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Nitrogen in Hungarian soils — nitrogen management relation to groundwater protection

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Abstract

Nitrogen is widely used in agricultural practice in different organic and inorganic forms to enhance crop productivity. After the growing season, a part of the nitrogen remains in forms sensitive to changes of the conditions, such as nitrate. In years with above-average precipitation a significant amount of nitrate can leave the rooting zone of various crops even when land is cropped annually. Integration of knowledge related to environmental conditions of a certain area with the soil, water and crop management practices helps to prevent the simultaneity of the unfavourable processes leading to nitrate leaching, thus water resources may be protected from nitrate pollution of agricultural origin. It is of increasing importance that such an approach be applied in the Hungarian crop production. Since the great spatial variability of soil-forming factors is clearly reflected by the heterogeneous (sometimes mosaic-like) soil cover in Hungary, differentiation of categories within the soil types is strongly needed for agricultural practices. Basic features of a computerized fertilizer recommendation system developed in RISSAC to characterize the soil fertility levels in Hungary are: classification of the soils into a new land-site category system characterized by 4-digit codes, and also into aggregated land-site groups with regard to the major plant nutrients; and characterization of the nutrient status of soil by establishing nutrient supply categories which consider also the fertilizer requirements of the main crops. Since during the last few decades Hungarian farmers have applied more N–P–K fertilizers than the crops required, and at the same time there was a large increase in other potential pollution sources, harmful side-effects such as unfavourable changes in the quality of surface and subsurface water resources were detected. Hence, it was imperative to develop methods to calculate N balances which take into account the amount of N originating from other sources than the applied mineral fertilizers and also N output via nitrate leaching down the soil profile. Comparison of the results of several long-term field trials conducted simultaneously at several experimental sites which differed in environmental characteristics such as soil type and climatic conditions was shown to provide a good basis for a more generalized quantification of the overall turnover of nitrogen and for calculating improved N balances. The results indicated that when the rational use of organic manures and N-containing fertilizers is based on the plant's N demand, the nitrogen balances are

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in equilibrium. The amount of N needed to obtain economically viable yields, while at the same time being in balance with the requirements of the crops and keeping the environment uncontaminated, varied in long-term trials from 0 to 50 kg ha^{-1} yr^{-1} on fertile soils, 50 to 100 kg ha^{-1} yr^{-1} on coarse textured soils, while 100 to 150 kg ha^{-1} yr^{-1} in farm field analysis. Residual effects of nitrate in long-term experiments proved that after proper application of N fertilizer the amount of the residual nitrogen was low and no nitrate-N accumulation was detected under the root zone even for coarse textured soils.

1. Introduction

The biogeochemical distribution of nitrogen on Earth is such that only traces of elemental nitrogen are found in the hydro- and biospheres (Söderlund and Svensson, 1976). Nitrogen has a special feature among the essential elements in plant nutrition; namely, that the majority of it is bound in organic forms in the soil–plant system, mostly in humus. Organic nitrogen occurs in many forms covering a range from the readily mineralizable (amino-N, amide-N, etc.) to non-hydrolisable forms, such as lignin. Nitrogen is released from the organic forms via mineralization, and thus becomes available for plants. Mineral (inorganic) N forms rarely exceed 2% of the total soil N, when the fertilization is based on mineral fertilizers using the balance sheet method. The proportion of nitrogen present in mineral forms is greatly affected by climatic and soil conditions, by soil microbial population, and by land use. The ratio between the organic and inorganic forms of nitrogen in soil can be modified only slightly over the years. However, under certain environmental conditions (dry climate, negative water balance, overfertilization) a great part of the surplus nitrogen can accumulate in the soil profile in the form of nitrate after the growing season (Németh et al., 1988; Németh, 1993).

One of the preconditions for obtaining high crop yields is an absence of N deficiency, with an adequate supply of available nitrogen. The oldest, most primitive methods to achieve this aim are to clear-cut the native forest, to break up grasslands, to begin to cultivate fallow land and to dry up marshlands and moors for use in agricultural production. These cultural activities characterize the relationship that has existed between man and nature for the past thousands of years. Above a certain population density, and a certain production limit, the amount of nitrogen originating from the soil organic matter, and from other natural sources, may not be sufficient to satisfy the requirements of the crops. Beyond this stage, materials containing nitrogen (animal manures, green manures, plant residues, inorganic fertilizers, sewage sludges) must be applied in sufficient quantities to better meet the nitrogen requirements of the crops.

When nitrogen originating from various sources is introduced into the soil N pool, the concentrations of the various N forms will increase via several N transformation processes. After the growing season, a part of the nitrogen remains in forms such as nitrate, which are sensitive to changes of the conditions. Consequently, because of these changes, these N forms may result in environmental hazards (leaching, denitrification, etc.). Nitrate leaching from the rooting zone depends on soil texture, several N transforming processes, fertilizer inputs, plant uptake of N, precipitation, evaporation and evapotranspiration. On areas which are characterized by frequent moisture deficits, it is usually assumed that nitrate leaching is unlikely to occur. Fundamentally this is true, but in years with above-average precipitation a significant amount of nitrate can leave the rooting zone of various crops even when land is cropped annually (Campbell et al., 1984; Kádár and Németh, 1993). Generally and particularly in the above-mentioned situation leaching occurs when N can be found as nitrate in the unsaturated zone, and simultaneously there is enough water to wash through the root zone. This is why in most cases where agriculture has been indicted for causing nitrate pollution, it has been due to poor soil, water and crop management practices (Campbell et al., 1994; Follett, 1989; Németh, 1993). Knowing the environmental conditions of a certain area helps to avoid the simultaneity of the unfavourable processes leading to nitrate leaching.

2. Soils of Hungary

For a better understanding of the role of mineral fertilizers in Hungarian agriculture, it is important to describe the natural (soil) resources. Soil represents a considerable resource for Hungary. Soil-forming factors (geology, climate, relief, hydrology, hydrogeology, vegetation, time elapsing from the beginning of soil formation, land use and human activities) show great spatial variability in Hungary. This is clearly reflected by the heterogeneous (sometimes mosaic-like) soil cover. A large amount of soil-related information is available in Hungary as a result of long-term observations, various soil surveys, analysis and mapping activities on national (1:500,000), regional (1:100,000), farm (1:10,000–1:25,000) and field scales (1:5,000), carried out during the last 60 years (Várallyay, 1990).

The distribution of the arable land in Hungary, according to the main soil-types based on the Hungarian, USDA and FAO soil-classification systems, is:

Hungarian	USDA	FAO	% of total arable land
Chernozem	Mollisol	Phaosem	21
Brown forest	Alfisol	Luvisol, Cambisol	35
Meadow	Vertisol, Mollisol	Vertisol, Gleysol	21
Sandy	Entisol	Arenosol	9

The distribution of the arable soils according to soil texture, is:

Soil texture	% of total
Sand	16
Sandy loam	10
Loamy	40
Loamy clay	19
Clay	7

These distributions of the main soil types and of soil textures are important for characterizing soil fertility and are favourable for a good agricultural production.

Among the three main soil types which cover most of the Hungarian agricultural land the chernozems generally have the highest organic matter and colloid contents, and deepest humus layer. These soils are well aerated, and their texture mostly loamy. They are well supplied with plant nutrients. The chernozems are migration type soils: allowing easy downward and upward flow. Groundwater does not influence them, and they are located in relatively dry climatic conditions.

