Uptake of mineral nitrogen from subsoil by winter wheat

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ABSTRACT

The apparent uptake of mineral nitrogen (N_{min}) from top- and subsoil layers during the growth of winter wheat (*Triticum aestivum* L.) was studied in Prague-Ruzyne on clay loam Chernozem soil in years 1996–2003. Two (N0, N1) and three treatments, unfertilized (N0), fertilized with 100 kg (N1) and 200 kg (N2) nitrogen per hectare were observed in years 1996–2000 and 2001–2003, respectively. The apparent uptake of nitrogen from soil layers was calculated from the changes of N_{min} content between sampling terms. Most of available mineral N in the soil down to 90 cm was almost fully depleted between tillering and anthesis in treatment N0. The uptake from subsoil layers was delayed and it continued during the period of grain filling in fertilized treatments. Nitrogen fertilization reduced utilization of N from subsoil. The apparent uptake of N from the zone 50–120 cm ranged from 21 to 62 kg N/ha in N0 and from 15 to 60 kg N/ha in N1 in years 1996–2000. In years 2001–2003 the corresponding values (50–130 cm) were 24–104 kg, 43–130 kg and 29–94 kg N/ha in treatments N0, N1 and N2, respectively. The uptake from 120 (130)–150 cm was around zero in a half of experimental years, and it reached at maximum 12 kg/ha in N0 in 1997. There was a strong linear relation between the amount of N_{min} in spring and the depletion of nitrogen from the zone 50–120 (130) cm, $R^2 = 0.94$, 0.91 and 0.99 in N0, N1 and N2, respectively.

Keywords: mineral nitrogen; N_{min}; available N supply; N depletion; subsoil; rooting depth; winter wheat

The concentration of mineral nitrogen ($N_{min} = N\text{-}NO_3^- + N\text{-}NH_4^+$) in soils that is available to crops is important information for evaluation of different N management systems and for effective nitrogen fertilization (Addiscott and Darby 1991, Sylvester-Bradley et al. 2001, Gastal and Lemaire 2002, Vaněk et al. 2003, Olfs et al. 2005). The actual content and distribution of N_{min} in a soil profile is the result of plant uptake, fertilization, mineralization, denitrification, leaching and immobilization. Crops absorb nitrogen from the both, top- and subsoil layers of soil profile, mostly in the form of nitrate and ammonium ions (Miller and Cramer 2004). The maximum utilization of soil nitrogen supply is also important for the reduction of nitrate leaching from the root zone. Residual nitrate after harvest is prone to leaching to subsoil layers during winter and spring and it increases undesirable nitrate concentration of surface and ground waters.

The utilization of nitrogen supply from subsoil layers is determined chiefly by crop demand for nitrogen, root morphological and physiological traits (King et al. 2003), forms, amount and distribution of available N in a soil, and soil moisture (e.g. Svoboda et al. 2000, Gastal and Lemaire 2002, Jeuffroy et al. 2002). The N_{min} in topsoil and shallow subsoil layers is taken as accessible for most crops thanks to a high root density and optimal soil conditions in the soil zones. The information when and to what extent the supply of N in subsoil layers (mostly in the form of nitrates) is available for crops is needed for a fine tuning of N fertilization rates. The possible agrotechnical measures for increasing nitrogen uptake from subsoil are of practical importance for farmers (Haberle et al. 2004, Hoad et al. 2004). However, it is hindered by a general lack of data on root distribution and N uptake from subsoil layers. Root length distribution observed in this experiment was presented by Svoboda and Haberle (2006).

The objective of the study was to determine the apparent uptake of mineral nitrogen from subsoil layers by winter wheat under different nitrogen fertilization rates.

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MATERIAL AND METHODS

The changes of mineral N ($N_{min} = N\text{-}NO_3^- + N\text{-}NH_4^+$) in soil layers were studied in the field experiment with winter wheat (*Triticum aestivum* L.), cultivars Samanta and Nela, in years 1996–2000 and 2001–2003, respectively. Rooting depth (Svoboda and Haberle 2006), soil moisture (Haberle and Svoboda 2000, Haberle et al. 2002), crop growth and nitrogen accumulation in shoots (Svoboda et al. 2000) were observed in the experiment.

