Simulation of nitrogen leaching and nitrate concentration in a long-term field experiment

Simulace vyplavení dusíku a koncentrace nitrátů v dlouhodobém polním pokusu

Jan HABERLE and Martin KÁŠ

Crop Research Institute, Drnovska 507, 16106 Praha, Czech Republic

Tel.: +420 2 3332 2254, haberle@vurv.cz

ABSTRACT

The effects of organic and mineral nitrogen fertilization on nitrogen leaching and nitrate concentration in percolated water were simulated using the CANDY model. In a long-term IOSDV field experiment carried out from 1983 to the present in Lukavec, Czech Republic, increasing nitrogen rates from 0 kg to 200 kg N*ha^{-1} in mineral fertilizers were combined with the application of farmyard manure or straw, the control treatment was without organic fertilization. The simulation results of four rotations in the years 1996 – 2007 are presented. In the treatments, the average simulated nitrogen leaching ranged from 2 kg to 71 kg N*ha^{-1} y^{-1}, the average nitrate concentrations were between 5 mg and 191 mg*l^{-1}. The average year concentration of nitrate about 40 mg*l^{-1} indicated increasing occurrence of concentrations above 50 mg*l^{-1} at daily basis. Nitrogen leaching and nitrate concentrations were non-linearly related to the total nitrogen inputs (R^2= 0.98), the organic fertilizer treatments only negligibly altered the form of the relationship. The average nitrate concentration exceeded 50 mg*l^{-1} at a total nitrogen input level about 150 kg N*ha^{-1}; this corresponding to an average leaching of 20 kg N*ha^{-1} y^{-1}.

KEYWORDS: mineral nitrogen rate, manure, straw, nitrate, leaching, model

SOUHRN

Pomocí modelu CANDY byl simulován vliv organického a minerálního hnojení na vyplavení dusíku a koncentraci dusíku v prosakující vodě. V dlouhodobém polním pokus IOSDV vedeném od roku 1983 do současnosti v Lukavci, Česká republika, byl sledován vliv rostoucích dávek dusíku, od 0 kg to 200 kg N*ha^{-1}, v kombinaci s aplikací chlévského hnoje a slámy, kontrolní varianta byla bez organického hnojení. V článku jsou prezentovány výsledky simulace čtyř rotací osevního postupu v letech 1996 – 2007. Průměrné vyplavení u jednotlivých variant se zvyšovalo s rostoucí dávkou dusíku ze 2 kg na 71 kg N*ha^{-1} rok^{-1}, průměrná roční koncentrace nitrátového dusíku v perkolující průsakové vodě se zvyšovala z 5 mg*l^{-1} až na 191 mg*l^{-1}.

Průměrná koncentrace nitrátů okolo 40 mg*l^{-1} indikovala zvýšený výskyt denních koncentrací nad 50 mg*l^{-1}. Vyplavení dusíku a koncentrace nitrátů byla v nelineárním vztahu k celkovému vstupu dusíku (R^2= 0.98). Aplikace organického hnojení měl zanedbatelný vliv na tvar uvedené regresní křivky. Podle tohoto vztahu průměrná koncentrace nitrátů překračovala hranici 50 mg*l^{-1} při úrovní celkového vstupu dusíku okolo 150 kg N*ha^{-1} rok^{-1}, což odpovídalo průměrnému vyplavení 20 kg N*ha^{-1} rok^{-1}.

KLÍČOVÁ SLOVA: dávka minerálního dusíku, hnůj, sláma, nitráty, vyplavení, model

INTRODUCTION

The diffuse leaching of nitrogen from farm fields, especially from arable soil, is one of major contributors to pollution of both surface and ground waters (De Ruijter *et al*. 2007; Fučík *et al.* 2008; Kvítek *et al*. 2009). To reduce these losses while sustaining profitable production, both the short- and long-term effects of different N management systems must be investigated. The understanding of the factors which determine the leaching rates is the precondition for establishing administrative restrictions on risky farming practices in water supply areas and other regions vulnerable to nitrate leaching. The restrictions neglecting site- and management-specific conditions may turn out to be either unnecessarily restrictive or ineffective, especially in the long-term (Van der Ploeg *et al*. 1995; Simmelsgaard 1998; Ruiz *et al*. 2002; Fučík *et al*. 2008).

