level that the EU limit (11.3 mg $l^{-1}$) in the surface water is not exceeded. DRAINMOD (Skaggs, 1981) was used to simulate the performance of the drainage system of an experimental field at the Hooibeekhoeve, situated in the Kempen, Belgium, using a 14-year period of climate data. Further the added-on module DRAINMOD-N (Brevé *et al*., 1997 a&b) was applied in order to examine the effect of drain spacings and management system, i.e. conventional versus controlled drainage, on the denitrification process, the nitrate-nitrogen leaching to the surface water and crop production.

# Theory

Denitrification is the reduction of nitrate, through nitrite, usually to di-nitrogen gas. The process is generally anoxic or anaerobic, and results in a big loss of nitrogen. Denitrification is a biological process and is encouraged by high soil temperatures and occurs during and after flood irrigation and/or heavy rainfall, sufficient to temporarily waterlog the soil. Under those conditions organisms use nitrate and nitrite as electron acceptors instead of oxygen. The process converts plant available N (nitrate) back to nitrogen gases that is lost to the atmosphere.

Nitrate ($NO_3^-$) ⇒ Nitrous oxide ($N_2O$) ⇒ Di-nitrogen ($N_2$)

The denitrification process produces two gasses, $N_2$ and $N_20$. The latter is a pollutant and is in part responsible for ozone decomposition in the upper atmosphere. Inefficient use of N fertilisers and unnecessary high loss of N through the denitrification process are therefore contributing to environmental degradation. The extent of fertiliser N loss during the crop's growth is variable and site dependent. The nitrogen cycle is shown in Fig. 1.

The DRAINMOD model (Fig. 2) was used in this study to simulate the performance of the drainage system and the related water table management. The model determines the average daily soil-water fluxes at the boundary between thin soil layers in which the soil profile is divided, calculating the water balance for each soil layer. A water content profile is generated based on the assumption of hydrostatic condition above the water table at the end of the day. In the saturated zone, vertical fluxes are linearly decreased from Hooghoudt's drainage flux at the depth of the water table to zero at the impermeable layer. This approach for computing fluxes and water contents proved to be reliable for soils with shallow water table as illustrated from a comparisons between the numerical solutions of the Richards equation for saturated and unsaturated flow and the results obtained with the DRAINMOD code (Skaggs *et al*., 1991; Kandil *et al*., 1992; Karvonen and Skaggs, 1993) and with SOIL & SOILN model (Ragab *et al.,* 1996). Since DRAINMOD fluxes are computed at midpoint between the drains or as the average vertical flux in the zone between drains depending on the drainage algorithm used, the predicted solute concentrations correspond to the same location.

DRAINMOD-N is an added-on module to DRAINMOD and simulates the nitrogen dynamics in drained soils. Nitrate-nitrogen ($NO_3$-N) is the main N pool considered in the model. The model is a quasi two-dimensional model because the nitrogen movement component considers only vertical transport in the unsaturated zone and both vertical and lateral transport in the saturated zone. The controlling processes considered by the model (Brevé *et al*., 1992) are rainfall deposition, fertiliser dissolution, net mineralisation of organic nitrogen, denitrification, plant uptake, and surface runoff and subsurface drainage losses. The change in $NO_3$-N in the soil solution can be represented by the advective-dispersive-reactive (ADR) equation:

$$\frac{\partial(\theta C)}{\partial t} = \frac{\partial}{\partial z}\left(\theta D \frac{\partial C}{\partial z}\right) - \frac{\partial(qC)}{\partial z} + \Gamma \qquad (1)$$

where: C is the $NO_3$-N concentration [M $L^{-3}$], $\theta$ is the volumetric water content [$L^3$ $L^{-3}$], q is the vertical water flux [L $T^{-1}$], D is the coefficient of hydrodynamic dispersion [$L^2$ $T^{-1}$], $\Gamma$ is a source/sink term [M $L^{-3}$ $T^{-1}$] used to represent processes such as plant uptake, transformations, etc., z is the co-ordinate direction along the flow path [L], and t the time [T]. An overview of the N-processes considered in DRAINMOD-N is given in Fig. 3.

The source/sink term in Eq. 1 can according to Brevé *et al*. (1997a) be described as:

$$\Gamma = \Gamma_{dep} + \Gamma_{fer} + \Gamma_{mnl} - \Gamma_{rnf} - \Gamma_{upt} - \Gamma_{den} \qquad (2)$$

where: $\Gamma_{dep}$ stands for rainfall deposition [M $L^{-3}$ $T^{-1}$], $\Gamma_{fer}$ for fertiliser dissolution [M $L^{-3}$ $T^{-1}$], $\Gamma_{mnl}$ for net mineralisation [M $L^{-3}$ $T^{-1}$], $\Gamma_{rnf}$ for loss [M $L^{-3}$ $T^{-1}$] in surface runoff, $\Gamma_{upt}$ for plant uptake [M $L^{-3}$ $T^{-1}$], and $\Gamma_{den}$ for denitrification [M $L^{-3}$ $T^{-1}$].
The denitrification is approximated by a first-order equation, as follows:

$$\begin{aligned} \Gamma_{den} &= K_{den} f_{den\theta} f_{temp} f_z \theta_i^1 C_i^1 && for\, \theta \geq \theta_{den} \\ \Gamma_{den} &= 0 && for\ \theta < \theta_{den} \qquad (3) \end{aligned}$$

where $K_{den}$ is the denitrification rate coefficient [$T^{-1}$], $\theta_{den}$ is a threshold water content [L $L^{-3}$] below which denitrification will not occur, $f_{den\theta}$ is a dimensionless soil water content factor for denitrification as defined below, $f_{temp}$ is a dimensionless temperature adjustment factor, and $f_z$ is a dimensionless depth factor that reflects the decrease of organic matter content with depth. Values for $K_{den}$ range from 0.004 to 1.08 $d^{-1}$ in the literature (Davidson *et al*., 1978; Johnsson *et al*., 1987).
The soil water content coefficient for denitrification is as follows:

$$f_{den_\theta} = \left( \frac{\theta - \theta_{den}}{\theta_{sat} - \theta_{den}} \right)^2 \qquad (4)$$

where $\theta_{sat}$ is the soil-water content at saturation. A detailed description of each functional relationship is given by Brevé *et al*. (1997 a&b).

## Materials

At the 'Hooibeekhoeve' in the community of Geel (north-eastern part of Belgium) an experimental field trial with maize was set up by the Belgian Soil Service (Coppens and Vanongeval,1998) from 1992 to 1995. The soil at the farm site is sandy and classified as a Haplic Podzol, mainly sandy soil with a distinct humus and/or iron B-horizon (a Zdg soil according to the Belgian Soil Classification System). The ground-water level fluctuates between 115 and 160 cm below surface. The first two years of the experiment, in 1993 and 1994, maize was sown, whereas in the last season, 1995, the field was left fallow. Different pig slurry fertiliser application packages were applied in spring or autumn. The fertiliser scenarios are listed in Table 1. $NO_3$-N in the fertiliser package is added to the soil solution by dissolution of the fertiliser.

Soil physical properties were determined in one plot of the Hooibeekhoeve (the Kempen, Belgium) for each distinguishable soil horizon, using undisturbed soil samples taken with Kopecky rings. van Genuchten-Mualem parameters for describing the hydraulic functions (van Genuchten and Nielsen, 1985) were fitted on both water retention and multi-step outflow data, using the multi-step outflow program (van Dam *et al*., 1990). Basic water retention and hydraulic conductivity curves were established by averaging individual curves for each soil layer. In addition, the soil texture was determined for each soil horizon (Ducheyne and Feyen, 1999). The soil physical properties are listed in Table 2. The field was intensively monitored during the experimental period. Every three weeks, soil samples were taken with an interval of 30 cm to a depth of 120 cm for mineral nitrogen measurements. Mineral nitrogen was measured in groundwater at 200 cm with the same time interval.