The experiment was conducted in Prague-Ruzyne (N50°05', E14°20'), altitude 340 m, average precipitation and temperature (1961–1990): 477 mm per year and 7.9°C, respectively. Cumulative sum of precipitation and temperature above 0°C in the experimental years in the site are shown in Figure 1, monthly data and average temperature and precipitation are given in Svoboda and Haberle (2006). The field is a fertile deep clay loam Chernozem soil on loess. The soil texture, basic agrochemical data and pre-crops are given in Svoboda and Haberle (2006).

Two treatments were observed in years 1996–2000; unfertilized with N (N0) and fertilized with 100 kg N/ha, split applied in nitrate ammonium in spring. In seasons 2000/2001 to 2002/2003 100 kg N/ha in nitrate calcium was applied before winter in treatments N1 and N2 to increase nitrogen content in subsoil. N1 treatment was not fertilized during the main growth period, in N2 treatment additional 100 kg N/ha in nitrate ammonium was split applied in spring. The experiments were established with six replications per treatment, area of plots was 33 m^2 (6 × 5.5 m).

The concentration of N_{min} in soil profile was determined several times during growth, from early spring to harvest, several days after maturity. Soil was sampled to the depth of 90 cm by 20 cm increments; top 10 cm was sampled separately. The layers 0–30 cm and 30–50 cm are referred to as top soil and shallow subsoil, respectively. The subsoil zone under 90 cm (down to 150 cm in 1996–2000) was sampled on selected dates. In years 1996–2000 soil was sampled in 30 cm increments under 90 cm, in years 2001–2003 in 20 cm increments. There were two replicates per treatment (three in spring and grain filling) formed by bulked soil from five or six (top soil) and three or four (subsoil) subsamples. Soil samples were kept in a transportable cooler during sampling and processed on the same or next day; soil was mixed

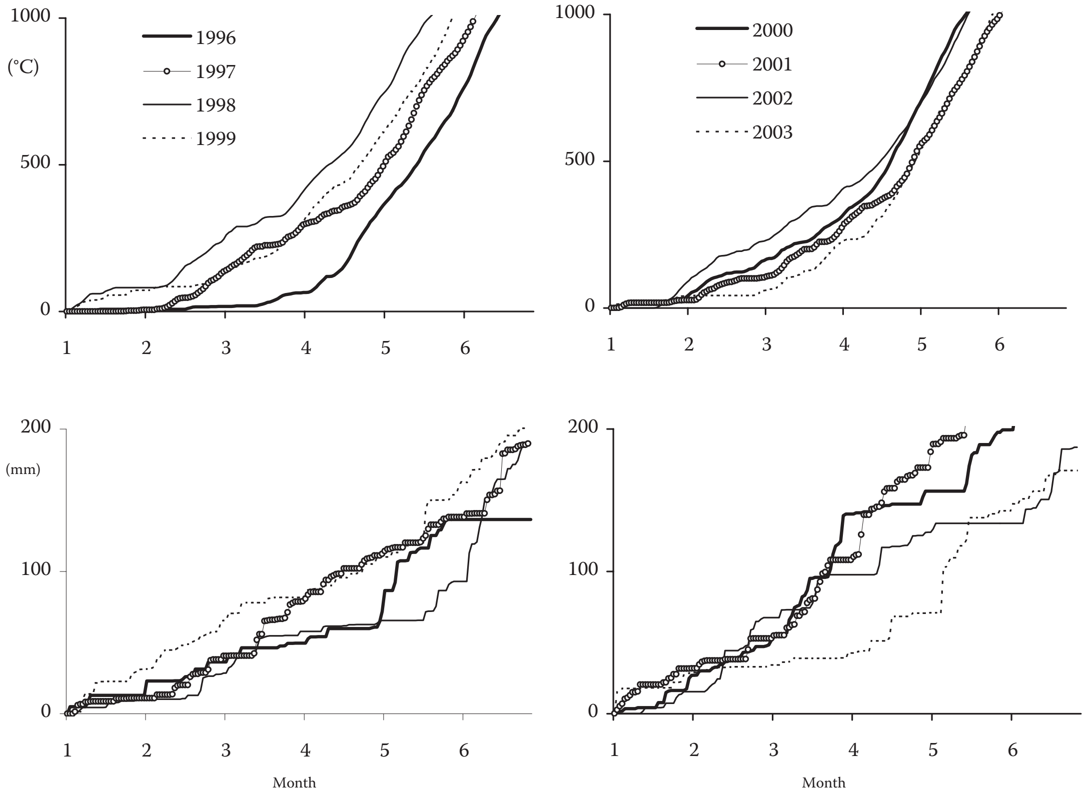

Figure 1. Average accumulated temperatures (above 0°C) and precipitation in experimental years from January to July in Prague-Ruzyne