In the brown forest soils the organic matter content is lower than in the chernozems, and the humus layer is not as deep. The fertility of these soils is moderate, and it is strongly correlated with the soil texture and the amount of the erosion. These are leaching type soils: downward flow is dominant, the groundwater has usually no influence (because of the depth of the groundwater table), and the climate is relatively humid.

In the meadow soils the organic matter content is high, the organic layer is deep. The fertility of these soils depends on the environmental conditions, on the presence of other elements, on salt accumulation in the upper soil layer, and on the clay content. These are hydromorphic type soils: upward flow is dominant, the groundwater has a strong influence, and the climate is relatively dry.

3. Soil fertility

3.1. Fertilizer recommendations

The fertility of the soil is influenced by the aforementioned properties and several other factors. The soil nutrient status is the most important factor affecting soil fertility; ecological conditions, climate, relief, etc., are also of significance. Soil fertility and productivity are not synonymous, though sometimes there are close correlations between them (fertility is only one of the factors influencing productivity, but a very important one).

Differentiation of categories within the soil types is strongly needed for agricultural practices. Generally an advisory and recommendation system summarizes our current knowledge about soil fertility, nutrient supply and limiting factors with respect to expected yield potential. One of the greatest difficulties encountered in making fertilizer recommendations is determining the amount of nitrogen which should be applied. In Hungary the widely used N fertilization recommendations are based on the organic matter (humus) content of the 0–25-cm soil layer (ploughed layer).

A systematic program (sampling, analysis, recommendation) for controlling the plant nutrient status of cultivated soils was organized in the mid-1970's in Hungary with cycles consisting of 3 years. Soils were grouped into six main categories according to their characteristics, as follows:

I. Chernozem soils
II. Brown forest soils
III. Meadow soils
IV. Sandy soils
V. Salt affected soils
VI. Soils with shallow depth

Table 1
N supply categories according to the organic matter content of the 0–25-cm soil layer

Soil categories [a]	Base saturation percentage	N supply categories				
		very poor	poor	medium	good	very good
		organic matter (%)				
I	> 42	< 2.00	2.01–2.40	2.41–3.00	3.01–4.00	> 4.01
	< 42	< 1.50	1.51–1.90	1.91–2.50	2.51–3.50	> 3.51
II	> 38	< 1.50	1.51–1.90	1.91–2.50	2.51–3.50	> 3.51
	< 38	< 1.20	1.21–1.50	1.51–2.00	2.01–3.00	> 3.01
III	> 50	< 2.00	2.01–2.50	2.51–3.30	3.31–4.50	> 4.51
	< 50	< 1.60	1.61–2.00	2.01–2.80	2.81–4.00	> 4.01
IV	30–38	< 0.70	0.71–1.00	1.01–1.50	1.51–2.50	> 2.51
	< 30	< 0.40	0.41–0.70	0.71–1.20	1.21–2.00	> 2.01
V	> 50	< 1.80	1.81–2.30	2.31–3.10	3.11–4.00	> 4.01
	< 50	< 1.40	1.41–1.80	1.81–2.60	2.61–3.50	> 3.51
VI	> 42	< 1.30	1.31–1.70	1.71–2.40	2.41–3.30	> 3.31
	< 42	< 0.80	0.81–1.20	1.21–1.90	1.91–2.80	> 2.81

[a] I = chernozem soils; II = brown forest soils; III = meadow soils; IV = sandy soils; V = salt-affected soils; VI = soils with shallow depth.

To characterize the N-supplying capacity of these soils, the basis of segregating them was to classify them into categories of very poor, poor, medium, good and very good in each of the six main soil groups. As well the humus content and texture of the upper 25-cm soil layer were other factors considered as basic parameters for this classification (Table 1). During the evaluation of the measured data, Baranyai et al. (1987) estimated the distribution of nitrogen in the different soil categories according to main soil type and administration (county) units. Based on organic matter (humus) content, they stated that nearly 60% of the Hungarian agricultural land was well supplied with nitrogen. Using this N database the territories belonging to the poor N-supplying and the good N-supplying categories can be delineated.

During the mid-1980's it seemed appropriate to elaborate a new computerized fertilizer recommendation system. This system was developed in the Research Institute for Soil Science and Agricultural Chemistry of the Hungarian Academy of Sciences. It was used to characterize more than 500,000 ha in recent years (Várallyay et al., 1992). Various categories were established within individual soil types (groups) to indicate the soil fertility level. In this system the amounts of nutrients to be applied for a growing season are calculated on the basis of the relationship of the soil nutrient supply vs. plant nutrient demand.

The structure of this recommendation system is as follows:

(1) The soils of the area concerned have to be classified according to a new land-site category system. The elementary units of land-site categories are characterized by a 4-digit code.

(a) The first digit of this code (from 1 to 8) refers to the main character of the water and substance regimes of soils (three categories, viz. migration type, leaching type, hydromorphic type) or to the major soil fertility limitations (five categories, viz. skeletal soils, salt-affected soils, shallow soils, peat soils, "human-made" soils).

Table 2
Nitrogen supply categories according to the organic matter content of the 0–25-cm soil layer (new advisory system)

Aggregated land-site groups [a]	N supply categories				
	very poor	poor	medium	good	very good
	Organic matter (%)				
I	< 1.0	1.0–1.7	1.8–2.4	2.5–3.0	> 3.0
II	< 1.5	1.5–2.0	2.1–3.0	3.0–3.5	> 3.5
III	< 2.0	2.0–2.5	2.6–3.5	3.6–4.0	> 4.0
IV	< 2.5	2.5–3.0	3.1–4.0	4.1–5.0	> 5.0
V				5.0–15.0	
VI				> 15.0	

[a] See footnote to Table 1.

(b) The second digit in the first three — "normal" soil — categories provides information about the soil texture, the third digit about the soil reaction and the carbonate status, and the fourth digit about the organic matter content.

(c) In the other five — fertility-limited categories — these 2nd, 3rd and 4th digits are specialized for the given major soil fertility limitation (Sarkadi and Várallyay, 1989; Várallyay et al., 1992).

Altogether 280 existing soil mosaics can be distinguished in Hungary on the basis of this classification system.

(2) The soils of the area concerned have to be classified into aggregated land-site groups, using a matrix table compiled by specialists on issues regarding the major plant nutrients. In this matrix table all 280 soil mosaics were classified into nutrient element-specific land-site groups. Six aggregated groups were distinguished for N, P, K and Mg, and three groups for Ca. The main advantage of the present system, as compared to the previous one, is that one elementary mosaic unit can be classified into different aggregated land-site groups established for the aforementioned elements. The introduction of this possibility makes the system flexible and reliable, considerably improving its applicability.

(3) The nutrient status of soil is characterized with "nutrient supply" categories. For nitrogen this is based on the measured organic matter content (Table 2). For phosphorus and potassium it is based on the AL-soluble P_2O_5 and K_2O contents (Várallyay et al., 1992). Five nutrient supply categories were distinguished for N, P and K, each from 1 (low) to 5 (high). The previously mentioned nutrient element-specific aggregated land-site groups can be put into the proper nutrient supply categories; thus 30 (6×5) units exist for each aforementioned macronutrients.