The extensive knowledge of N behaviour in agro-ecosystems has been embodied into mathematical models, which are then used to seek sustainable and profitable N management and fertilization systems under variable soil and climate conditions. There are numerous models of wide range of complexity, from simple empirical to mechanistic ones, simulating nitrogen in soils, usually coupled with plant and atmosphere environments (for reviw see e.g. Shaffer 2002 or Cannavo *et al*. 2008). These models, such as the CANDY used here (Franko *et al*. 1995), are employed to simulate N transformation and transport in soils. Nitrogen losses are closely connected with sustainable management of the soil’s fertility, principally the amount and quality of the soil’s organic materials (e.g. Kubát *et al*. 2001). The data from long-term experiments offers the only feasible way to verify the effects of different soil and crop management scenarios with a decades-long perspective (Kunzová & Hejcman 2009; Černý *et al*. 2010). The value of these experiments is the use of the same crop rotation and inputs of organic and mineral fertilizers in long-term. With data on nitrogen input and export in harvest they enable to calculate the balance of N in the system. On the other side, the experiments usually provide only little data needed for calibration and validation. The CANDY model is specially suitable for long-term experiments as it does not directly simulate growth and nutrient uptake, but the dry matter and nitrogen yields are inputted as observed in an experiment. The approach increases the reliability of simulation of long-term nitrogen balance in comparison with models where deviations may cumulate in a long-term. In CANDY, simulated amounts of N in the system are indirectly adjusted to reality due to exact data on input of N in fertilizers and export in yields or straw in the course of experimental years. The balance of N is the main factor determining amount of N potentially available to leaching.

The aim of this study was to evaluate the impacts of increasing mineral nitrogen rates in combination with organic fertilization on N leaching and nitrate concentration using a simulation model.

MATERIALS AND METHODS

An IOSDV experiment

The long-term field experiment has been carried out from 1983 to the present in Lukavec, Czech Republic, as a member of the network of Internationale Organische Stickstoff Dauerdüngungs Versuche (IOSDV) international experiments (Káš *et al*. 2010). The experimental site (49°33´ N, 14°58´ E) is 620 m a.s.l., the soil is sandy-loam Eutric Cambisol, and the average temperature and precipitation are 6.9°C and 686 mm. The region falls within the zone vulnerable for an increased risk of nitrate leaching. It belongs to the Švihov water reservoir catchment, where a relatively high concentration of nitrate still persists, despite some effort in the previous years (Kvítek *et al*. 2009).

Crop rotation is winter wheat, winter barley, and potatoes; all crops are grown in a year. The experiment has three organic fertilization treatments: 1) without manure (MIN), 2) 30 t*ha^{-1} of farmyard manure to potatoes (FYM), and 3) 4 t*ha^{-1} of wheat and barley straw plough down (STR). These were in combination with five nitrogen fertilization rates of 0, 40, 80, 120, and 160 kg N*ha^{-1} for the cereals, or 0, 50, 100, 150, and 200 kg N*ha^{-1} on the potatoes (denoted as N1 through N5, respectively). In the STR treatment, 50 kg N*ha^{-1} was applied on the straw in all N variants. In the MIN and FYM treatments, the straw was cleared off of the field. Manure contributed on average 150 kg N*ha^{-1}, straw 19 - 25 kg N*ha^{-1}. For more detail on the experiment see Káš *et al*. (2010).

The mineral N content in the 0 - 60 cm layer in the N1 and N4 variants of the MIN, FYM, and STR treatments were determined in the wheat (after potatoes), in both autumn and spring during 2000 - 2007. In 2006, the total C and N content in the 20 cm topsoil was determined.

