THE EFFECT OF WATER SUPPLY DURING GRAIN GROWTH ON THE UTILIZATION OF SOIL MINERAL NITROGEN BY WINTER WHEAT*

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The effect of water supply on the utilization of soil mineral nitrogen (N_{min}) from top- and subsoil by winter wheat was studied on loamy clay soil in Praha-Ruzyně in the years 2004–2006. The water regime was differentiated from heading by covering plots with movable shelter during rain and with drip irrigation. Wheat was grown with no N and 200 kg $N.ha^{-1}$ (N0 and N1, resp.). Water shortage during the period of grain formation reduced the utilization of N_{min} supply in 0–90 cm in respective years by 64 kg, 20 kg and 69 kg $N.ha^{-1}$ in N1 treatment, in comparison with rain-fed control, and by 91 kg, 25 kg and 98 kg $N.ha^{-1}$ in comparison with irrigated treatment. In N0 treatment the reduction reached 18 kg $N.ha^{-1}$ in 2004, and was under 5 kg $N.ha^{-1}$ in 2005 and 2006. The reduced apparent utilization of N_{min} supply under water shortage corresponded with decrease of N yield of shoots (correlation coefficient > 0.93 and 0.97 in N0 and N1, resp.), however, the slope of regression differed among experimental years and between N0 and N1 treatments.

water regime; available nitrogen; soil profile; depletion; uptake; residual N; root system; wheat

INTRODUCTION

The supply of available water is the main yield limiting factor in rain-fed intensive crop production with optimum doses of nutrients and effective plant protection. Under transition climate conditions of the Czech Republic, with fluctuating precipitation and temperature, water consumption of high-yielding wheat crop generates temporary water shortage even in years with moderate precipitation. At shooting and later stages, the periods of the highest water consumption, winter supply of easily available water in upper layers of soil profile is often depleted, and wheat crop depends on precipitation and deep subsoil supply (Haberle et al., 2002).

Low water availability decreases growth and demand for N, dry soil reduces the uptake of nitrogen by mass flow and diffusion of ions to roots. Hence, water shortage decreases the effectiveness of N uptake and utilization (Semenov et al., 2007). The authors explain that during water shortage much of inorganic soil N is in the unavailable fraction of soil water and thus inaccessible to the plant. Generally, water stress and other stressors generate series of plant responses at different levels. They include the regulation of nutrient uptake and efflux of chemicals to rhizosphere (Michalík, Bauerová, 2001)

Winter wheat utilizes own N reserves during grain formation (e.g. Masoni et al., 2007) but substantial amounts of N, up to 60%, may be depleted during grain growth in some years depending on crop demand for N and growing conditions (Chen et al., 2006; Haberle et al., 2006; Gooding et al., 2007; Masoni et al., 2007; Semenov et al., 2007). Total N_{min} supply and distribution in soil zones are highly variable in years and with a year and depend on many factors, especially on inputs of mineral and organic fertilizers in actual and previous seasons (e.g. Vaněk et al., 2003). Residual nitrogen that was not accumulated in plant biomass due to water shortage increases the risk of N losses by leaching. However, to quantify the effect is not simple, as actual N_{min} concentration in soil layers depends not only on N depletion by plants but also on other biological processes. To optimise N inputs and to minimise economical and environmental risks better understanding of soil nitrogen utilization during grain growth is needed.

The objective of the study was to determine the effect of water deficit and ample water supply during grain formation on the utilization of top and subsoil mineral nitrogen supply by winter wheat.

MATERIAL AND METHODS

Field experiment with winter wheat (*Triticum aestivum* L., cv. Nela) was performed on loamy clay Chernozemic soil in Praha-Ruzyně in the years 2004–2006. The site conditions: N 50° 05' W 14° 20', altitude 340 m, normal precipitation and temperature (1961–1990): 477 mm per year and 7.9 °C, respectively. The total precipitation from March to July was 256 mm, 322 mm and 317 mm in respective years, and 312, 380 and 338 from January to July. Using movable shelter (WS) and drip irrigation (IR) soil water content was managed to simulate the effect of dry and wet growth seasons during grain formation on the utilization of N from soil; control plots (RC) depended solely on precipitation. From dough stage the sheltering and irrigation was terminated. The shelter was used only during stronger rains to minimise changes of microclimate in the wheat canopy. The approach was successful thanks to

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accurate short-time weather forecast and on-line radar image of approaching clouds. Irrigation was applied to keep soil moisture at 80–90% of field capacity in 0–90cm layer. No more than 10 mm of water was applied in one dose. There were four to six replications in RC treatments constituted by 5.5 x 6 m plots, four replications in IR and WS treatments were performed by dividing plots 5.5 x 8 m and 5.5 x 5 m, resp., to sub-plots.