(4) The new system also takes into account the fertilizer requirements of the main crops, on the basis of specific nutrient contents [specific nutrient contents = N, P_2O_5 and K_2O (kg ha^{-1}) for the production of 1 t[1] yield]. This basic value has yet to be

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[1] 1 t = 1 metric tonne = 10^3 kg.

Table 3
Fertilizer consumption and farmyard manure use in the Hungarian agriculture, 1931–1992 (*Agricultural Statistical Yearbooks*, 1950–1993)

Periods	FYM [a]	Active ingredients (1000 t yr^{-1})				Fertilizer
	(Mt yr^{-1})	N	P_2O_5	K_2O	total	(kg ha^{-1} yr^{-1})
1931–1940	22.4	1	7	1	9	2
1951–1960	21.2	33	33	17	83	15
1961–1965	20.6	143	100	56	299	57
1966–1970	22.2	293	170	150	613	109
1971–1975	14.8	479	326	400	1,905	218
1976–1980	14.3	556	401	511	1,468	250
1981–1985	15.4	604	394	495	1,493	282
1986–1990	13.2	559	280	374	1,213	230
1991	8.0	140	23	33	196	37
1992	11.1	148	21	20	189	36

[a] Farm yard manure.

corrected by multiplication (efficiency) factors corresponding to the nutrient supply categories of the specific site.

(5) The following modifying factors were also taken into consideration:

1. (i) influence of the previous crops on N requirement (it is a negative value for
2. legumes and positive for cereals, maize, sunflower, etc.).
3. (ii) nutrient content of plant residues remaining on the field after harvest
4. (excluding subsurface biomass).

3.2. Fertilizer consumption

During the last few decades, Hungarian farmers have applied more N–P–K fertilizers than the crops required. The statistical data show that before World War II the plant nutrient status of Hungarian soils was rather low, due principally to the negative nutrient balance (insufficient inputs to balance the crop-removed nutrients). Since the mid-1950's there has been a sharp increase in fertilizer consumption (Table 3).

During the development of Hungarian agriculture from the early 1960's fertilization was one of the most important factors (together with new, intensive high-yielding crop varieties, mechanization and complex plant protection). Use of mineral fertilizers in larger amounts was introduced in Hungary in the mid-1960's, and from the mid-1970's their proportion reached 75% of the total nutrients applied (including farmyard manures). It was necessary to apply more fertilizers because of three reasons: (a) to satisfy the higher nutrient requirements of the intensive crop varieties; (b) to improve the poor nutrient status of the soil; and (c) to balance the decreasing rate of farmyard manure application. The sharp increase in the consumption of mineral fertilizers was necessary and rational at that time. The relatively cheap price of fertilizers as well as the subsidization policy of the Government (subsidy) also had strong influence on this

Table 4
Sources of nitrogen in Hungarian agriculture between 1938–1990

Periods	(kg ha^{-1})						Organics in the % of the total consumption
	Root residues	Aftermat [a]	Liquid manure	FYM [b]	Fertilizer	Total	
1938	5.5	–	–	20.8	0.4	26.6	98.6
1950	4.2	–	–	19.7	2.1	26.0	92.1
1960	5.7	–	–	11.8	14.3	31.9	55.1
1965	6.3	–	0.5	16.7	37.0	60.5	38.8
1970	8.4	–	0.8	18.9	84.8	112.8	24.8
1971–1975	9.8	13.2	0.7	19.0	107.6	150.3	28.4
1976–1980	10.4	15.6	1.3	18.8	108.7	155.1	29.9
1981–1985	11.9	19.7	1.6	20.7	125.6	179.3	30.0
1986–1990	12.2	21.7	2.0	21.7	130.4	187.9	30.6

[a] Above-ground residues.
[b] Farm yard manure.

increase. The sources of N applied in the Hungarian agriculture between 1938–1990 are summarized in Table 4 after Fekete (1992).

Hungarian agriculture was much criticized later that this intensive fertilization was unnecessary, and led to harmful side-effects such as unfavourable changes in the quality of surface and subsurface water resources. It is a fact that these side-effects were already detected and registered in the period of increasing mineral fertilization. However, this coincidence does not necessarily prove a causal relationship, because at the same time there was a large increase in other potential pollution sources (e.g., concentrated animal husbandry farms, tourism, introduction of drinking water supply without canalization, increase in industrial and municipal waste disposal, hobby gardens).

For nearly 15 years (between 1975 and 1989) a plateau can be observed in the amount of nutrients applied yearly (Table 3). The total annual consumption of fertilizers were almost constant in this period with normal yearly fluctuations being ~ 1.3–1.4 Mt yr^{-1} active ingredients (0.55–0.60 Mt of N, 0.35–0.40 Mt of P and 0.45–0.50 Mt of K). These amounts correspond to an average rate of 250–300 kg ha^{-1} NPK. During this period the amount of N, P and K applied was higher than plant uptake (with ~ 15% for N, ~ 200% for P and ~ 150% for K), and the soil was thus enriched, mostly with P and K. The extra amount remaining in the soil reached 500 kg ha^{-1} P (1145 kg ha^{-1} P_2O_5) and 1000 kg ha^{-1} K (1205 kg ha^{-1} K_2O) on average. Consequently, the nutrient supplying capacity of the soil was increased. From 1990, when political and economical changes started, and free market practices were introduced in Hungary, mineral NPK application dropped sharply, and in 1992 and 1993 it almost ceased. Only 15 kg ha^{-1} N, 1 kg ha^{-1} P_2O_5 and 1 kg ha^{-1} K_2O were applied on average as mineral fertilizer to the arable land in these 2 years. This situation implies that it became very important to know how long the soils would continue to provide adequate amounts of P and K, and yet support reasonably high yields.

4. Nutrient balances of Hungarian agriculture

Hungary has a continental type of agriculture which focuses on crop production in the agricultural land use, and has a high rate of cereal production in mono- and biculture. The average yield of the main agricultural crops expanded considerably during the time of the sharp fertilizer increase (Table 5). In addition to the introduction of new, intensive, high-yielding crop varieties, mechanization and complex plant protection, the adequate nutrient supply of cultivated crops played an important role in this yield increase.

The maintenance of soil fertility has to be based mainly on the application of mineral fertilizers (Németh and Kádár, 1991). During the last few decades, farmers applied more nitrogen than the crops needed. The budgetary approach of the Hungarian agricultural land use (Table 6) shows that the overall nitrogen balance became positive in the early 1970's (with an average of 7 kg ha^{-1} N) and remained positive till the end of the 1980's (the positive balances varied between 16 and 27 kg ha^{-1} N in this period; Kádár, 1987; Csathó, 1994).