Simulation with the CANDY model

The nitrate leaching and concentration in water percolated under 120 cm depth were simulated using the CANDY model (Franko *et al*. 1995). The whole period from 1983 was simulated, herein, we present the results of four rotations in the years 1996 - 2007. This model simulates the carbon and nitrogen dynamics in a soil profile soil - using daily weather, observed yields and data on field management. The model further simulates soil temperature, gasesous losses of N to atmosphere or water percolation and balance. The model has been validated in several experiments, and successfully compared with other models (Abraham *et al*. 1997; Smith *et al*. 1997; Franko *et al*. 2007). We found a reasonable agreement between the observed and simulated soil temperatures, soil moistures, and the nitrogen uptake distributions from a soil profile in the experiments with wheat at Lukavec and Ruzyně (not published). The data on soil Nmin, total C and N contents are used here to validate the long-term simulation of C and N.

The types and amounts of nitrogen fertilizers, manure, straw, sowing, harvest time, time and depth of soil tillage, and other data were inputs into the model. The observed grain and tuber yields were inputted, the N concentrations of wheat (1.50-1.80% N) and barley (1.30-1.80% N) grain, tubers (0.30-0.45% N), and straw (0.40-0.75% N) in the treatments were calculated from the data obtained during the years 1999 - 2002. The field capacity (FC) of the 0 - 30 cm and 30 - 60 cm layers was set 0.25 $cm^{-3}*cm^{-3}$, the FC of the 60 - 120 cm layer was 0.20 $cm^{-3}*cm^{-3}$, and wilting point was set 12.6 $cm^{-3}*cm^{-3}$ according to average of laboratory (soil water retention curves) and field data, saturated hydraulic conductivity was estimated to 450 mm, 450 mm and 400 $mm.day^{-1}$ from data on soil texture and database of soil data supplied with the model . The daily meteorological data from the Czech Hydrometeorological Institute's climatological station at Kramolín-Křešín 6 km away were used. The nitrogen deposition from the atmosphere was set at 35 kg $N*ha^{-1}$ y^{-1} as an average of reported decreasing deposition in the country during the experiment duration.

RESULTS AND DISCUSSION

Simulation of nitrogen leaching

The average amount of N leached under the depth of 120 cm rose non-linearly with the nitrogen rates, from 2 to 37 kg, 3 to 63 kg, and 3 to 71 $kg*ha^{-1}$ y^{-1} in the MIN, STR, and FYM treatments, respectively (Table 1). There was a strong year variability of the N leaching and nitrate concentration (Figure 1) however, it was not connected with a specific crop in the rotation. The expected relationship of leaching to water surplus (simulated flow to groundwater in a year) was mostly positive, although not strong (correlation coefficients from -0.1 to 0.8 in treatments). Nor was there a significant relationship between leaching and the previous or current year's yield. Consequently, the year variability in the leaching was the result of these factors in combination with the amount of mineral N that had accumulated in the soil profile from previous seasons. A significant year variability of the leaching and nitrate concentration of seepage water is common (e.g. Ruiz *et al*. 2002; Kvítek *et al*. 2009). The simulation results suggest that observed decreasing or increasing trends in N leaching and nitrate concentration should be evaluated and confirmed for the longer term, as recommended by e.g. Köhler *et al*. (2006) and Sieling and Kage (2006).

Table 1. The average simulated N leaching and nitrate concentration in years 1996-2007.

N rates	Average leached N $kg*ha^{-1}$			Average nitrate concentration $mg*l^{-1}$		
	Organic fertilizers treatments					
	MIN	FYM	STR	MIN	FYM	STR
N1	2	3	2	5	9	6
N2	2	8	5	5	22	14
N3	4	20	12	12	53	35
N4	10	37	30	29	99	81
N5	37	71	63	99	191	168

Simulation of nitrate concentration

The average simulated nitrate concentrations in percolated water exceeded the level of 50 mg.l^{-1} frequently only with the highest N rate (N5) in the MIN treatment; while in the STR and FYM treatments, this level had already been reached with the N4 and N3 rates, respectively (Figure 1). Only in few cases during the experimental period daily concentrations overcame over 50 mg.l^{-1} under lower N rates, N4, N3 and N2 in MIN, STR and FYM treatments. The average concentration about 40 mg.l^{-1} indicated increasing occurrence of concentrations above 50 mg*l^{-1} at daily basis. The higher N losses and nitrate concentrations in the respective N rates of the FYM and STR treatments, in the comparison with the MIN one, were the result of the increased total N inputs in the treatments (Figure 2), as will shortly be discussed further.