and ground where needed; fraction under 2 mm was analyzed. Soil was shaken in 2% K_2SO_4, 1:5 soil:solution ratio for 1 hour; NO_3^- and NH_4^+ were determined by colorimetry (FIA). The results are expressed in kg N/ha using average bulk density of respective layers.

The apparent depletion of nitrogen was calculated as a change of N_{min} content in a soil layer between sampling terms. The change of N_{min} between early spring, before the application of nitrogen fertilization (the highest total content of N_{min} during year in N0) and the period of grain filling (the lowest level of N_{min}) were used for the comparison of apparent uptake from subsoil among treatments in experimental years.

The effect of treatment and year on the apparent N uptake were analysed with two-way ANOVA.

RESULTS AN DISCUSSION

In this contribution the results of an eight-year study of apparent uptake of mineral nitrogen from subsoil by winter wheat are presented.

Mineral N content in subsoil

The N_{min} content and distribution in soil profile at spring before the main growth period varied greatly in experimental years (Figures 2 and 3). The proportion of ammonium N was low, mostly under 15% of total N_{min}, throughout the experiment.

The amount of N_{min} on spring sampling terms, in March and April, in unfertilized treatment N0 in subsoil 50–120 (130) cm ranged between 25 and

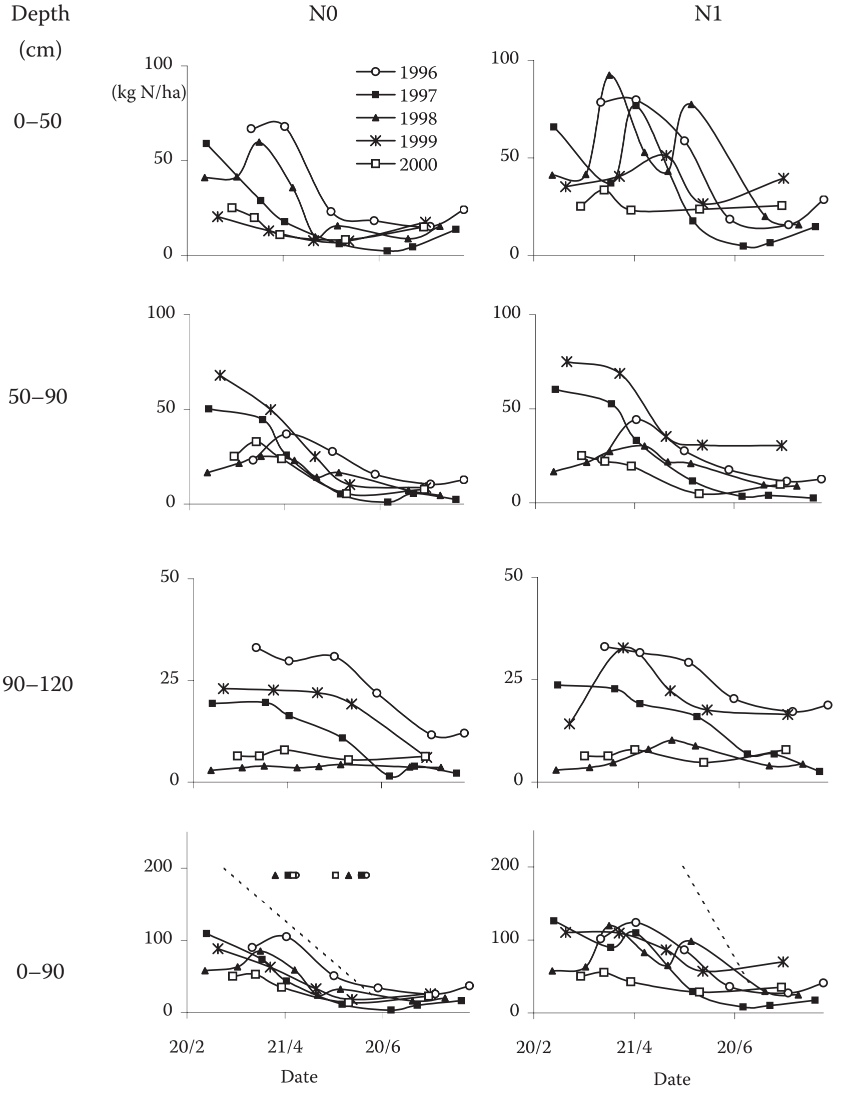

Figure 2. The changes of N_{min} in soil layers under winter wheat in 1996–2000; the calculated rates of apparent uptake of N 2 kg and 4 kg N/ha/day are shown as line for N0 and N1 treatments, respectively; the growth stages-stem elongation and flowering are indicated by symbols above curves for 0–90 cm