During the simulation period the field was cropped with maize. Organic manure only as a fertiliser was applied. Missing data, required to run the model, were either supplementary measured or reconstructed by using the pedo-transfer functions of Vereecken (1988), as indicated by Ducheyne and Feyen (1999). The 3-year data (1992-1995) were used to extensively calibrate and validate the DRAINMOD/DRAINMOD-N models.

The soil, crop and nitrogen parameters were calibrated resulting in a set of representative parameters for the given soil-crop condition. The calibration of the model parameters was carried out by trial and error (Loague and Green, 1991). The calibration of DRAINMOD-N model is based on field data of the fertiliser scenario number 3 (30 ton $ha^{-1}$ pig slurry applied in spring), see Table 1. The calibrated model (DRAINMOD-N) was validated versus data collected on the field fertiliser scenario number 5 and applied to simulate the nitrate transport in the soil profile for the other scenarios (1, 2 and 4). After having calibrated and validated the models, a scenario-analysis was performed to assess the effect of changes in denitrification process on the nitrate-nitrogen leaching.

In the scenario-analysis, which was carried out for the period 1985-1998, the properties of the field plot of the Hooibeekhoeve, were used for model calibration and validation. Further it was assumed that the field was equipped with a subsurface drainage system consisting of parallel, 10 cm diameter, corrugated plastic drains. The drainage designs evaluated consisted of five drain spacings (10, 25, 50, 100, and 300 m). The management treatments included conventional (drains with free outlet, not submerged) and controlled (water level in the outlet must rise to the weir elevation before drainage occurs) drainage. The total fertiliser package considered in the scenario-analysis, was 160 kg N $ha^{-1}$, applied in two dressings. Detailed inputs for the maize production practices and $NO_3$-N transport and transformation variables are listed in Table 3. The maize production practices used in the simulations are characteristic for the sandy region of the Kempen (El-Sadek *et al*., 2001).

## Results and Discussion

Effects of drainage system management and drain spacings on the nitrogen budget components (denitrification, nitrate leaching and plant uptake) are shown in

Figs. 4 and 5. The average annual rainfall of the simulation period (14-year) is 867.5 mm. Simulation results indicate that increasing the drain spacings reduces subsurface drainage while it increases surface runoff and ET. Furthermore, controlled drainage reduces subsurface drainage and increases surface runoff, as compared to conventional drainage. The magnitude of these changes increases with the intensity of the controlled drainage management. The average annual drainage discharge and surface runoff as affected by system management (conventional and controlled drainage) and drain spacings are shown in Table 4.

Simulation results reveal that increasing the drain spacings reduces $NO_3$-N drainage losses and net mineralisation, but increases $NO_3$-N runoff losses and denitrification. In addition, controlled drainage increases denitrification and runoff losses, as compared to conventional drainage. Results of the scenario-analysis show that under Belgium climate conditions in the winter season total $NO_3$-N losses (subsurface drainage plus surface runoff) can be substantially reduced with controlled drainage. It expected that when using wide drain spacings, the water table level would rise and the denitrification amount of nitrate-nitrogen also is likely to rise and subsequently the amount of $NO_3$-N available for leaching is expected to decrease. On the other hand, there would be a corresponding reduction in the uptake of $NO_3$-N by the plant. The complete results of the scenario-analysis of the $NO_3$-N denitrification, leaching and plant uptake in kg ha$^{-1}$ for the whole simulation period are shown in tables 5, 6 and 7 respectively.

For instance, for conventional drainage, in 1992 using a drain spacings of 300 m caused rise the water table level and the denitrification amount increased from 203.1 kg ha$^{-1}$ (using a drain spacings of 10 m) to 410.6 kg ha$^{-1}$. The $NO_3$-N leaching amount decreased from 215.0 kg ha$^{-1}$ (for a drain spacings of 10 m) to 49.7 kg ha$^{-1}$ (using a drain spacings of 300 m). Moreover, the plant uptake also decreased to 191.9 kg ha$^{-1}$ when compared with 270 kg ha$^{-1}$ using 10 m as drain spacings. Using controlled drainage as a drainage strategy, in 1993 a drain spacings of 300 m has led to a 48.2% increase in denitrified $NO_3$-N, a reduction of 84% in the $NO_3$-N leaching and a reduction of 23.1% in the plant uptake, as compared to the same field with a 10 m drain spacings.

Controlled drainage usually leads to an increase in the denitrification process. The effect, however, depends on the magnitude and duration of the rise in water table level. In 1995 and for a drain spacings of 100 m, the amount of denitrification was 229.8 kg ha$^{-1}$ and 277.6 kg ha$^{-1}$ under conventional and controlled drainage systems respectively. As a result of the rise in the amount of denitrification, the $NO_3$-N leaching decreased from 70.7 (with conventional drainage) to 67.2 kg ha$^{-1}$. The corresponding reduction in the plant uptake was 16.0 kg ha$^{-1}$ using controlled drainage instead of conventional drainage. The relationships (obtained from simulation) between the amount of $NO_3$-N leached-denitrification and $NO_3$-N taken up by plant-denitrification for different drain spacings (using the conventional drainage system) is shown in Fig. 6.

The $NO_3$-N leached-denitrification relationship in Fig. 6 is adverse relation, this means that by increasing the $NO_3$-N denitrification amount, the $NO_3$-N leaching amount is decreasing. The relation is decreasing with increasing the drain spacing. For example, for the drain spacing of 300 m, all the $NO_3$-N leaching values are under 60 kg ha$^{-1}$ for different $NO_3$-N denitrification amounts where for the drain spacing of 25 m the maximum $NO_3$-N leaching is 331 kg ha$^{-1}$. The $NO_3$-N taken up by plant in presence of the denitrification process described here as plant uptake-denitrification relationship is also adverse relation. By increasing the $NO_3$-N denitrification amounts, the $NO_3$-N taken up by plant gets decreasing. The $NO_3$-N losses in plant uptake are between 244.6 and 270.0 kg ha$^{-1}$, using 25 m as a drain spacing that produces the maximum crop production. On other hand, if the $NO_3$-N denitrification amount is low, this would cause an increase in $NO_3$-N leaching to ground and surface waters. The drain spacing of 300 m has led to an increase in the $NO_3$-N denitrification amount and a reduction in the $NO_3$-N plant uptake, reducing its minimum to 173.8 kg ha$^{-1}$ (in 1995). Figure 6 illustrates that the optimum drain spacing could be designed to achieve the maximum crop production by maximizing the plant-N uptake and minimizing the adverse impact on the environmental.

As could be expected, the results indicated that for the small drain spacings the total dry matter production of the maize crop is maximum, and equal to 14,500 hg ha$^{-1}$. This is the assumed maximum for the given location and climate condition. As can be seen in Fig. 7 for the drain spacings of 25 m (conventional drainage system) the $NO_3$-N plant uptake is maximum for the whole simulation period, and therefore the total dry matter production is constant. For the drain spacings of 50 m plant uptake is less than maximum in wet years, but for most years even with this drain spacings the maximum yield of 14,500 kg ha$^{-1}$ was obtained. Increasing the drain spacings above 50 m results in a reduction of plant uptake and consequently in dry matter production.