The nitrate concentrations simulated within N input levels common in farms (100-200 kg.ha^{-1}) were in the range of data found in surface waters in the region. The average nitrate concentration from the monitoring of nitrate concentrations in 25 tributaries in the Švihov catchment of the Trnava river (2006-2008) was 38 (±23) mg*l^{-1} (Holas - personal comm.); this corresponds to a N input level ca. 140 kg N*ha^{-1} y^{-1} in this long-term experiment (Figure 2). Kvítek *et al*. (2009) reported average nitrate concentration values between 20 and 50 mg*l^{-1} in the same district as Lukavec in the nineties; Fučík *et al*. (2008) reported average values between 10 and 110 mg*l^{-1} in the catchment of Švihov (1992 - 2006).

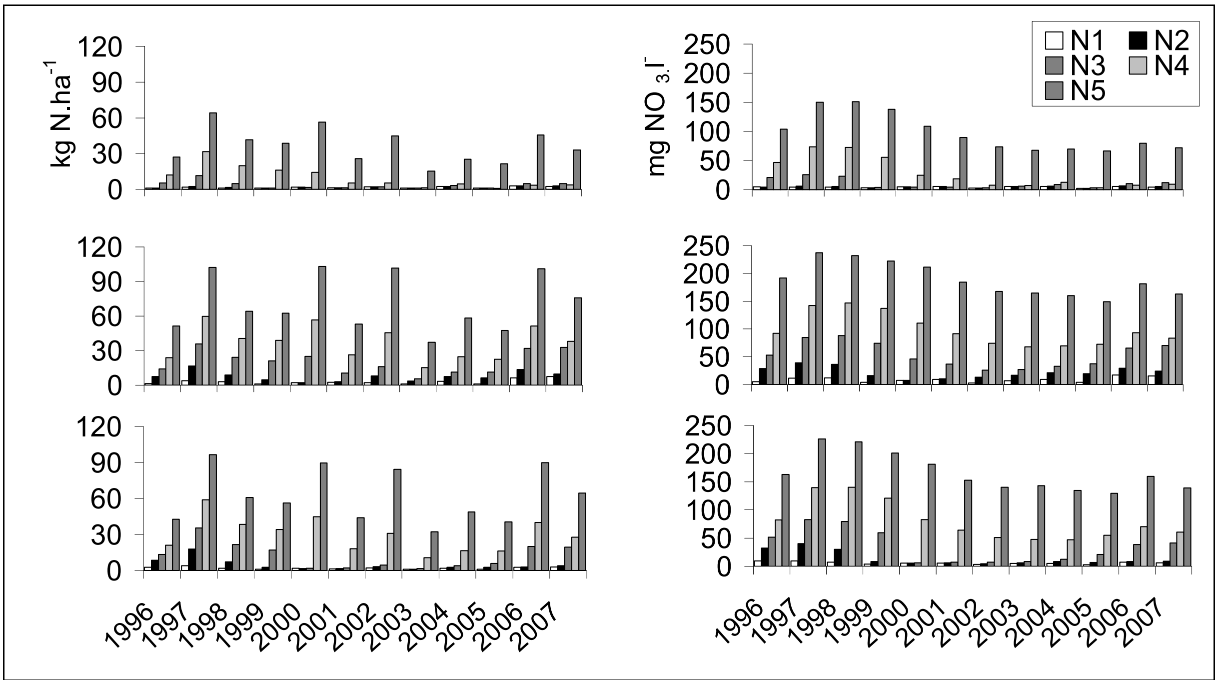

Figure 1. Simulated nitrogen leaching (left) and nitrate concentration (right).