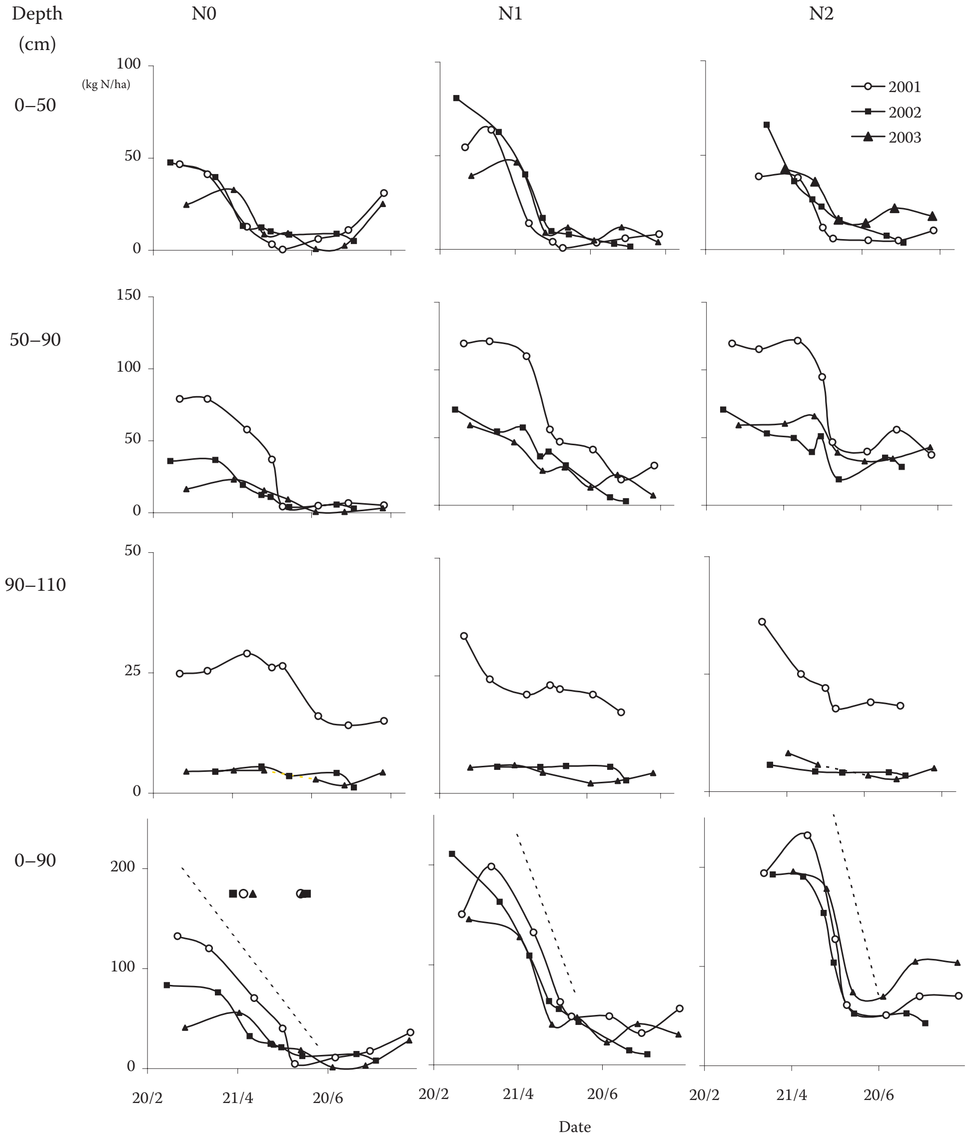

Figure 3. The changes of N_{min} in soil layers under winter wheat in 2001–2003; the calculated rates of apparent uptake of N 2 kg, 4 kg and 6 kg N/ha/day are shown as line for N0, N1 and N2 treatments, respectively; the growth stages are indicated by symbols above curves for 0–90 cm.

133 kg N/ha, the average of all years was 60 ± 3 kg and 61 ± 34 kg N/ha, respectively (55 kg and 54 kg N/ha in years 1996–2000). The highest values of N_{min}, 70 kg, 91 kg and 133 kg N/ha, were observed in 1997, 1999 and 2001, respectively, the seasons following dry years (Figure 1). The lowest supply of N_{min} in subsoil in spring was found in 1998, 2000 and 2003, from 25 to 32 kg N/ha. The N_{min} content in deep subsoil, in 120–150 cm reached 28, 19, 4, 5 and 11 kg N/ha in years 1996–2000, respectively. Subsoil N_{min} on spring terms in N1 was similar to N0 in years 1996–2000, 58 ± 27 kg and 63 ± 28 N/ha, while in 2001–2003 it was higher, 113 ± 50 kg and 101 ± 47 kg N/ha, due to the autumn N application and nitrate leaching to subsoil. The (residual) content of N_{min} after harvest in subsoil zone 50–120 (130) cm reached on average 13 ± 7 kg and 23 ± 18 kg N/ha in N0 and N1, respectively, in years 1996–2000 and 15 ± 9 kg, 29 ± 24 kg and 58 ± 18 kg N/ha in N0, N1 and N2, respectively in years 2001–2003 (Figures 2 and 3).

Standard errors of N_{min} are not shown in figures to improve their readibility. The errors of N_{min} in the whole layer 0–90 cm in spring moved between 2 and 10 kg N/ha, only in 1999 it reached 16 kg N/ha, but there was an evident shift of nitrogen to the next layer 90–120 cm due to leaching in one replication. In treatments N1 and N2 (2001–2003) the standard errors was over 10 kg of N only in 2002. Standard errors of N_{min} in the stage of grain filling or harvest were low in N0 due to a general low N_{min} concentrations, in N1 and N2 it got in half years over 10 kg N/ha but under 20 kg N/ha. The data confirm the reliability of the calculation of apparent uptake.