In the last two decades public concerns regarding the issues of environmental protection has become quite noticeable all around the world (Follett, 1989; Addiscott et al., 1991; Németh and Kádár, 1991; Campbell et al., 1994). This is one of the reasons why the fate and behaviour of the chemicals applied in agriculture are still of interest to researchers. As previously mentioned, nitrogen plays a special role among nutrient elements. While the portion of other nutrients (mostly of P and K) which is not taken up by crops will tend to accumulate in the upper soil layers, increasing both the total and the available nutrient contents of the soil, a significant portion of the surplus nitrogen may leave the rooting zone via erosion, surface runoff, leaching, denitrification and

Table 5
Average yields of the main agricultural crops in Hungary, 1951–1992 (*Agricultural Statistical Yearbooks*, 1950–1993)

Periods	(t ha^{-1})				
	Wheat	Maize	Sugar beet	Sunflower	Potatoes
1951–1955	1.46	2.06	18.69	1.07	8.77
1956–1960	1.50	2.31	21.20	1.10	10.46
1961–1965	1.86	2.61	24.64	0.96	7.91
1966–1970	2.43	3.23	32.52	1.11	10.45
1971–1975	3.32	4.17	33.00	1.24	11.74
1976–1980	4.06	4.85	33.64	1.61	14.16
1981–1985	4.63	6.11	38.90	1.98	18.23
1986	4.36	6.29	36.18	2.19	18.63
1987	4.37	6.13	36.30	2.09	15.97
1988	5.45	5.46	39.33	1.95	18.50
1989	5.24	6.22	43.98	1.95	18.60
1990	5.05	3.99	36.09	1.95	16.92
1991	5.19	6.71	37.16	2.07	15.76
1992	4.07	3.65	27.19	1.78	16.85

Table 6
Nitrogen balances (in kg ha^{-1}) of the arable land in Hungary (after Kádár, 1987; Csathó, 1994)

Balance units	1932–1936	1960–1964	1971	1975	1984	1990	1991
Uptake by crops	40	47	64	80	96	80	103
Returned by:							
organic manures	7	7	8	9	15	12	11
fertilizer	–	16	57	79	96	55	23
by-products	–	–	6	8	12	10	14
Total returned	7	23	71	96	123	77	48
Balance	−33	−24	7	16	27	−3	−55
Return/uptake (%)	18	49	111	120	129	96	46

volatilization. There are also some internal nitrogen transformation processes in the soil, such as mineralization and immobilization. There are some data about overall N balance in various countries which take into account all processes (e.g., Fleckseder, 1992). For an agricultural system mineralization and immobilization, atmospheric N deposition, leaching and gaseous losses are usually in equilibrium, thus these fluxes are balanced when considered over a long period. Consequently, for non-leguminous arable cropping systems, the major source of N input will be N fertilizers (organic and mineral) and the main source of output will be N in harvested grain (Campbell and Zentner, 1993). Usually these two sources are taken into account to calculate a simplified nitrogen balance (Tanji et al., 1977; Lund, 1982; Hill, 1986; Németh et al., 1988; Goss et al., 1994).

5. Elementary units of nitrogen balance

The main units of the nitrogen balance in cropping systems are the added nitrogen (off site N) on the input side, and the nitrogen content of the harvested crops on the output side. The amount of nitrogen leaving the system during or after the growing season is the environmentally most important variable.

In fertilizer recommendations the total quantity of N required by the crops determines the quantity of N which must be introduced during the growing season. This total quantity of N needed is based on the N demand of the expected yield which is more or less a function of the productivity of the field in the past.

Comparison of the results of long-term field trials conducted simultaneously at several different experimental sites provides a good basis for a more generalized quantification of the overall turnover of N and calculation of N balances, at the same time indicating also the impact of the environmental circumstances. Such approaches will be shown in the following sections.

6. Nitrogen balances from long-term fertilizer experiments

6.1. Nagyhörcsök Experimental Station

This experimental site is located 110 km SW from Budapest. The soil of this site is a migration type (calcareous chernozem), with relatively deep (100 cm) humus layer. The organic matter content is 3.0% in the ploughed layer and 1.1% at 100-cm depth. The average depth of the groundwater table is 13–15 m. The average mean temperature is 10.9°C, the annual precipitation is 550–600 mm, 60% of it is expected during the growing season. The soil moisture regime is also migration (chernozem) like; the annual precipitation is not enough to leach soluble salts through the soil profile down to the water table.

On selected plots (unfertilized plots and the plots which had received 100, 200 and 300 kg ha^{-1} yr^{-1} nitrogen fertilization) deep-drillings were carried out twice, in the 12th and in the 17th year of the experiments, in both years in July after the harvest of the cultivated crops. Soil samples were taken from the profiles at 20-cm intervals to a depth of 6 m. Soil moisture content of the samples were determined immediately (gravimetrically), the mineral-N (nitrate-N and exchangeable ammonium-N) and other

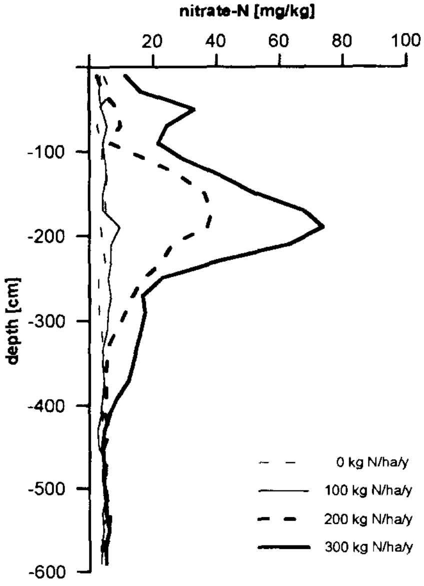

Fig. 1. Nitrate-N accumulation in the soil profile in long-term experiment conducted at Nagyhörcsök (1985).

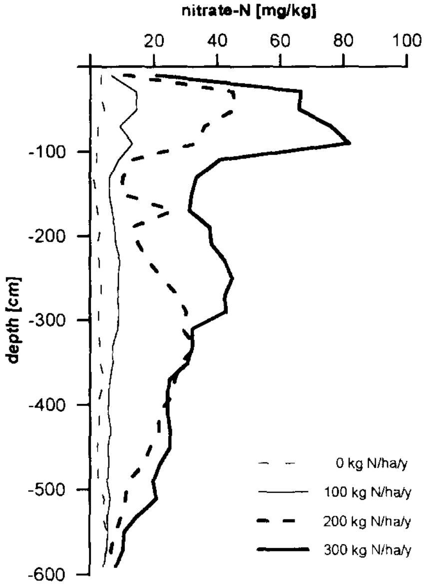

Fig. 2. Nitrate-N accumulation in the soil profile in long-term experiment conducted at Nagyhörcsök (1990).

chemical analyses (humus, total-N, pH, base saturation, AL-P, AL-K) were done after air-drying the soils.

From the beginning of the experiments till the 17th year the following crops were grown: winter wheat, winter wheat, maize, maize, potato, winter barley, oat, sugarbeet, sunflower, poppy, winter oil-seed rape, mustard, spring barley, oil-flax, soybean, hemp and peas (Kádár and Németh, 1993).

The nutrient balances were calculated from the amount of applied fertilizer, the nitrogen taken up by the plants and the nitrate-N remaining in the soil profiles.

First it can be state that nitrate-N accumulation in the subsoil was directly proportional to N rate with the accumulations being much greater by the 17th year than after 12 experimental years. Nitrate-N distribution in the profiles of the various nitrogen treatments in the 12th year of the experiment are shown in Fig. 1, while Fig. 2 shows similar results for the 17th experimental year. In 1985 (after 12 years) significant nitrate-N accumulation was found between 60 and 200 cm in the intensively fertilized treatments which received 200 and 300 kg ha^{-1} yr^{-1} N. These curves differed significantly from each other, while practically no difference was measured between the nitrate-N content of unfertilized plots and of the plots which had received the lower application rate (100 kg ha^{-1} yr^{-1} N). The amounts of nitrogen accumulated in the profiles of the plots fertilized yearly with 300 kg ha^{-1} N were ten times higher than those measured in the unfertilized plots. The effect of overfertilization on the residual nitrate-N form could be detected down to 350–400 cm (Németh et al., 1988).