The relationship between N inputs and simulated N leaching and concentration

The simulated average N leaching and nitrate concentrations were in a tight (R2= 0.98, n=15) non-linear association with the increasing total N inputs in the fertilizers, manure, and straw (Figure 2). Correspondingly, the relationship between the total N inputs and the yields was similar in all three treatments (Káš *et al*. 2010). The regression of total N inputs on the average nitrate concentration suggested further that the level of 50 mg*l^{-1} was reached with N input 148 kg N*ha^{-1} y^{-1}, corresponding to an average simulated N leaching 22 kg N*ha^{-1} y^{-1} (Figure 2). The average leaching about 17 kg*ha^{-1} y^{-1} indicate increasing occurrence of daily concentrations above the limit 50 mg*l^{-1}. Similar levels of N leaching (20 kg N*ha^{-1}) and nitrate concentration (46 mg*l^{-1}) was observed by Beaudoin *et al*. (2008), generally however, a great range in the relationships should be expected with versatile soil, climate, and agronomy conditions. Dresler *et al.* (2011) found that application of nitrogen fertilizer above 121 kg N*ha^{-1} caused a significant increase in the nitrate concentration in the surface soil layer. The average consumption of nitrogen fertilizers decreased to about 80-100 kg N*ha^{-1} in last two decades in the Czech Republic (Grzebisz *et al.* 2010) but cash crops, as winter wheat or winter rape, get higher than average rates of nitrogen.

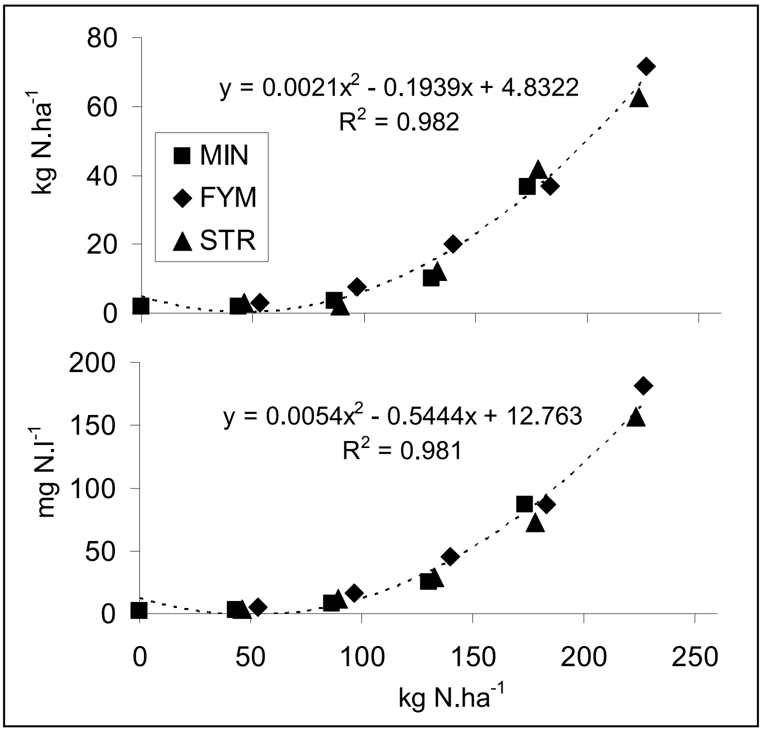

Figure 2. The relationship of total nitrogen input and average nitrogen leaching (top) or nitrate concentration (bottom).

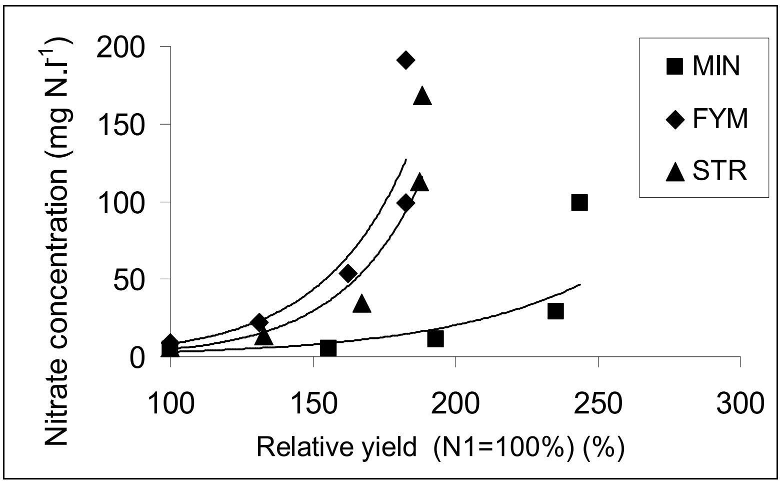

Figure 3. The relationship of increase of yield relative to N1 treatment to nitrate concentration. Fitted exponential curves are shown.