The progress of apparent N depletion from the soil profile during growth

Winter wheat quickly depleted available N from top soil (0–30 cm) and shallow subsoil (30–50 cm) during fast growth from full tillering to anthesis (Figures 2 and 3). The depletion of N from a top soil was delayed in dry spring 1998 due to a slow dissolvation of granulated fertilizer. The apparent uptake of N from subsoil was delayed in comparison with upper layers (Figures 2 and 3) as expected from the root growth to depth (Svoboda et al. 2000, Sylvester-Bradley et al. 2001). N_{min} supply in the layer 0–90 cm was almost completely exhausted by wheat crop not fertilized with nitrogen between full tillering and anthesis. Wheat extracted available nitrogen to very low concentrations about 1–3 ppm but other processes (e.g. competition for N by micro-organisms) could contribute to it, as well. At harvest the N_{min} content slightly increased in most years (Figures 2 and 3). The depletion of subsoil layers started later in treatments N1 and more pronouncedly in N2 in comparison with N0.

The apparent uptake of N from soil profile

The apparent uptake of N from soil was calculated as the difference between N_{min} contents on sampling terms. The highest uptake of N_{min} from subsoil was observed between early spring in March and the period of grain filling in July (Table 1). Similar values were observed when N_{min} on the second spring sampling term (April) was used. Using N_{min} at harvest (instead of at grain filling) slightly decreased calculated apparent uptake due to the increase of N_{min} around harvest (Figures 2 and 3).