Winter wheat was cultivated under zero (N0) and high (N1 – 200 kg $N.ha^{-1}$) fertilization rates. In N1 100 kg $N.ha^{-1}$ (in nitrate calcium) was applied before winter to increase N_{min} content in subsoil and 100 kg $N.ha^{-1}$ (in ammonium nitrate) was split applied in spring. The changes of mineral N ($N_{min} = N\text{-}NO_3^- + N\text{-}NH_4^+$) in soil layers were determined several times during growth, soil was sampled to the depth of 90–130 cm by 20 cm increments, top 10 m layer was sampled separately. Two replications bulked from two (WS), four or six samples were taken. Except for sampling shortly after N fertilization in spring above 90–99% of N_{min} was found in nitrate. Standard analytical method was used (2% K_2SO_4, 1:5 soil:solution ratio for 1 hour; colorimetry – FIA). The results were expressed in kg $N.ha^{-1}$ using average bulk density of respective layers. The uptake of N was calculated from growth analysis and N concentration of plants. Root distribution was determined at heading and at about dough stage.

The results were analyzed with two-way ANOVA, the differences between treatments were tested by LSD.

RESULTS AND DISCUSSION

Soil water

In treatment WS, water content was reduced using the shelter from initial 200 mm, 245 mm and 260 mm at the end of stem elongation or booting in years 2004–2006, to 170–150 mm and 140–150 mm water in 0–90 cm zone at heading and at the start of grain formation, respectively. Soil moisture dropped to the low levels in drought periods of years 1995, 1997, 1998, 2000 and 2003 under winter wheat in the same experimental field but for shorter period than here (Haberle et al., 2002). Using drip irrigation (IR) about 80–90% of field capacity in 0–90 cm layer, by 130–170 mm more than in control treatment, was reached and maintained from anthesis to dough stage. Soil water content in RC depended on precipitation; in 2004 initially high moisture supply was gradually depleted during grain filling and ripening, while in 2005 and 2006 it increased towards maturity. A high nitrogen supply increased slightly water consumption in WC and IR in years 2005 and 2006 in comparison with N1. The root growth and uptake of water from deep subsoil layer under sampled depth 90–130 cm is none or small in winter wheat under the site conditions and could not alter the impact of the water regimes on the crop (Haberle, Svoboda, 2000; Svoboda, Haberle, 2006).

Soil mineral nitrogen

In all treatments the content of $N\text{-}NH_4^+$ was mostly under 5–10% of total $N_{min,}$ with the exception of several samples of top soil in spring (before the start of differentiated water supply). It excludes the possibility of negative effect of reduced assimilation of ammonium under water stress (Michalík, Bauerová, 2001). A low proportion of $N\text{-}NH_4^+$ is not unusual in the fertile soil when no organic fertilizers are used (Haberle et al., 2006) but under different conditions a high content of the ammonium (e.g. Galuščáková et al., 2006) may affect the impact of water supply.

In unfertilized treatment (N0) N_{min} during grain growth, with exception of two cases in 2004, was depleted to low levels under 35 kg $N.ha^{-1}$ in 0–90 cm in all years and treatments (Fig. 1). The effect of water regime was significant in 50–90 cm ($P = 0.011$) but not significant in layers 0–50 cm a 0–90 cm ($P = 0.65$ and 0.054). Similarly the effect of year and interaction of year and water treatment was significant only in 50–90 cm. The differences among treatments were small (under 5 kg $N.ha^{-1}$) and insignificant in 2005 and 2006 as the result of depletion of available N to physiologically minimum available concentration (Robinson et al., 1991). Only in 2004 with a high spring supply of N_{min}, residual N after harvest was significantly higher in WS by 17 and 18 kg $N.ha^{-1}$ than in RC and IR.

In spite of a low N_{min} in N0 treatment the concentration of N_{min} in 0–50 cm increased at maturity in comparison with the start of grain filling in all years. Probable reason was enhanced mineralization of root derived materials and soil organic matter thanks to increasing soil moisture and little or none demand for N during senescence. The second sampling term during grain formation (July 18th–20th) was performed at the stage of yellow ripening with no green leaves in treatments N0 and in fertilized stressed plants (N1/WS). We observed similar increase of N_{min} at the end of wheat growth in previous years in the same field (Haberle et al., 2006).