The expected dependence of nitrate concentration on the nitrogen input or balance was observed by many authors (e.g. Simmelsgaard & Djurhuus 1998; Sieling & Kage 2006; Adomaitis *et al*. 2008). However, Köhler *et al*. (2006) showed that even a strong decrease of N fertilization (severely reducing yields) did not substantially lower nitrate leaching within a period of five seasons, due to the mineralization of soil organic matter. The rapid increase of leaching and nitrate concentration above a certain level of nitrogen input, described by many authors, corresponds to diminishing increases of the yields at high N inputs (Figure 3) (Káš *et al*. 2010).

Observed and simulated soil mineral N, and total soil C and N

The comparison of observed and simulated soil mineral N (Nmin, 0-60 cm) contents and apparent decrease between autumn and spring validate the model performance. Observed Nmin averaged over years had a positive significant correlation with the average simulated data of the respective treatments (r=0.93 and 0.84, n=6). When data from all years and treatments were pooled the relationship was significant but loose (r=0.61, n=72). The model underestimated the observed Nmin content on average by 21 kg*ha^{-1}, the best agreement, in contrast to Abraham *et al*. (1997), was found in FYM treatment (difference 11 kg N*ha^{-1}) while in MIN it was 31 kg N*ha^{-1} (22 - 46 kg N*ha^{-1}); the reasons of high Nmin values in MIN treatment are not obvious and for the analysis more data will be needed. Correspondingly, the observed data showed higher apparent decrease of Nmin between autumn and spring (Haberle *et al*. 2009), on average, -12 kg*ha^{-1} and -17 kg*ha^{-1} in the simulated and observed data, respectively. The differences between observed and simulated Nmin amounts in individual years suggest need for further improvement, but as obvious from many studies, the simulation of actual Nmin content is a difficult task (Franko *et al.* 2005; Beaudoin *et al*. 2008).

Both, model and experiment showed increase of total C and N in FYM and STR treatments in comparison with MIN one, as observed by numerous authors (e.g. Scherer *et al*. 2011). The observed Ctot in the top 0 - 20 cm soil layer, were higher with the FYM and STR than they were in the MIN by 0.11% - 0.29% and 0.02% - 0.18%, respectively, simulated values were higher by 0.12% - 0.13% and 0.15% - 0.16%, respectively. The observed data showed more pronounced increase of Ctot with N rates in comparison with model outputs.

The observed Ntot in 0-20 cm were higher by 0.004% - 0.023% and by -0.001% to 0.013% (from -30 kg to 630 kg N*ha^{-1}) in the FYM and STR than they were in the MIN. The model simulates total N in a whole system (0-120 cm), and it was increased in the FYM and STR, when compared with the MIN data by 486 - 912 kg N*ha^{-1} and 523 - 977 kg N*ha^{-1}, respectively.

In summary, the differences among simulated and observed C and N data are within deviations commonly found in such experiments. The presented results suggest that N losses (leaching) might be less in FYM treatment and greater in MIN than predicted with model. Also, the leaching was probably greater under low N inputs than predicted by the model. But, thanks to specific feature of the CANDY model, the use of observed yield and N export data as input values, the balance of N must be similar in model and reality.

CONCLUSIONS

The simulation clearly presented the impacts of nitrogen inputs on N leaching over the long-term. The model showed that greater leaching and nitrate concentrations in the treatments with straw and manure were the result of greater total N inputs. The comparison of the observed and simulated contents of the soil nitrogen and carbon confirms the reliability of simulated N losses but also suggests some underestimation of losses in treatment without farmyard manure and under low N rates.

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