The optimal combination of maximizing denitrification and minimizing nitrate leaching is one that maximises profit (i.e. higher yield) and minimises the negative environmental impact. Results of the scenario-analysis indicate that $NO_3$-N losses to the environment could be substantially reduced by increasing the denitrification amount below the level required for maximum profits from grain sales. That is, if the environmental objective is equal or of greater importance than profits from the agriculture crops, the denitrification amount can be designed and managed to reduce $NO_3$-N losses while still providing an acceptable profit. These results are very important for policy and decision makers as they will have the difficult task to strike a balance between the economic gains in terms of crop yield and the environmental protection aspect.

Cost benefit results indicate that for the given climate-crop-soil combination a conventionally drained system with 25 m drain spacing and 1.25 m drain depth, is close to optimal. The optimum spacing is 50 m. The predicted net profit associated with this optimum system is 16 687 BEF ha$^{-1}$. For a drain depth of 1.0 m, profit will be reduced by 1 422 BEF ha$^{-1}$, but drainage outlets 1.25 m deep may not be available in some cases. Furthermore, the deeper the drains $NO_3$-N losses increase as will be discussed below.

Clearly, the ideal drainage design and management combination is one that maximizes profit and minimizes environmental impact. The economic analysis indicates that the maximum profit for the Geel soil would be obtained with a conventional drainage system, with 50 m drain spacing and 1.25 m drain depth.

However, these systems would not be optimum from the water quality perspective. The total nitrate-nitrogen losses associated with the drainage systems producing maximum profit for 225, 275 and 325 kg N $ha^{-1}$ fertilizer application strategies are 28, 33 and 38 kg $ha^{-1}$ $yr^{-1}$, respectively.

Although it was found that the maximum predicted profits were obtained for 50 m spacing, in practice smaller spacings are applied because they are based on conservative design considerations. The applied conservative drain spacings satisfy the production objective, as indicated by crop yield, even though profits are somewhat reduced. Thus, $NO_3$-N losses to the environment can be reduced by fitting the drainage system design to the crop-soil system such that the drainage density is not greater than required (i.e., drain spacings as wide as possible and drain depths as shallow as possible). Results also indicate that $NO_3$-N losses to the environment could be substantially reduced by reducing the drainage density below the level required for maximum profits from grain sales. That is, if the environmental objective is of equal or greater importance than profits from the agriculture crops, the drainage systems can be designed and managed to reduce $NO_3$-N losses while still providing an acceptable profit.

For example, increasing the drain spacing from 50 to 100 m with conventional drainage, with a 275 kg N $ha^{-1}$ fertilizer application and 1.0 m drain depth would reduce total $NO_3$-N losses by 20%, from 37 to 29 kg $ha^{-1}$, while reducing profits by only 260.40 BEF $ha^{-1}$. Under those conditions the risk of large losses in yields and profits during wet years will increase, but the reduction in $NO_3$-N losses to surface waters will decrease, which overall might be of greater value. If a 1.0 m drain depth is used, the projected reduction in total $NO_3$-N losses is estimated at 17.3%. This would result in a reduction in profit of about 1 122.3 BEF $ha^{-1}$, but this may be warranted by the accompanying significant reduction in $NO_3$-N losses. That is, from a societal point of view, it may become less expensive to pay greater prices for grain compared to treating the water to remove excessive $NO_3$-N. The cost for the removal of 17.3% $NO_3$-N is estimated at 1 955.2 BEF $ha^{-1}$. Another way to decreasing total $NO_3$-N loss is by improving the surface conditions. However, the obtained decrease is not substantial as compared to the associated decrease in profit.

Simulated results indicate that using controlled drainage could reduce total nitrate-nitrogen loss, with however an additional sacrifice in profit. If controlled drainage is used, total $NO_3$-N losses can be decreased by 4.6% (from 76 to 72 kg $ha^{-1}$) for 1.50 m drain depth, 25 m drain spacing and 275 kg N $ha^{-1}$ fertilizer application, as compared to the conventionally drained system. The decrease in profit associated with this management modification is not substantial (15.16 BEF $ha^{-1}$). Although the controlled drainage may not affect profits, it may substantially decrease $NO_3$-N losses, and thus, meet both the production and environmental objectives.

The effect of drain depth on predicted annual profit and $NO_3$-N losses is shown in Fig. 7. Results in Fig. 7 show that profits increase with drain depth, because deeper drains can be placed farther apart thereby reducing costs. However, $NO_3$-N losses also increase with drain depth, and the net profit, plotted as the broken curve at the top of Fig. 7, does not consider the environmental costs of the increased nitrogen load. For example, annual $NO_3$-N loads could be reduced by 25 kg $ha^{-1}$ by reducing the drain depth from 1.5 to 0.75m.

Skaggs and Chescheir (1999) used data presented by Schwabe (1996) to estimate the costs of reducing N loading to the Neuse River in North Carolina. Based on Schwabe's data they used a relatively low cost of US$8 $kg^{-1}$ of N to estimate the economic benefits of reducing the $NO_3$-N loading in agricultural drainage waters. A background loading of 10 kg $ha^{-1}$ was assumed, and this "treatment cost" was applied to predicted loads greater than 10 kg $ha^{-1}$. The same method was used in this study. A "treatment cost" of 320 BEF per kg of $NO_3$-N in excess of a background loading of 10 kg $ha^{-1}$ was assumed and subtracted from the net profit to give the profit curve shown in Fig. 7. As was the case for the North Carolina site (Skaggs and Chescheir, 1999), when the effect of environmental costs was considered, maximum profit was predicted for the shallow 0.75 m drain depth (Fig. 7).

## Conclusions

The critical limits for $NO_3$-N concentrations in groundwater and surface waters are debatable and still under discussion, but the likely outcome is that these limits will become more and more stricter. As the Denitrification process is the most important nitrogen loss process, in this study, the water table level was used to control the denitrification amount in order to reduce nitrate-nitrogen leaching to ground and surface waters. In this work, data of a 14-year period, collected between 1985-1998, from experimental field in Flanders, Belgium, were used.

The predicted rate of denitrification, mineralisation, plant uptake and leaching depends on several model input data/parameters that should be measured or estimated for each application. These data are not always easily determined with high accuracy for each application. It is important to know which of the input data/parameters has the greatest effect on model predictions so that high accuracy level could be ensured in monitoring such parameter for which the model is most sensitive. Cumulative denitrification in the soil profile was found to be sensitive to the standard rate coefficient for denitrification ($K_{den}$), the mineralisation standard rate coefficient ($K_{min}$), and mildly sensitive to dispersivity, and it was insensitive to $NO_3$-N content in crops and nitrogen content in rain. The sensitivity analysis results indicated also that, the $NO_3$-N loss in subsurface drainage is most sensitive to the standard rate coefficient for denitrification.

The optimal combination of drainage design and management is one that maximizes profit and minimizes environmental impact. Results of the scenario-analysis indicate that $NO_3$-N losses to the environment could be substantially reduced by reducing the drainage density below the level required for maximum profits from grain sales. That is, if the environmental objective is equal or of greater importance than profits from the agriculture crops, the drainage systems can be designed and managed to reduce $NO_3$-N losses while still providing an acceptable profit. From a societal point of view, it may become less expensive to pay higher grain prices than paying the costs for removing $NO_3$-N in excess of the tolerance level. The cost to remove 17.3% $NO_3$-N is estimated at 1 955.2 BEF $ha^{-1}$ for conditions used in simulation.

## References

Brevé, M.A., R.W. Skaggs, H. Kandil, J.E. Parsons, and J.W. Gilliam. 1992. *DRAINMOD-N, a nitrogen model for artificially drained soils*. Proceedings of the Sixth International Drainage Symposium. ASAE, St. Joseph, MI 49085-9659: 327-344.