The uptake of N_{min} from the zone 50–120 cm ranged from 21 kg to 62 kg N/ha in N0, 15 kg to

Table 1. The apparent uptake of N_{min} from specific soil layers (kg N/ha) between early spring and the period of grain filling; negative values denote no apparent uptake, i.e. the apparent increase of N_{min} content between spring and grain filling

Treatment	Layer (cm)	1996	1997	1998	1999	2000	2001	2002	2003
		apparent uptake (kg N/ha)							
N0	0–50	53.4	56.8	34.0	13.3	17.7	35.7	42.7	22.1
	50–70	14.8	28.9	18.7	26.1	14.1	49.4	20.3	7.2
	70–90	10.7	15.8	15.3	31.7	5.6	29.7	12.7	8.5
	90–120 (130)	22.3	16.2	–0.3	3.9	1.0	24.5	8.9	8.0
	50–120 (130)	47.8	60.9	33.8	61.7	20.6	103.6	41.9	23.7
	120–150	7.4	12.3	–0.8	–1.7	3.7			
N1	0–50	64.2	54.9	22.9	10.1	1.4	67.3	132.8	68.0
	50–70	13.9	28.1	17.1	25.3	9.6	79.8	50.3	27.1
	70–90	10.7	18.3	14.5	19.0	6.2	20.7	17.4	9.7
	90–120 (130)	14.9	13.1	–0.5	–3.6	–0.6	29.7	9.1	6.1
	50–20 (130)	39.5	59.5	31.1	40.7	15.2	130.2	76.8	42.9
	120–150	4.6	7.7	–0.7	–4.6	–0.8			
N2	0–50						67.3	125.9	16.0
	50–70						71.7	31.7	16.1
	70–90						1.9	10.6	8.7
	90–130						20.2	6.4	4.1
	50–130						93.8	48.7	29.0

60 kg N/ha in N1 in years 1996–2000. In years 2001–2003 the corresponding values (50–130 cm) were 24–104 kg, 43–130 kg and 29–94 kg N/ha in treatments N0, N1 and N2, respectively (Table 1). The analysis of variance confirmed a significant effect of year on the depletion from subsoil ($P < 0.01$ and $P < 0.05$ for the two experimental periods). It can be attributed to a strong relation between amount of N_{min} in early spring and apparent uptake from subsoil, $R^2 = 0.94$, 0.91 and 0.99 in N0, N1 and N2, respectively (Figure 4). The slopes of regression line suggest that 72, 68 and 57% of the early spring supply in subsoil was apparently utilized by wheat crop in treatments N0, N1 and N2, respectively. We did not find any consistent relation between weather conditions in experimental years (Figure 1) and apparent uptake of N from subsoil.

The effect of N fertilization (N0, N1) on nitrogen depletion from subsoil was insignificant in the first period ($P = 0.47$) and when only N0 and N1 treatments from all years 1996–2003 were analysed ($P = 0.09$), but significant ($P = 0.027$) in the second experimental period (2001–2003) due to the reduced utilization of N from deep layers in treatment N2. Average N_{min} depletion from deep layers 90–120 cm and 120–150 cm was 10.6 ± 9.5 kg and 5.3 ± 7.8 kg N/ha, respectively in N0, and 8.5 ± 10.9 N/ha and 1.2 ± 4.9 kg N/ha in N1 (1996–2000). The depletion from layer 120 (130)–150 cm was about zero in half of the years, and at maximum it reached 12 and 7 kg N/ha in 1997 and 1996.

In field experiments performed in comparable environments authors also reported that the available N in the zone down to about one meter could be extracted by winter wheat crop and 90 cm is a standard depth of sampling for N_{min} spring supply (Burns 1980, Barraclough et al. 1989, Cabelguenne and Debaeke 1998, Devienne-Barret et al. 2000, Olfs et al. 2005). On deep soils mineral nitrogen in the zone under 120–150 cm or even deeper is indicated as accessible for winter wheat roots (Burns 1980, Kuhlman et al. 1989, Addiscott and Darby 1991, Lucas et al. 2000). There is little data on (apparent) uptake of nitrogen from deep soil layers by wheat and it is often deduced from rooting depth and depletion of soil water.