After 17 years significant increases could be observed in the nitrate-N accumulation as compared to the values measured after 12 years. These were due partly to the crop rotation in the last 5 years (the amount of N taken up by the cultivated plants during this period was less than in earlier years) and to the drought that occurred during the growing seasons (Kádár and Németh, 1993). The changes may be summarized as follows:

(i) More nitrate-N was measured in the profiles down to 600 cm than at the time of the first drilling. The average increases in the 600 cm are 2.9 mg kg^{-1} after the yearly application of 100 kg ha^{-1} N; 8.7 mg kg^{-1} in the 200-kg-ha^{-1}-yr^{-1}-N treatment, and 12.5 mg kg^{-1} in the 300-kg-ha^{-1}-yr^{-1}-N treatment. These values show — when we take into account the 1.4-kg-dm^{-3} soil bulk density of the experimental site — that an excess of 244 kg N accumulated during this 5-year period in the profiles of the lowest nitrogen treatment than during the first 12 years. As well as plus 731 and 1050 kg ha^{-1} nitrogen were accumulated in the other two treatments, respectively,

(ii) The nitrate-N concentrations of the unfertilized plots and of the plots which had received 100 kg ha^{-1} yr^{-1} N during the last 5 years differed significantly (after 12 years these two treatments had similar values),

(iii) The peak of the nitrate-N accumulation was not as well defined as after the 12th year, the surplus nitrate-N had been leached to 5.5-m depth in the profiles of overfertilized plots by the 17th year.

A nitrogen budget of this experiment is shown in Table 7. Nitrogen uptake was calculated from the N content of grain and of above-ground residues, because neither of them were returned to the land. During the first 12 years the plants grown on the plots fertilized with 300 kg ha^{-1} yr^{-1} N took up only 240 kg more nitrogen (20 kg N yearly) than the plants which received 100 kg ha^{-1} yr^{-1} N. The balance calculated only from the amounts of added fertilizer and nitrogen taken up by plants show a negative value at the lowest fertilization rate (100 kg ha^{-1} yr^{-1} N). After the yearly application of 200 kg ha^{-1} N the balance was positive with 459 kg N (38 kg ha^{-1} yr^{-1} N) and after fertilizing with 300 kg ha^{-1} yr^{-1} N it was positive with 1557 kg ha^{-1} N (130 kg ha^{-1} yr^{-1} N).

If we take into account in all treatments the same amount of nitrogen coming into the system from other sources (the amount of nitrogen taken up by plants on unfertilized plots indicates this value — 1318 kg ha^{-1} N during 20 years) the balances become positive even in the lowest N treatment. According to this calculation the yearly positive balances are 60 kg ha^{-1} N at the lowest N fertilization treatment, 148 kg ha^{-1} N in the next N treatment, whereas after yearly application of 300 kg ha^{-1} N the balance was 240 kg ha^{-1} N. As the amount of the nitrogen coming from other sources is decreasing with increasing fertilizer application, the amount of this nitrogen lies probably between these two calculated values. For the lowest N fertilization rate between 30 and 60 kg ha^{-1} yr^{-1} N (30 kg ha^{-1} yr^{-1} N because of the negative balance based only on the applied fertilizer dose and the nitrogen content of the cultivated plants), for the 200-kg-ha^{-1}-yr^{-1}-N treatment between 0 and 148 kg ha^{-1} yr^{-1} N, while for the highest N treatment between 0 and 240 kg ha^{-1} yr^{-1} N.

The balance calculation after 17 experimental years shows that during the last 5 years the cultivated plants took up less nitrogen yearly, than in the previous years (Kádár and Németh, 1993). This was due partly to the lower N demand of the last five cultivated crops, and partly due to the drought conditions experienced during this period. This

Table 7
Cumulative estimated N balances (in kg ha^{-1}) of the long-term fertilizer experiment (Nagyhörcsök Experimental Station)

Items of N balance	Nitrogen treatments			
	N_0	N_{100}	N_{200}	N_{300}
July 1985 (after 12 experimental years):				
Added N	–	1,200	2,400	3,600
Taken up by crops	1,318	1,804	1,941	2,043
Balance	−1,318	−604	459	1,557
Difference to N_0		714	1,777	2,875
NO_3-N found in the soil (0–600 cm) [a]		41	664	1,466
July 1990 (after 17 experimental years):				
Added N	–	1,700	3,400	5,100
Taken up by crops	1,557	2,177	2,301	2,476
Balance	−1,557	−477	1,099	2,623
Difference to N_0		1,080	2,656	4,180
NO_3-N found in the soil (0–600 cm) [a]		382	1,495	2,613

[a] Amount of nitrate-N in the 0–600-cm soil layer (difference to N_0).

feature can also be seen from the differences between the nitrogen added as fertilizer and the nitrogen taken up by the plants. After 12 experimental years the yearly differences in the two positive balanced nitrogen treatments were 38 and 130 kg ha^{-1} N as mentioned above, while in the average of the last 5 years these values increased to 128 and 213 kg ha^{-1} N, respectively.

The average yearly nitrogen uptake of the grain and above-ground residues in the first 12 years in the lowest treatments was 150 kg ha^{-1} N, in the 200-kg-ha^{-1}-yr^{-1}-N treatments it was 162 kg ha^{-1} N, while in the 300-kg-ha^{-1}-yr^{-1}-N treatments it was 170 kg ha^{-1} N. The corresponding N uptake values in the average of the last 5 years were 75, 72 and 87 kg ha^{-1} N, respectively. This lower nitrogen uptake resulted in the balance being less negative in the 100-kg-ha^{-1}-yr^{-1}-N treatment than 5 years earlier, and the balances in the other two treatments became more positive. A great part of this 5-year surplus nitrogen could be found in the soil profiles in the form of nitrate (Fig. 2).

6.2. *National Long-term Fertilizer Experimental Network*

The same type of balance was done using data of the National Long-term Fertilizer Experimental Network. The experimental series chosen for our measurements started in

1968 on nine experimental stations in different parts of Hungary, on different soil types, under diverse environmental conditions (supervised by PANNON Agricultural University, Keszthely). The crop rotation practice and the fertilization treatments were identical at all sites. In the first four cycles (1968/1969–1983/1984) winter wheat, maize, maize and winter wheat were grown, and in the following cycle winter wheat, maize, sunflower and winter wheat were sown. For the budgetary analysis the specific nitrogen content of the crops (i.e. N content of 1 t harvested crops together with crop aftermath) were determined in each treatment on each site.