Brevé, M.A., R.W. Skaggs, J.E. Parsons, and J.W. Gilliam. 1997a. DRAINMOD-N, a nitrogen model for artificially drained soils. Trans. *ASAE*, 40 (4): 1067-1075.

Brevé, M.A., R.W. Skaggs, J.W. Gilliam, J.E. Parsons, A.T. Mohammad, G.M. Chescheir, and R.O. Evans. 1997b. Field testing of DRAINMOD-N. Trans. *ASAE*, 40 (4): 1077-1085.

Coppens, G., and L. Vanongeval. 1998. *Modellering van de migratie van nutriënten in de bodem.. Activiteitenverslag van de Bodemkundige Dienst van België*. Rapport 98/00/3, 40pp, (in Ducth).

Davidson, J.M., D.A. Graetz, P. Suresh, C. Rao, and H.M. Selim. 1978*. Simulation of nitrogen movement, transformations, and uptake in plant root zone*. USEPA, EPA-600/3-78-029, Athens, GA.

Ducheyne, S., and J. Feyen. 1999. *A procedure to reduce model uncertainty by comparison with field data illustrated on a nitrogen simulation model*. Proceeding of EurAgEng's IG on Soil and Water Int. Workshop on Modelling of transport processes in soils at various scales in space and time. Leuven, Belgium, 24-26 Nov.: 457-466.

El-Sadek, A., J. Feyen, and W. Skaggs. 2001: Economics of nitrate loss from drained agricultural land. Accepted for publication in *Journal of Environmental Engineering*.

Johnsson, H., L. Bergstrom, and P.E. Jansson. 1987. Simulated nitrogen dynamics and losses in a layered agricultural soil. *Agriculture, Ecosystems and Environment* 18:333-356.

Loague, K., and R.E. Green. 1991.Statistical and graphical methods for evaluating solute transport models: overview and application. In: P.J. Wieringa (Ed.), Validation of low and transport models for the unsaturated zone. *J. Contam. Hydrol*., **7**: 51-73.

Kandil, H., C.T. Miller, and R.W. Skaggs. 1992. Modelling long-term solute transport in drained, unsaturated zones. *Water Resources Research*, 28: 2797-2809.

Karvonen, T., and R.W. Skaggs. 1993. *Comparison of different methods for computing drainage water quantity and quality*. In Proc. Workshop on Subsurface Drainage Simulation Models, The Hague. ICID-CIID-CEMAGREF: 201-216.

Ragab, R., D.M., Cooper, G.L., Harris, and J.A. Catt. 1996. Simulating nitrate leaching under winter wheat grown on a structured clay soil considering by-pass flow. *J. of Hydrology*. 182: 157-173.

Schwabe, K. A. 1996. Source heterogeneity, resource characteristics and the performance of marketable permits. PhD thesis, North Carolina State University, Raleigh, 149pp.

Skaggs, R. W., and G. M. Chescheir. 1999. Effects of subsurface drain depth on nitrogen losses from drained lands. ASAE/CSAE-SCGR Annual International Meeting, Paper No. 99-2086, Toronto, Canada.

Skaggs, R.W., T. Karvonen, and H. Kandil. 1991. *Predicting soil water fluxes in drained lands*. ASAE paper No. 91-2090, St. Joseph, MI: ASAE.

Skaggs, R.W. 1981. *Methods for design and evaluation of drainage water management systems for soils with high water tables, DRAINMOD*. North Carolina State University, Raleigh, North Carolina, USA.

van Dam, J.C., J.N.M. Stricker, and P. Droogers. 1990. *From one-step to multi-step. Determination of soil hydraulic functions by outflow experiments*. Rep. 7, De. Of Water Resour., Agric. Univ., Wageningen, The Netherlands.

van Genuchten, M.Th.., and D.R. Nielsen. 1985. On describing and predicting the hydraulic properties of unsaturated soils. *Annales Geophysicae*, 3 (5): 615-628.

Vereecken, H. 1988. *Pedotransfer functions for the generation of the hydraulic properties for Belgian soils*. PhD-Thesis No. 171, Faculty of Agricultural and Applied Biological Sciences, K.U.Leuven, Belgium: 254 p.

Table 1: Field treatments

| Treatment | Description of fertiliser package |
|---|---|
| 1 | 30 ton ha$^{-1}$ pig slurry applied in autumn |
| 2 | 120 ton ha$^{-1}$ pig slurry applied in autumn |
| 3 | 30 ton ha$^{-1}$ pig slurry applied in spring |
| 4 | 120 ton ha$^{-1}$ pig slurry applied in spring |
| 5 | 60 ton ha$^{-1}$ pig slurry applied in autumn + 60 ton ha$^{-1}$ applied in spring |

Table 2: Soil physical properties of the experimental field at the Hooibeekhoeve

| Soil parameter | | Soil horizon (cm) | | | |
|---|---|---|---|---|---|
| | | 0-35 | 35-50 | 50-100 | 100-20 |
| Van Genuchten | | | | | |
| | $\theta r$ | 0.055 | 0.019 | 0.011 | 0.017 |
| | $\theta s$ | 0.48 | 0.43 | 0.42 | 0.42 |
| | $\alpha$ | 0.016 | 0.028 | 0.032 | 0.019 |
| | m | 1.574 | 1.686 | 1.85 | 1.804 |
| | n | 0.365 | 0.407 | 0.459 | 0.446 |
| Mualem | | | | | |
| | Ksat, cm d$^{-1}$ | 50.47 | 18.6 | 15.55 | 13.15 |
| | $\lambda$, cm d$^{-1}$ | 2.031 | 4.041 | 3.314 | 4.007 |
| Soil texture (%) | | | | | |
| | Clay | 2 | 7 | 2 | 2 |
| | Silt | 5 | 16 | 3 | 3 |
| | Sand | 93 | 77 | 95 | 95 |

Table 3: Summary of inputs for DRAINMOD-N

| | |
|---|---|
| ***Soil properties:*** | |
| $\theta_{wp}$ ($cm^3\ cm^{-3}$) | 0.17 |
| Bulk density (g $cm^{-3}$) | 1.6 |
| Organic nitrogen in top soil (μg $g^{-1}$) | 3200 |
| $K_{mnl}$ ($d^{-1}$) | $3.5x10^{-5}$ |
| $K_{den}$ ($d^{-1}$) | 0.40 |
| ***Drainage system parameters:*** | |
| Drain depth (m) | 1.25 |
| Drain spacings (m) | 10, 25, 50, 100, 300 |
| Surface storage (cm) | 2.5 |
| Effective drain radius (cm) | 2.5 |
| ***Maize production parameters:*** | |
| Desired planting date | May 4 |
| Length of growing season (d) | 120 |
| N-fertiliser input (kg N $ha^{-1}$) | 160 |
| Date fertiliser application | May 6, May 14 |
| Depth fertiliser incorporated (cm) | 10 |
| Total dry matter production (kg $ha^{-1}$) | 14500 |
| ***Other nitrogen model parameters:*** | |
| Dispersivity (cm) | 10 |
| $NO_3$-N content of plant (per cent) | 1.55 |
| $NO_3$-N concentration of rain (mg $l^{-1}$) | 0.8 |

Table 4: The average annual drainage discharge and surface runoff as affected by system management (conventional and controlled drainage) and drain spacings

| Drain spacing (m) | Conventional drainage | | Controlled drainage | |
|---|---|---|---|---|
| | Drainage discharge (cm) | Surface runoff (cm) | Drainage discharge (cm) | Surface runoff (cm) |
| 25 | 39.16 | 0.12 | 38.85 | 0.16 |
| 50 | 37.3 | 0.34 | 36.85 | 0.42 |
| 100 | 34.99 | 1.11 | 33.98 | 1.95 |
| 300 | 30.5 | 5.07 | 29.24 | 6.26 |