There was a general agreement between rooting depth after anthesis (Svoboda and Haberle 2006) and the depth of N depletion from subsoil. But the results do not support a strong relation between N_{min} content and root growth in deep subsoil; for instance in 2000 with a low N_{min} and a relatively deep rooting. Recent reviews on N uptake regulation in crops show the complexity of the processes (Jeuffroy et al. 2002, Gastal and Lemaire 2002, Miller and Cramer 2004). The relation might be modified by an interaction with soil moisture that is known to affect root distribution. The evaluation was further complicated by a low N_{min} content under 90 cm in half of experimental years (1998, 2000, 2002 and 2003). In years when the N_{min} content under 90 cm was above 20 kg N/ha there was always an evident depletion from the deep subsoil.

The insignificant effect of nitrogen fertilization rate 100 kg N/ha on apparent uptake corresponds with little differences in root depth and distribution between N0 and N1 treatments in the experiment (Svoboda and Haberle 2006). As shown by Svoboda et al. (2000) wheat's demand for nitrogen was not fully saturated in N1 as proved by nitrogen dilution curves (Devienne-Barret et al. 2000, Gastal and Lemaire 2002, Jeuffroy et al. 2002). It probably stimulated the uptake from subsoil. In treatment N2 (2001–2003), with a high concentration of N_{min} in both, top and subsoil, the depletion of subsoil layers was delayed and a high amount of N_{min} was left in subsoil in contrast with N0 and N1 (Figure 3).

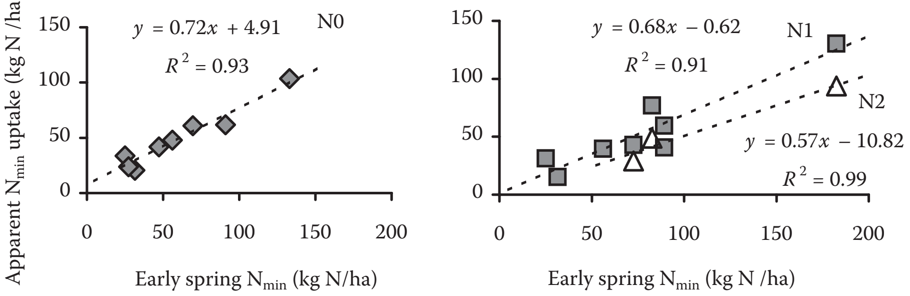

Figure 4. The relation between early spring supply of N_{min} in subsoil 50–120 (130) cm and apparent uptake from the zone in years 1996–2003

The effect of a high concentration of available nitrogen in top soil on reduction of depletion from deep subsoil layers was observed by Kuhlman et al. (1989) in winter wheat and in other crops as referred by Cabelguenne and Debaeke (1998). Our results suggest that the reduction of soil depletion from deep subsoil is the result of both, less demand for nitrogen (satisfied from top layers) and slightly reduced rooting depth and rooting density (Svoboda and Haberle 2006).

The apparent depletion of nitrogen from soil, as deduced from changes of N_{min} during growth, may be disguised by other processes, namely by leaching, mass flow with water and diffusion of nitrate ions, denitrification, nitrification and immobilization. There are indices supporting the assumption that these factors did not play an important role in subsoil under the experimental condition (Kuhlman et al. 1989). The most significant, nitrogen depletion was in accordance with progress of roots to depth and maximum rooting depth generally corresponded with observed depth of nitrogen depletion. Water depletion from subsoil in the experiment (Haberle and Svoboda 2000) had a similar course as that of nitrogen. The winter wheat quickly extracted water from upper layers, which prevented leaching of nitrate from top to deep subsoil during growth. Further, the concentration of N_{min} below rooted layers was low in experimental years, except for 1997, so the possible nitrate transport from the layers by diffusion and mass flow was not important. Mineralization of N takes place predominantly in top soil with a high content of organic matter.

The main results of our experiment may be summarized as follows: most of available mineral N in the soil profile down to at least 90 cm was depleted by winter wheat between full tillering and anthesis or the start of grain filling under no fertilization or the reasonable N dose 100 kg/ha. The depletion of subsoil nitrogen was delayed and reduced at the fertilization rate of 200 kg N/ha. Winter wheat was able to extract N from deep subsoil zones under 90 cm.

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