Deep-drilling to 3-m depth to determine nitrate-N was carried out on eight of the nine experimental stations, in July 1988, following the harvest of winter wheat with, using a method similar to that described for Nagyhörcsök experiment. Soil samples were taken in 4 replications from the unfertilized plots and from the plots which had received 50, 150 and 250 kg ha^{-1} N in each year. During the 20 experimental years the rate of N fertilization was changed twice (keeping the appropriate steps between the treatments). The altered N application rates were consistent with the increasing farm application rate of the nitrogen [this is why the sum of the amounts applied over 20-year period (see Tables 8 and 10) is not equal to 20 × 50, 20 × 150 and 20 × 250]. The observed nitrate-N accumulations in the soil profiles were discussed earlier by (Németh, 1993,1994). The investigated eight soils belong to three groups according to the

Table 8
Cumulative N uptake by the cultivated crops at the National Long-term Fertilizer Experimental Network

Experimental sites	Added N in fertilizers (kg ha^{-1} yr^{-1} N)			
	0	50	150	250
	(kg ha^{-1} N/20 yr)			
	0	715	2,425	4,135
N UPTAKE (kg ha^{-1}/20 yr):				
Chernozem soils:				
Hajdúböszörmény	2,757	3,924	4,353	4,894
Karcag	1,958	2,761	3,242	3,462
Iregszemcse	2,076	2,797	3,114	3,471
Nagyhörcsök	1,791	2,817	3,086	3,654
Brown forest soils:				
Bicsérd	2,712	3,777	4,588	5,088
Kompolt	2,081	2,920	3,445	3,943
Putnok	2,072	2,864	3,328	3,976
Alluvial soil:				
Mosonmagyaróvár	22,171	32,978	3,513	3,829

Table 9
Cumulative N balance comparing the added fertilizer N minus the nitrogen taken up by the cultivated crops at the National Fertilizer Experimental Network

Experimental sites	Added N in fertilizers			Added N in fertilizers		
	(kg ha^{-1} yr^{-1} N)			(kg ha^{-1} yr^{-1} N)		
	50	150	250	50	150	250
	(kg ha^{-1} N/20 yr)			(kg ha^{-1} N/20 yr)		
	715	2,425	4,135	715	2,425	4,135
	N balance			Net [a] N balance		
Chernozem soils:						
Hajdúböszörmény	−3,209	−1,928	−759	−452	829	1,998
Karcag	−2,046	−817	673	−89	1,141	2,631
Iregszemcse	−2,082	−689	664	−6	1,837	2,740
Nagyhörcsök	−2,102	−661	481	−311	1,130	2,272
Brown forest soils:						
Bicsérd	−3,062	−2,163	−953	−350	549	1759
Kompolt	−2,205	−1,020	192	−124	1,061	2,273
Putnok	−2,149	−903	159	−77	1,169	2,231
Alluvial soil:						
Mosonmagyaróvár	−2,583	−1,088	306	−311	1,184	2,577

[a] Nitrogen taken up by the crops of the unfertilized plots was subtracted.

Hungarian soil classification system: four were chernozem soils (Hajduböszörmény, Karcag, Iregszemcse, Nagyhörcsök), three were brown forest soils (Bicsérd, Kompolt, Putnok) and one an alluvial soil (Mosonmagyaróvár).

6.2.1. Nitrogen uptake

Nitrogen uptake of plants in the two most fertile soils (at Hajduböszörmény and at Bicsérd) was on average 50 kg ha^{-1} yr^{-1} higher for the average of the treatments, whereas on the unfertilized plots N uptake was 25–50 kg ha^{-1} yr^{-1} higher than at the other six experimental sites (Table 8). The yearly nitrogen uptake of the harvested crops on the unfertilized plots was 110 kg ha^{-1} (average of all the eight experimental sites), while for the treated plots the values were 157, 179 and 202 kg ha^{-1}, respectively for increasing N rates.

6.2.2. N budget analysis

The differences between the added fertilizer N and nitrogen uptake of the crops in the three nitrogen treatments are summarized in Table 9. In all soils crops took up more N than was applied at the two lowest N rates (balance values negative) but at the highest N rate this was only true for the two most fertile soils. Not surprisingly more N was taken up from non-fertilizer sources the lower the rate of N applied. On the other six experimental sites the balances became positive with annual applications of 250 kg ha^{-1} N, i.e. the yearly applied 250-kg-ha^{-1}-N rate exceeded the N demand of the crops. One of the other sources of N — the most important among them — is the nitrogen originating from the organic matter content of the soil via mineralization. As data of the crop nitrogen uptake were obtained also on the unfertilized plots, we can use N in this check to estimate amount of N derived from other sources. The results of this calculation are shown in Table 9.

Balances in Table 9 include an estimate of N mineralized from soil organic matter or supplied by other sources (e.g., atmospheric deposition) based on N uptake in the unfertilized plots. N content of the crops grown on the unfertilized plots were subtracted from the nitrogen content of the fertilized plots, respectively. (The quantity of N taken up from unfertilized plots of experiments is often used as approximation of the amount of genuine soil N mineralized.) The results of this calculation show that the N balances are still negative for the 50-kg-ha^{-1}-N treatment at all experimental sites. The N balance depended on both the N uptake of the crops (which in this treatment varied between 2761 and 3924 kg ha^{-1} N/20 yr, or 138 and 196 kg ha^{-1} yr^{-1} N), and on the original fertility of the land (characterized by the N uptake on the unfertilized plots, varying between 1790 and 2757 kg ha^{-1} N/20 yr, or 90 and 138 kg ha^{-1} yr^{-1} N). This means that nitrogen originating from the soil — or from other sources — varied between 90 and 138 kg ha^{-1} yr^{-1} N depending on environmental circumstances (i.e. soil physical, chemical and biological properties and climatic conditions).

After yearly applications of 150 and 250 kg ha^{-1} N the N balances became positive, with values varying between 27 and 92 kg ha^{-1} yr^{-1} N at the 150-kg-ha^{-1}-N rate and between 88 and 137 kg ha^{-1} yr^{-1} N when the rate was 250 kg ha^{-1} N. On the most fertile soils the balances were less positive than on the others. The highly positive balances after overfertilization are shown also by the calculation of the net N balance, based on the nitrogen uptake of the harvested crops on the unfertilized plots, as well as in the specific nitrogen content of crops on differently fertilized plots. At most experimental sites, after yearly applications of 150 and 250 kg ha^{-1} N, the specific nitrogen content of the harvested yields exceeded the values usually observed in Hungary (especially for sunflower). The usual values are 27 kg t^{-1} N for winter wheat, 25 kg t^{-1} N for maize and 41 kg t^{-1} N for sunflower on a medium N-supplied soil in Hungary.

In the plots of the fertilized treatments the real contribution of the other — non fertilizer — sources to the crop nitrogen nutrition lies somewhere between the values obtained in the two balance calculations shown in Table 9. For instance, on Hajdúböszörmény soil supply from non-fertilizer sources does not exceed 2757 kg ha^{-1} N/20 yr and is not less than 759 kg ha^{-1} N/20 yr. Furthermore including the nitrogen content of the control (unfertilized) plants as a constant in the calculations results in overestimation of the mineralization on plots with nitrogen fertilization treatments. The results also show that the optimum rate of the nitrogen fertilization resulting in a net N balance near to zero was between 50 and 150 kg ha^{-1} yr^{-1} N for the specific experimental circumstances.