Table 5: $NO_3$-N losses by denitrification process as affected by system management (conventional and controlled drainage) and drain spacings

| Year | Conventional drainage | | | | | Controlled drainage | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 10 m | 25 m | 50 m | 100 m | 300 m | 10 m | 25 m | 50 m | 100 m | 300 m |
| 1985 | 63.8 | 79.8 | 121.4 | 309.3 | 434.9 | 85.1 | 94.5 | 160.4 | 352.3 | 433.7 |
| 1986 | 138.0 | 186.3 | 311.3 | 356.0 | 369.2 | 137.2 | 194.4 | 306.1 | 339.6 | 369.1 |
| 1987 | 171.8 | 193.7 | 232.3 | 324.0 | 355.7 | 207.0 | 223.3 | 248.9 | 337.2 | 358.7 |
| 1988 | 187.5 | 231.9 | 305.4 | 356.6 | 356.4 | 194.6 | 236.5 | 304.4 | 343.8 | 355.6 |
| 1989 | 123.8 | 139.9 | 164.9 | 147.2 | 182.2 | 119.0 | 136.6 | 155.6 | 142.5 | 153.7 |
| 1990 | 140.4 | 151.6 | 166.8 | 217.1 | 448.6 | 139.9 | 151.3 | 164.6 | 219.1 | 436.7 |
| 1991 | 153.6 | 181.1 | 257.9 | 327.4 | 289.2 | 153.4 | 181.1 | 257.8 | 326.1 | 290.2 |
| 1992 | 203.1 | 236.0 | 310.7 | 393.0 | 410.6 | 203.0 | 236.8 | 315.3 | 398.6 | 416.9 |
| 1993 | 174.8 | 197.5 | 228.3 | 275.9 | 335.6 | 174.7 | 197.6 | 227.7 | 275.0 | 337.9 |
| 1994 | 158.8 | 179.2 | 201.3 | 278.3 | 296.0 | 172.9 | 189.5 | 210.4 | 288.8 | 300.6 |
| 1995 | 127.2 | 143.3 | 155.0 | 229.8 | 243.7 | 151.2 | 162.9 | 170.1 | 277.6 | 262.4 |
| 1996 | 106.1 | 124.1 | 213.7 | 309.5 | 307.0 | 95.3 | 116.3 | 209.6 | 285.6 | 311.4 |
| 1997 | 173.9 | 185.8 | 184.7 | 246.8 | 371.2 | 186.5 | 194.8 | 203.4 | 270.5 | 382.0 |
| 1998 | 252.5 | 314.8 | 427.8 | 502.9 | 503.4 | 257.3 | 319.6 | 427.5 | 480.1 | 495.3 |

Table 6: $NO_3$-N losses to subsurface drainage as affected by system management (conventional and controlled drainage) and drain spacings

| Year | Conventional drainage | | | | | Controlled drainage | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 10 m | 25 m | 50 m | 100 m | 300 m | 10 m | 25 m | 50 m | 100 m | 300 m |
| 1985 | 65.7 | 64.0 | 64.4 | 62.6 | 44.5 | 65.8 | 63.0 | 72.6 | 62.2 | 44.5 |
| 1986 | 131.6 | 127.1 | 117.8 | 78.4 | 59.1 | 127.3 | 126.2 | 114.0 | 80.6 | 59.1 |
| 1987 | 161.6 | 143.3 | 99.8 | 69.9 | 47.1 | 162.7 | 140.5 | 92.6 | 66.3 | 45.5 |
| 1988 | 265.5 | 222.6 | 142.9 | 87.7 | 43.8 | 251.3 | 209.7 | 132.3 | 83.0 | 55.2 |
| 1989 | 122.6 | 103.4 | 66.0 | 32.5 | 13.5 | 115.2 | 98.4 | 61.2 | 31.4 | 21.8 |
| 1990 | 118.3 | 96.8 | 59.4 | 35.9 | 49.6 | 113.5 | 93.3 | 56.3 | 35.4 | 47.1 |
| 1991 | 139.0 | 124.8 | 90.7 | 53.5 | 31.8 | 135.0 | 121.7 | 87.8 | 54.6 | 30.6 |
| 1992 | 214.5 | 180.7 | 115.8 | 65.2 | 49.7 | 209.9 | 177.0 | 111.9 | 70.9 | 46.1 |
| 1993 | 207.3 | 168.6 | 108.9 | 62.1 | 33.7 | 204.3 | 165.8 | 106.0 | 60.7 | 32.7 |
| 1994 | 219.0 | 177.5 | 103.6 | 55.6 | 41.0 | 214.4 | 175.0 | 101.2 | 54.9 | 39.7 |
| 1995 | 173.7 | 145.5 | 81.9 | 70.7 | 35.4 | 164.4 | 136.8 | 76.5 | 67.2 | 33.0 |
| 1996 | 97.2 | 80.0 | 55.7 | 35.6 | 23.1 | 90.4 | 76.1 | 54.3 | 33.2 | 22.7 |
| 1997 | 99.0 | 77.9 | 48.0 | 30.2 | 33.0 | 93.9 | 72.3 | 45.5 | 33.3 | 34.5 |
| 1998 | 398.4 | 331.0 | 196.8 | 93.7 | 43.2 | 379.1 | 314.8 | 182.8 | 78.3 | 41.5 |

Table 7: $NO_3$-N losses in plant uptake as affected by system management (conventional and controlled drainage) and drain spacings.

| Year | Conventional drainage | | | | | Controlled drainage | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 10 m | 25 m | 50 m | 100 m | 300 m | 10 m | 25 m | 50 m | 100 m | 300 m |
| 1985 | 266.1 | 266.3 | 261.4 | 237.3 | 184.2 | 269.3 | 262.4 | 249.3 | 221.4 | 183.9 |
| 1986 | 270.0 | 270.0 | 269.2 | 221.0 | 182.9 | 270.0 | 270.0 | 269.9 | 215.5 | 182.9 |
| 1987 | 270.0 | 270.0 | 269.7 | 234.7 | 204.7 | 270.0 | 270.0 | 263.7 | 221.2 | 198.5 |
| 1988 | 269.2 | 268.8 | 256.6 | 224.0 | 204.2 | 270.0 | 267.0 | 249.1 | 220.3 | 198.4 |
| 1989 | 266.9 | 266.8 | 263.4 | 218.8 | 203.5 | 267.1 | 267.0 | 263.0 | 219.0 | 207.3 |
| 1990 | 265.1 | 264.4 | 253.8 | 218.7 | 207.0 | 265.1 | 264.4 | 253.8 | 219.0 | 204.4 |
| 1991 | 270.0 | 270.0 | 269.1 | 235.0 | 213.8 | 270.0 | 270.0 | 269.1 | 234.8 | 213.7 |
| 1992 | 270.0 | 270.0 | 270.0 | 217.3 | 191.9 | 270.0 | 270.0 | 270.0 | 213.9 | 189.2 |
| 1993 | 270.0 | 270.0 | 260.1 | 225.3 | 207.9 | 270.0 | 270.0 | 260.3 | 224.4 | 207.7 |
| 1994 | 256.0 | 255.7 | 247.8 | 215.4 | 194.7 | 265.9 | 262.3 | 252.4 | 215.7 | 192.5 |
| 1995 | 246.1 | 244.6 | 236.3 | 219.7 | 173.8 | 256.4 | 252.8 | 236.5 | 203.8 | 159.1 |
| 1996 | 270.0 | 270.0 | 270.0 | 260.8 | 242.6 | 270.0 | 270.0 | 270.0 | 253.4 | 238.9 |
| 1997 | 270.0 | 270.0 | 270.0 | 246.2 | 204.8 | 270.0 | 270.0 | 270.0 | 242.3 | 200.8 |
| 1998 | 270.0 | 270.0 | 270.0 | 240.2 | 197.5 | 270.0 | 270.0 | 270.0 | 224.9 | 190.6 |

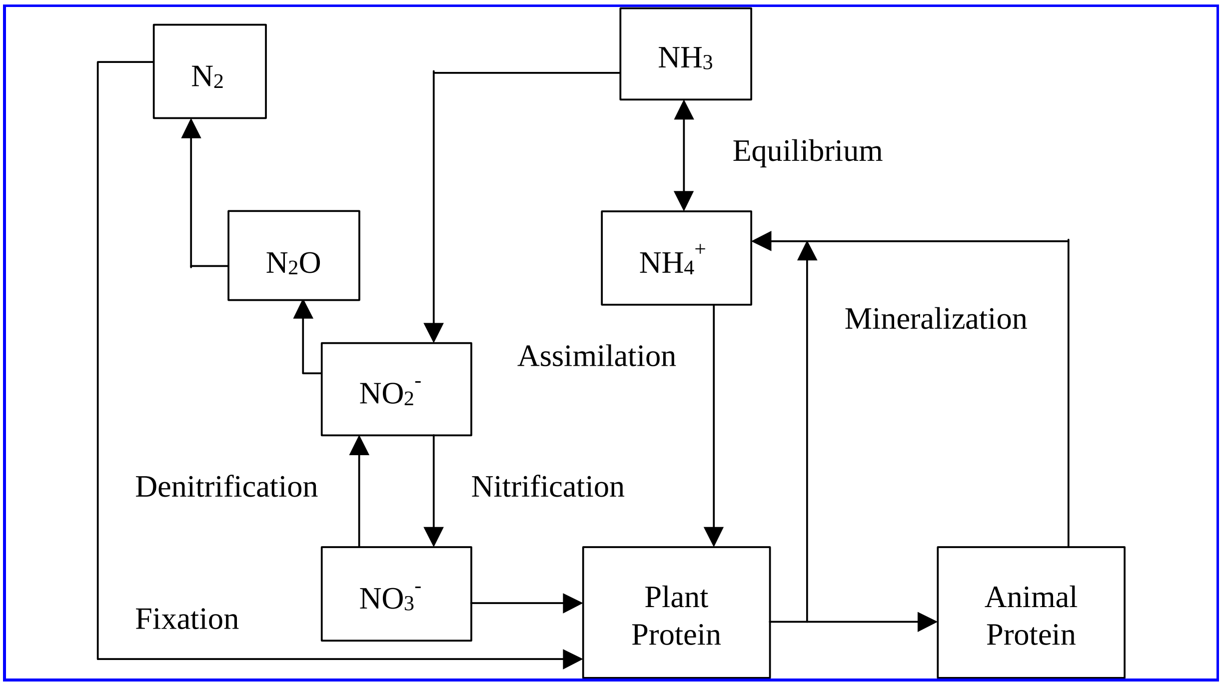

Figure 1: Nitrogen cycle

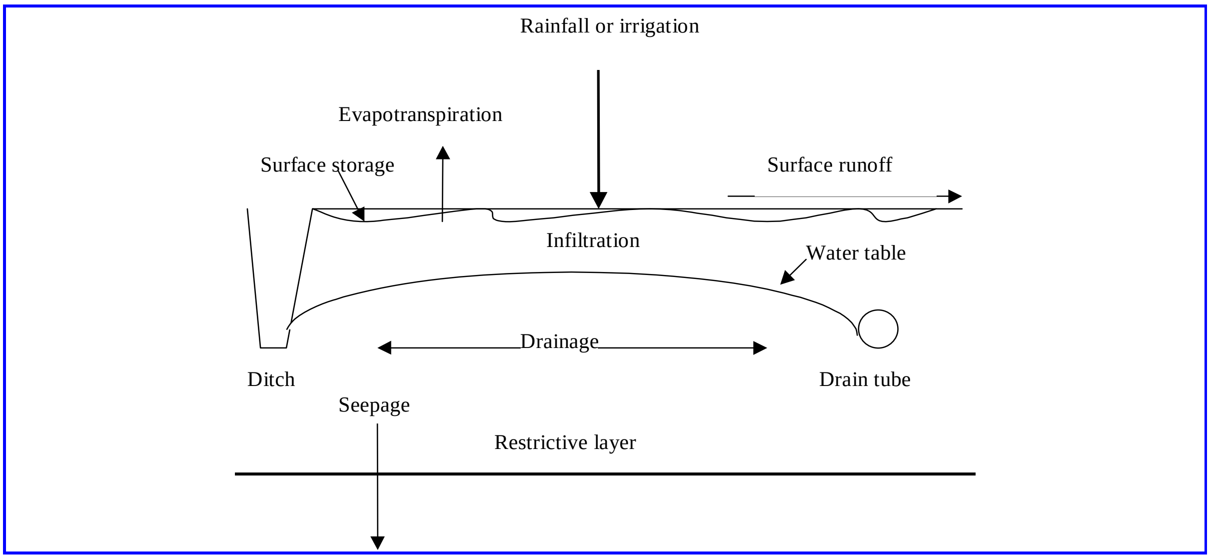

Figure 2: Two-dimensional presentation of the drainage system as described mathematically in DRAINMOD