Table 10
Cumulative N balances calculated with the residual nitrate-N content of the soil profiles at National Long-term Fertilizer Experimental Network (net nitrogen balances [a])

Experimental sites	Added N in fertilizers			
	(kg ha^{-1} yr^{-1} N)			
	0	50	150	250
	(kg ha^{-1} N/20 yr)			
	0	715	2,425	4,135
N UPTAKE (kg ha^{-1}/20 yr):				
Chernozem soils:				
Hajdúböszörmény [b]	−2,894	−599	548	1,473
Karcag	−2,117	−348	540	1,884
Iregszemcse	−2,257	−200	874	1,959
Nagyhörcsök	−1,990	−522	703	1,863
Brown forest soils:				
Bicsérd	−2,884	−558	255	1,070
Kompolt [c]	−2,212	−219	918	2,044
Putnok [c]	−2,159	−198	1,058	2,063
Alluvial soil:				
Mosonmagyaróvár	−2,555	−537	660	1,745

[a] Nitrogen taken up by the crops of the unfertilized plots was subtracted.
[b] Nitrate-N in the 0–200-cm soil layer.
[c] Nitrate-N in the 0–100-cm soil layer.

Having obtained the results of nitrogen balance calculations for the eight experimental sites, our next aim was to determine how and where this extra nitrogen could be detected in the soil–plant system. The N balance was expanded to account for profile-accumulated nitrate-N (Table 10).

These calculations were made on the basis of the data shown in Table 9 where the amount of nitrogen taken up by the crops of the unfertilized plots were subtracted from the amounts of N taken up on fertilized plots. The amounts of nitrogen found in the form of nitrate in the soil profiles were similar in the first two treatments, i.e. on unfertilized plots and in the 50-kg-ha^{-1}-yr^{-1}-N treatments at all locations. At the two higher N doses, higher nitrate-N accumulation was found in the profiles of chernozem soils, than on the brown forest soils. This means that when this type of budgetary calculation shows positive N balances, a greater part of the surplus nitrogen can be found in the profiles of chernozem soils than in the more frequently leached brown forest soils.

On the basis of the 20-year balance study it was shown, that even when nitrate leached into the deeper layers (or found in the soil profile) was subtracted in the balance calculations, the nitrogen balances became positive after yearly application of 150 and 250 kg ha^{-1} N. This positive balance varied under diverse soil and environmental conditions between 13 and 53 kg ha^{-1} yr^{-1} N in the 150-kg-ha^{-1}-yr^{-1}-N treatments, and between 54 and 103 kg ha^{-1} yr^{-1} N in the 250-kg-ha^{-1}-yr^{-1}-N treatments.

7. Farm-field nitrogen balances

A nitrogen balance study was based on 10 consecutive years from 1979 to 1988 made in 1988 in northwestern part of Hungary on farm-fields with a total area of 1178 ha. The simplified N balances gave positive results only on five of 21 fields analysed (Table 11), i.e. in most cases crops took up more nitrogen than what was applied as organic manures and fertilizers.

The results of our N balance calculations based on both the long-term field experiments and farm-field study indicate that when the rational use of organic manures and N-containing fertilizers is based on the plant's N demand, the nitrogen balances are in equilibrium. According to our results the amount of N needed to obtain economically viable yields, while at the same time being in balance with the requirements of the crops and keeping the environment uncontaminated, varied between 100 to 150 kg ha^{-1} yr^{-1} under Hungarian environmental conditions. The appropriate use of N-containing materials may help to avoid unfavourable side-effects, among which groundwater contamination may be considered as the most important.

Table 11
Nitrogen balances (in kg ha^{-1}/10 yr) conducted on large-scale farm fields in northwestern Hungary

Field	N taken up by crops	Fertilizer N	Balance
1	1,276	1,082	−194
2	1,094	847	−247
3	1,136	748	−388
4	1,226	1,028	−198
5	654	708	543
6	983	949	−34
7	1,044	980	−64
8	861	608	−253
9	1,576	1,023	−553
10	1,411	971	−440
11	1,343	1,044	−299
12	1,179	1,091	−88
13	1,390	1,136	−254
14	940	1,389	449
15	2,043	897	−1,146
16	555	1,194	639
17	1,180	867	−313
18	1,418	1,125	−293
19	1,404	1,164	−240
20	864	1,025	162
21	805	947	142

8. The residual effects of nitrogen

Residual nitrogen may remain in the form of nitrate in profiles of many soils under Hungarian environmental conditions (negative water balance, deep groundwater table, migration type soils, etc.) as it was shown in Figs. 1 and 2. The surplus N, in the form of NO_3-N, may accumulate in the profile or may be leached to deeper soil layers, or to the groundwater, depending on the physical characteristics of the soil and on environmental conditions. If the peak of NO_3-N accumulation remains in the rooting zone, then this N can be taken up by the crops, satisfying their N demands. The mineral-N fertilization recommendation systems are based on determination of this N (the NO_3-N, or NO_3-N plus exchangeable NH_4-N) content of a certain soil layer. To better understand the role of mineral-N in the nutrition of cultivated plants, it is necessary to investigate the fate and behaviour of these N forms, more specifically to study the accumulation, distribution and movement of NO_3-N in the different soil profiles. If the N fertilizer recommendation is based on field experiments in which the fertilizer response is well calibrated, this part of the previously surplus N should also be taken into consideration. Proper crop rotations including deep-rooted scavenger plants like winter oil-seed rape, alfalfa, sunflower and safflower are needed to utilize this nitrogen.

Long-term N fertilization experiments were established with identical treatments in two different growing areas: one on a calcareous sandy soil (Örbottyán) and the other on a calcareous chernozem soil (Nagyhörcsök). The aim was to create differences in mineral-N content in the soil profiles in order to determine their N-supplying capacity and whether the accumulated nitrate may be regarded as supply index for crop production. In the first 3 years of the experiments four rates of fertilizer-N were applied. In the 4th year the original plots were divided into five smaller ones onto which five spring fertilizer levels were applied. In this 4th year winter oil-seed rape was the indicator plant. In the following 3 years again the basic four fertilizer-N treatments were applied, and in the 8th year a division of the plots was made similarly as in the 4th year with five spring fertilizer-N levels applied to each original plots. This time winter wheat was the indicator plant. The effects of the residual-N and of the freshly applied fertilizer-N on the yield of the winter oil-seed rape and winter wheat were compared. The results showed that under certain environmental conditions N may accumulate in the soil profile in the form of nitrate, resulting from N fertilization in previous years, to such an extent that it must be taken into consideration when the fertilizer rates to be applied are determined. This is important not only for an economical management and for the protection of the environment, but also for a better quality of yield. The calculations can be reliably performed if based on the measurement and calibration of the mineral-N content of the soil.