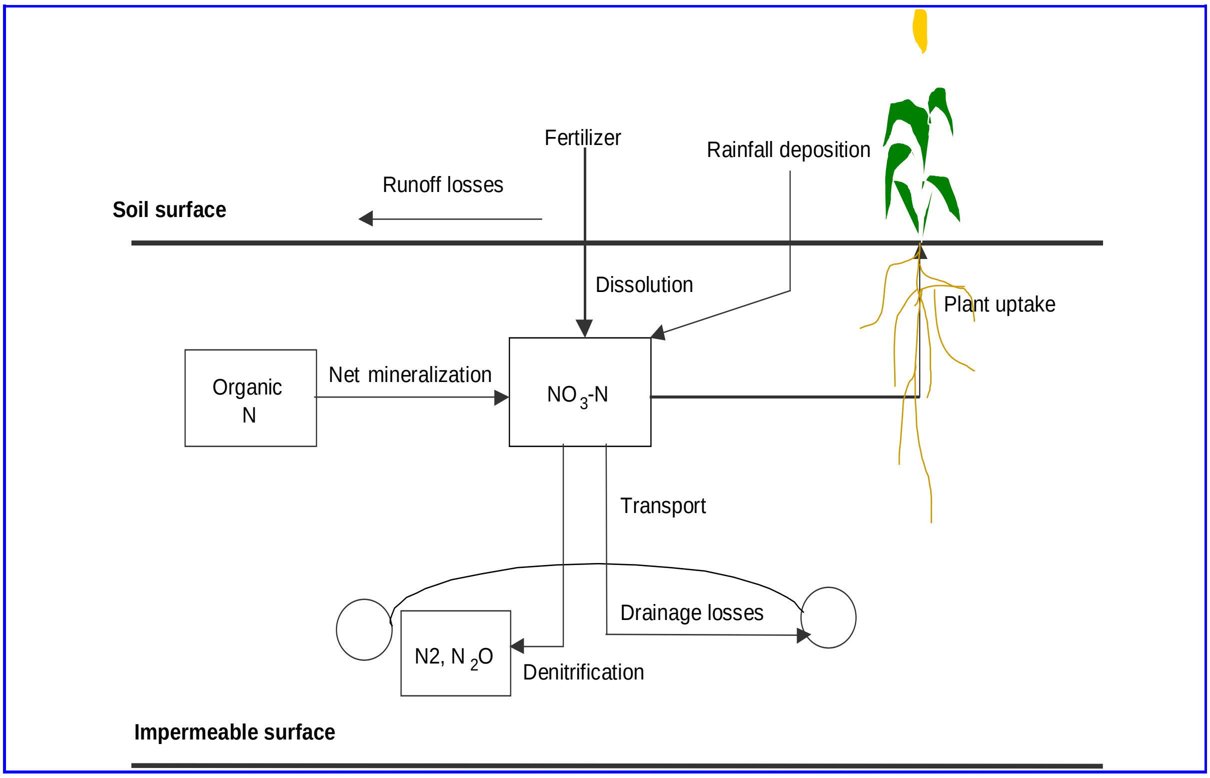

Figure 3: Schematic presentation of the nitrogen cycle, as described in DRAINMOD-N

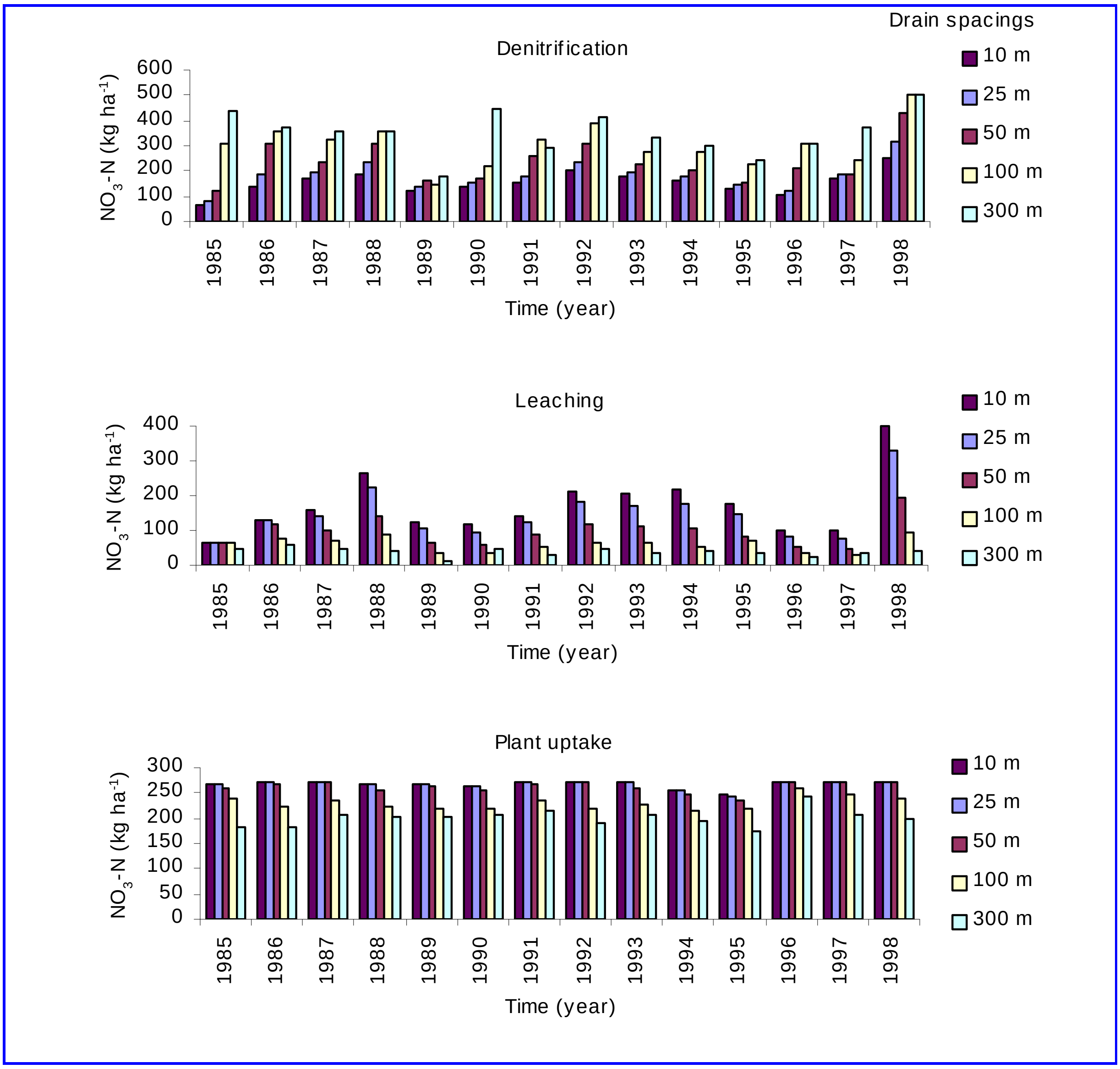

Figure 4: Predicted annual $NO_3$-N losses in denitrification process, subsurface drainage and plant uptake as affected by system management (conventional drainage) and drain spacings

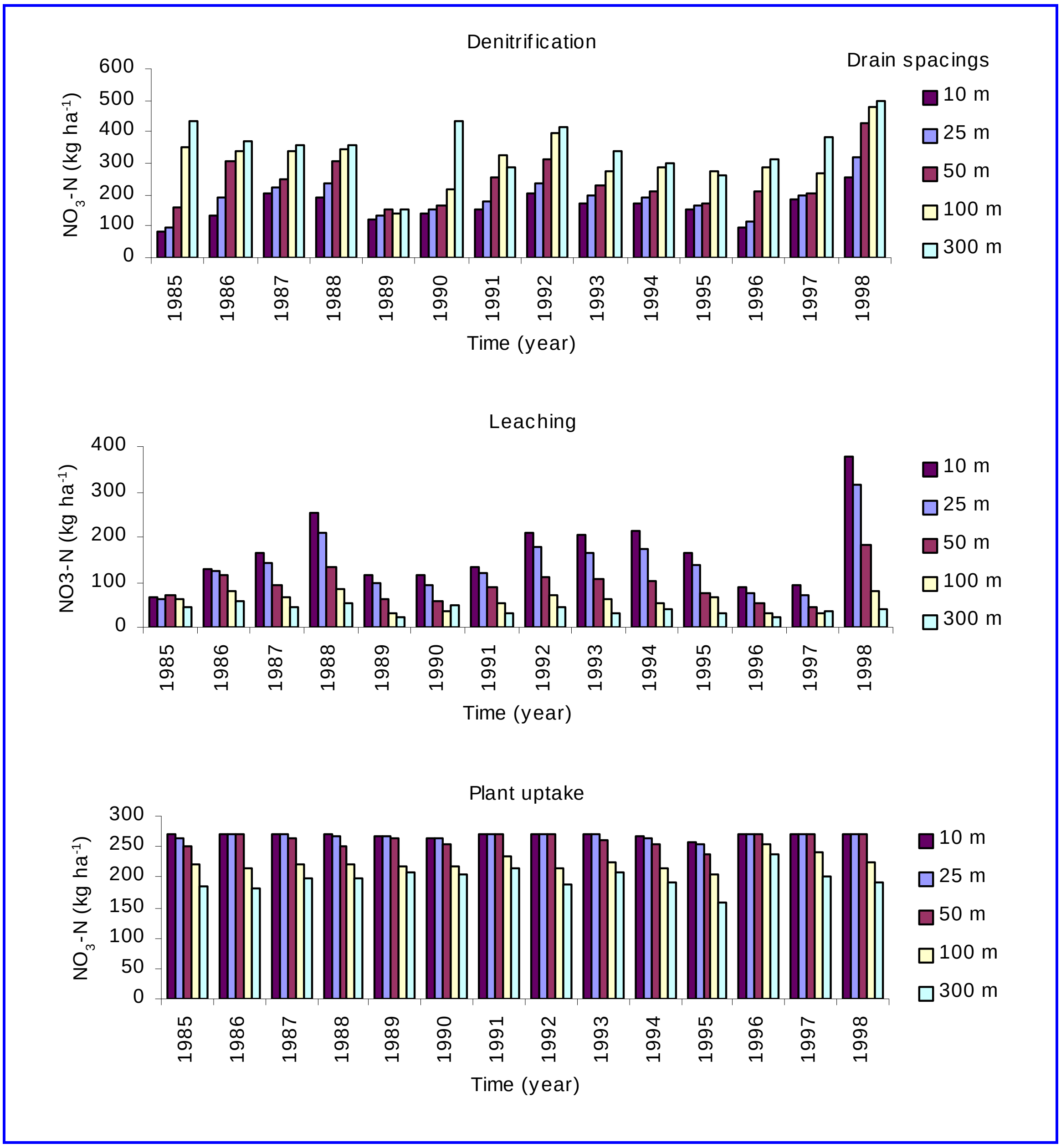

Figure 5: Predicted annual NO$_3$-N losses in denitrification process, subsurface drainage and plant uptake as affected by system management (controlled drainage) and drain spacings

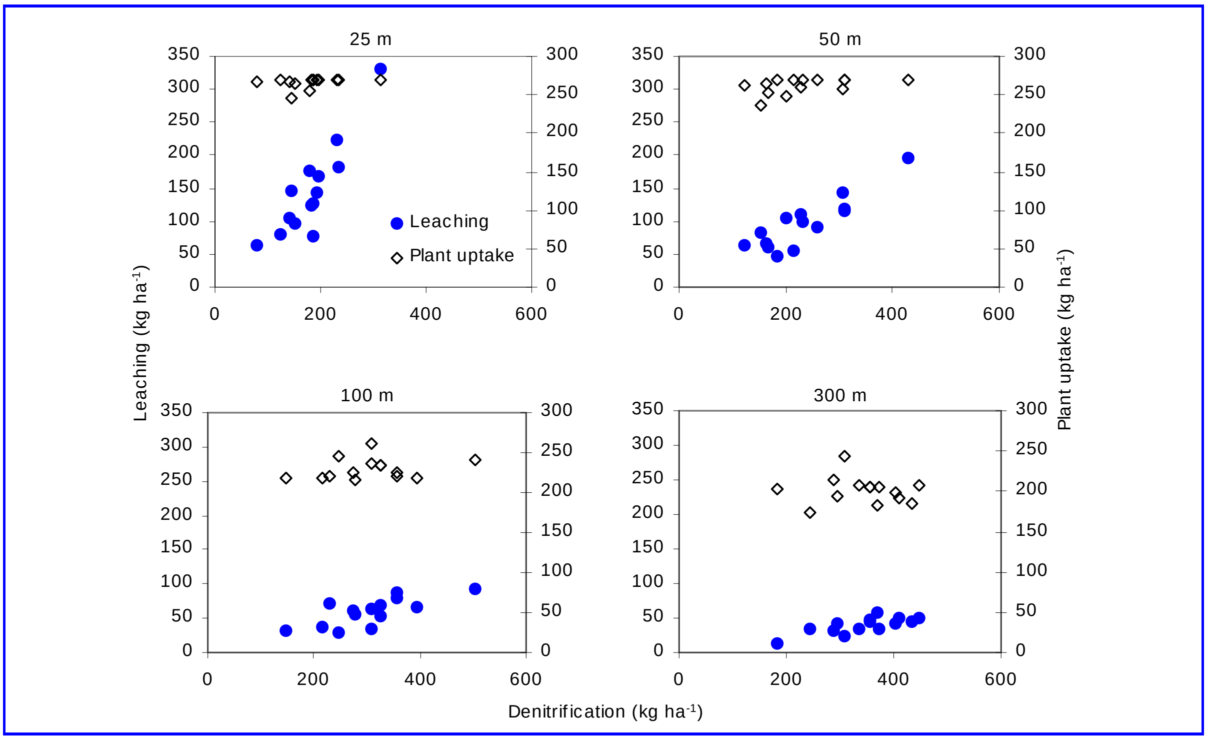

Figure 6: The relationships (simulation results) between the amount of $NO_3$-N leached-denitrification and the amount of $NO_3$-N taken up by plant-denitrification as a function of drain spacings (conventional drainage system)

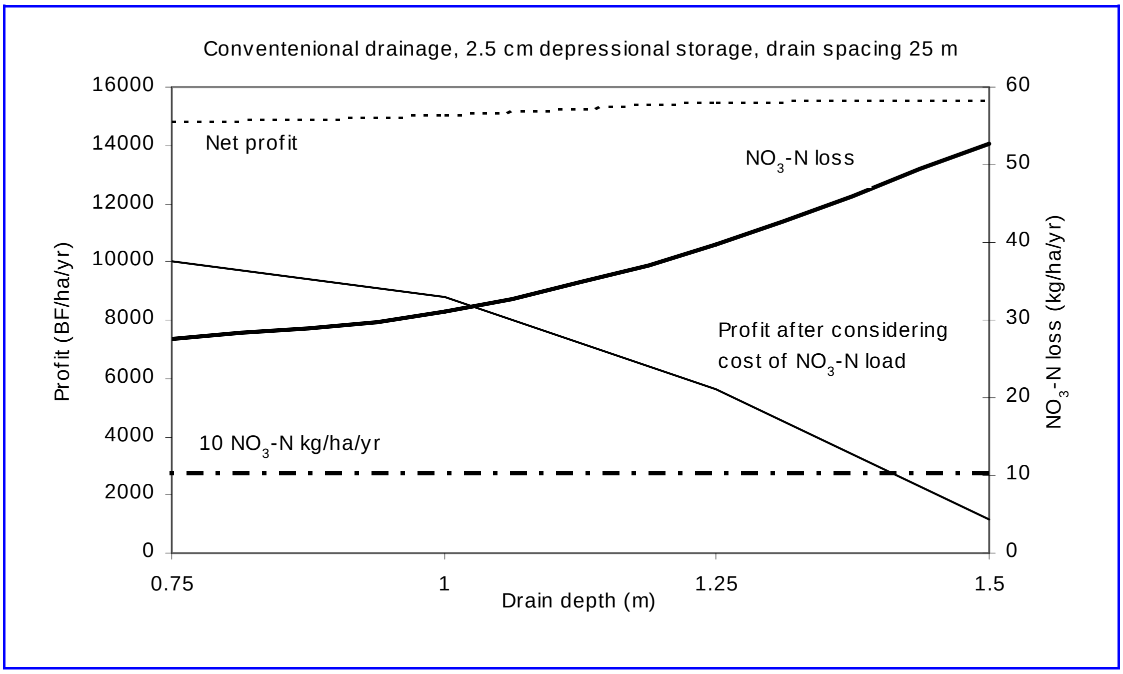

Figure 7. Effect of drain depth on profit as impacted by environmental costs of $NO_3$-N loss. Results based on 225 kg $ha^{-1}$ fertilizer application (after similar plot presented by Skaggs and Chescheir (1999) for a site in North Carolina)