8.1. Yields of the cultivated crops

8.1.1. Winter oil-seed rape

In the sandy soil the yield of the winter oil-seed rape varied between 0.95 and 2.04 t ha^{-1} (the lowest yield was measured on the double-control plots, always with 0 N application). In the average of the original treatments (main treatments) the yield was

Table 12
Yield of winter oil-seed rape in residual N experiments (1988, mean of 4 replications)

Nitrate N (mg kg^{-1}) in 0–100-cm soil layer	N top-dressing rates applied in spring (kg ha^{-1})						
	0	50	100	150	200	$LSD_{5\%}$	mean
Sandy soil (t ha^{-1}):							
4.2	0.95	1.15	1.28	1.64	1.39		1.28
5.0	0.86	1.33	1.68	1.44	1.54	0.30	1.37
6.0	1.32	1.37	1.65	1.58	1.79		1.54
11.3	1.56	1.79	1.70	2.04	1.87		1.79
(a) $LSD_{5\%}$				0.35			0.22
(b) Mean	$\overline{1.17}$	$\overline{1.41}$	$\overline{1.57}$	$\overline{1.68}$	$\overline{1.65}$	$\overline{0.15}$	$\overline{1.50}$
Chemozem soil (t ha^{-1}):							
11.3	1.34	1.52	1.79	2.32	2.43		1.88
13.4	2.26	1.36	2.58	2.37	2.44		2.40
26.7	2.38	2.48	2.61	2.46	2.57	0.23	2.50
41.8	2.37	2.56	2.52	2.53	2.48		2.49
(a) $LSD_{5\%}$			0.33			0.26	
(b) Mean	$\overline{2.08}$	$\overline{2.23}$	$\overline{2.37}$	$\overline{2.42}$	$\overline{2.48}$	$\overline{0.12}$	$\overline{2.32}$

significantly higher on the plots which received 300 and 450 kg ha^{-1} yr^{-1} N than in the control treatments as a consequence, and contained 6.0 and 11.3 mg NO_3-N/kg soil, respectively, in the profile at the spring sampling. A significant residual effect of the highest N dose (450 kg ha^{-1} yr^{-1} N, corresponding to 11.3 mg kg^{-1} NO_3-N in the profile) was detected at every spring fertilizer-N level. If > 100 kg ha^{-1} N were applied in spring, only a slight increase was observed in the yield of the winter oil-seed rape, the differences among the higher spring application rates were not significant (Table 12).

In the chernozem soil, yields varied between 1.34 and 2.61 t ha^{-1} (the lowest yield was again measured on the double control plots). The residual effect of N fertilization was detected in the yields of all previously fertilized plots. When the residual nitrate-N in the profiles was 26.7 and 41.8 mg kg^{-1} the yield of the indicator plant was as high, even without spring N application, as in the N control plots (containing 11.3 mg kg^{-1} NO_3-N as residual) with addition of 150 and 200 kg ha^{-1} N as spring N fertilizer. The residual effect of the previous N application was so efficient, that the 100-kg-ha^{-1}-N spring application was significantly effective ($P = 5\%$) only on the former (main treatments) control plots and on the plots with 13.4 mg kg^{-1} NO_3-N in the profile.

Table 13
Yield of winter wheat in residual N experiments (1992, mean of 4 replications)

Nitrate N (mg kg^{-1}) in 0–100 cm soil layer	N top-dressing rates applied in spring (kg ha^{-1})						
	0	50	100	150	200	LSD	mean
Sandy soil (t ha^{-1}):							
4.2	0.51	1.69	1.90	1.97	1.81		1.57
4.9	1.44	1.95	2.05	1.77	1.91	0.74	1.82
6.5	2.09	2.19	2.06	1.60	1.92		1.97
6.9	2.24	2.48	2.14	2.31	2.10		2.26
(a) LSD$_{5\%}$				0.74			0.62
(b) Mean	$\overline{1.57}$	$\overline{2.08}$	$\overline{2.04}$	$\overline{1.91}$	$\overline{1.93}$	$\overline{0.23}$	$\overline{1.91}$
Chernozem soil (t ha^{-1}):							
4.3	2.21	3.64	5.00	5.46	5.95		4.45
10.1	5.60	5.92	5.86	5.94	5.81	0.46	5.83
35.0	5.49	5.36	5.64	5.63	5.37		5.50
47.2	5.26	5.35	5.19	5.13	5.00		5.18
(a) LSD$_{5\%}$				0.46			0.38
(b) Mean	$\overline{4.64}$	$\overline{5.07}$	$\overline{5.42}$	$\overline{5.54}$	$\overline{5.53}$	$\overline{0.14}$	$\overline{5.24}$

Application of as much as 150 and 200 kg ha^{-1} N in spring resulted only in minor yield increases of the winter oil-seed rape.

From the above results it can be concluded that on the less fertile calcareous sandy soil, the effect of the spring N fertilization was greater than the residual effect of profile-accumulated nitrate. In contrast, on the fertile chernozem soil no differences were observed between the residual effect of the previous N fertilization and the effect of the fresh spring N application. With the improvement of soil N supply the amounts of fresh fertilizer-N needed for the optimum yield decreased on both soils: from 150 to 50 kg ha^{-1} N on the sandy soil, and from 200 to 0–50 kg ha^{-1} N on the chernozem soil.

8.1.2. Winter wheat

The yield of winter wheat varied between 0.51 and 2.48 t ha^{-1} on the calcareous sandy soil (Table 13). The lowest yield was measured on the double-control plots. The utilisation of the previous N fertilization without fresh N application was very efficient; its residual effect was significant ($P = 5\%$) for each main treatment as compared to the double-control plots. The residual effect of the highest main treatment was significant ($P = 5\%$) not only relative to the double-control treatment, but also to the first main N fertilization level. The average yield of the spring N fertilization treatments shows that all previous fertilizer levels had a pronounced positive effect on the yield of the winter wheat, but the increase was significant ($P = 5\%$) only at the highest main treatment level. In the main control treatments the effects of all five spring N application rates were significant ($P = 5\%$), but no significant ($P = 5\%$) increases from spring N application were detected in the previously fertilized treatments. Summarizing the results, it can be concluded that the positive effects of the residual N were measurable at all spring N application rates.

In the calcareous chernozem soil, the yield of the winter wheat crop varied between 2.21 and 5.95 t ha^{-1} (Table 13). Significant ($P = 5\%$) increases were observed in the yield at all residual N levels in the spring control and in the spring 50-kg-ha^{-1}-N treatments, as well as in the mean of the spring fertilization rates. It appears that at N application rates higher than the first main fertilizer level (150 kg ha^{-1} N) the amount of residual N was so high that it had a negative (decreasing) effect on yield. All spring N fertilization rates significantly ($P = 5\%$) increased the yield of the winter wheat at the original control levels, not only as compared to the double-control treatment, but also between the four original N treatments as well. Spring N fertilization was effective up to 150-kg-ha^{-1}-N rate, as related to the mean yields of the main treatments. The winter wheat yield was greatly affected by the residual N on the previously fertilized plots, while no positive effects of spring N application could be detected.

Comparing the effects of the residual N and of spring N application it can be concluded, that on the calcareous sandy soil, whereas on the calcareous chernozem soil 0–50 kg ha^{-1} N were the optimal N fertilization rates, respectively, under the specific environmental conditions.

9. Groundwater protection

The nitrogen (mostly nitrate) reaching the groundwater originates from various sources, one of which is the non-point load from agricultural land use. The contamination of the shallow groundwater is partly caused by intensive agricultural activities via increased nitrate leaching.

The goal of efficient N management is to minimize or eliminate nitrate leaching losses, this involves controlling the excess nitrogen (in the form of nitrate) in the root zone at the end of the growing season, as well as those periods when intensive rainfall is probable. The aforementioned nitrogen studies and trials provided a good experimental basis to support this aim. Evaluation of the experimental data sets showed that it is possible to improve the nitrogen management practices to match the expectations for securing stable and sufficient yields and for protecting the environment as well.

All the experimental data which were discussed above showed that after the appropriate use of N fertilizer the amount of the residual nitrogen was as low as in the unfertilized plots, and no nitrate-N accumulation was detected under the root zone even for the coarse textured soils. We conclude that the harmful effect of the fertilization can be avoided when N fertilizers are applied at the recommended rates, taking into account the N demand of the crops for the expected yield, and the specific environmental conditions.

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