In fertilized treatment (N1) significantly higher N_{min} content was observed during grain filling in comparison with N0 in 2004 and 2006. Under the high N supply the effect of water regime on residual N was significant in 0–50 cm and 0–90 cm ($P \leq 0.01$), in the zone 50–90 cm the effect was weak ($P = 0.042$). The N_{min} content in 0–50 cm in WS was significantly higher (at $P \leq 0.05$) in comparison with RC a IR; in 0–90 cm N_{min} in WS was significantly higher than in IR. The effect of year on residual N_{min} in 50–90 cm and 0–90 cm was highly significant ($P \leq 0.001$). Water stress during grain formation decreased apparent utilization of N from soil layer 0–90 cm, that is increased residual N_{min} in respective years by 18 kg, 4 kg a 3 $kg.ha^{-1}$ in N0, and by 64 kg, 20 kg and 68 kg $N.ha^{-1}$ in N1 in comparison with rain fed control, and by 19 kg, 5 kg, 1 kg. ha^{-1} (N0) and by 91, 25 and 98 kg $N.ha^{-1}$ (N1) in comparison with irrigated crop (Fig. 1). The data on N_{min} dynamics during grain development showed different behaviour. In N0 and in WS treatment the N_{min}

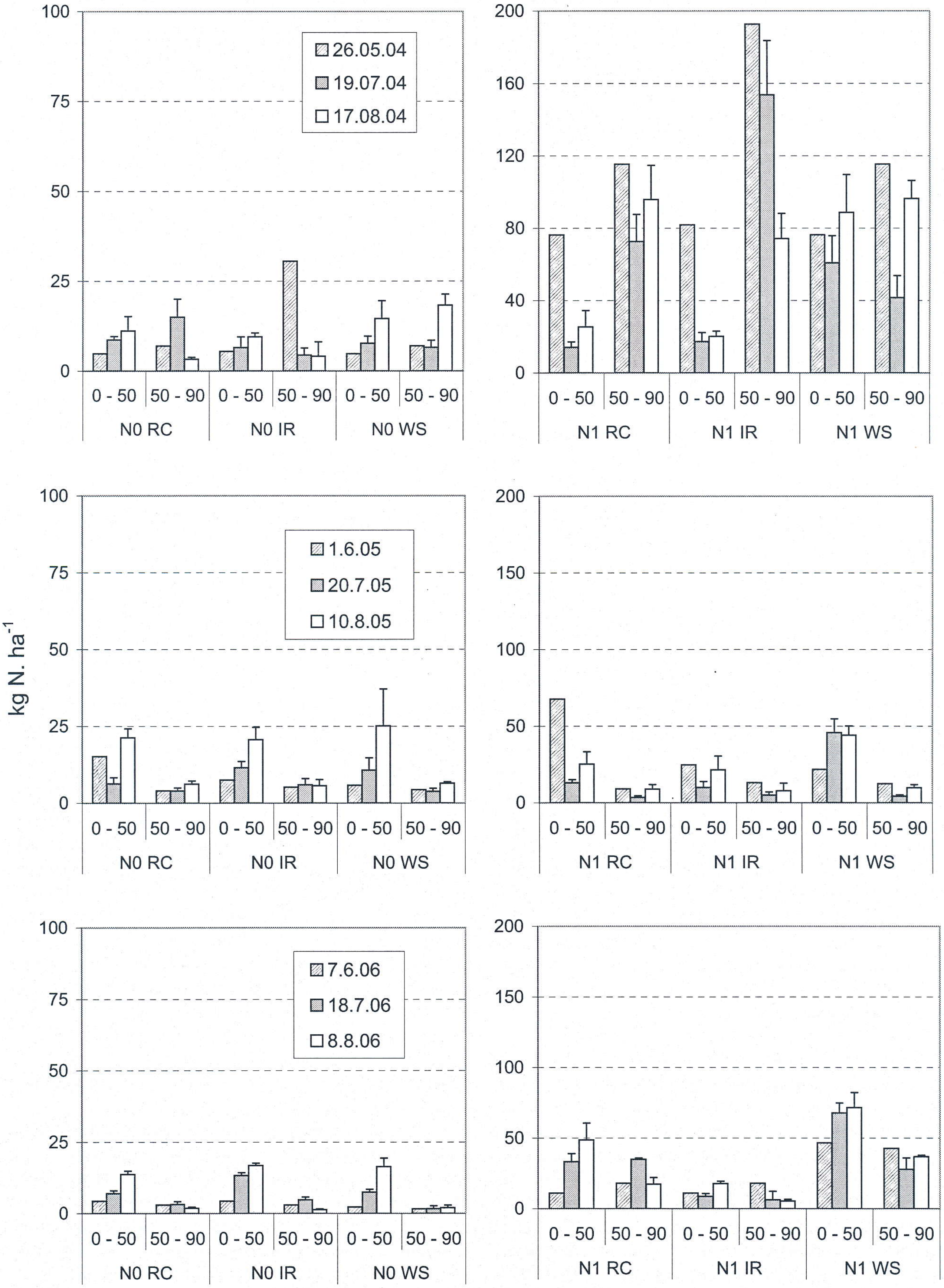

Fig. 1. The effect of water regimes on N_{min} supply at the start of water differentiation, at the end of grain filling and after harvest in experimental years under zero (N0) and 200 kg $N.ha^{-1}$ (N1) fertilization

RC – rain fed control, IR – ample water supply, WS – water shortage

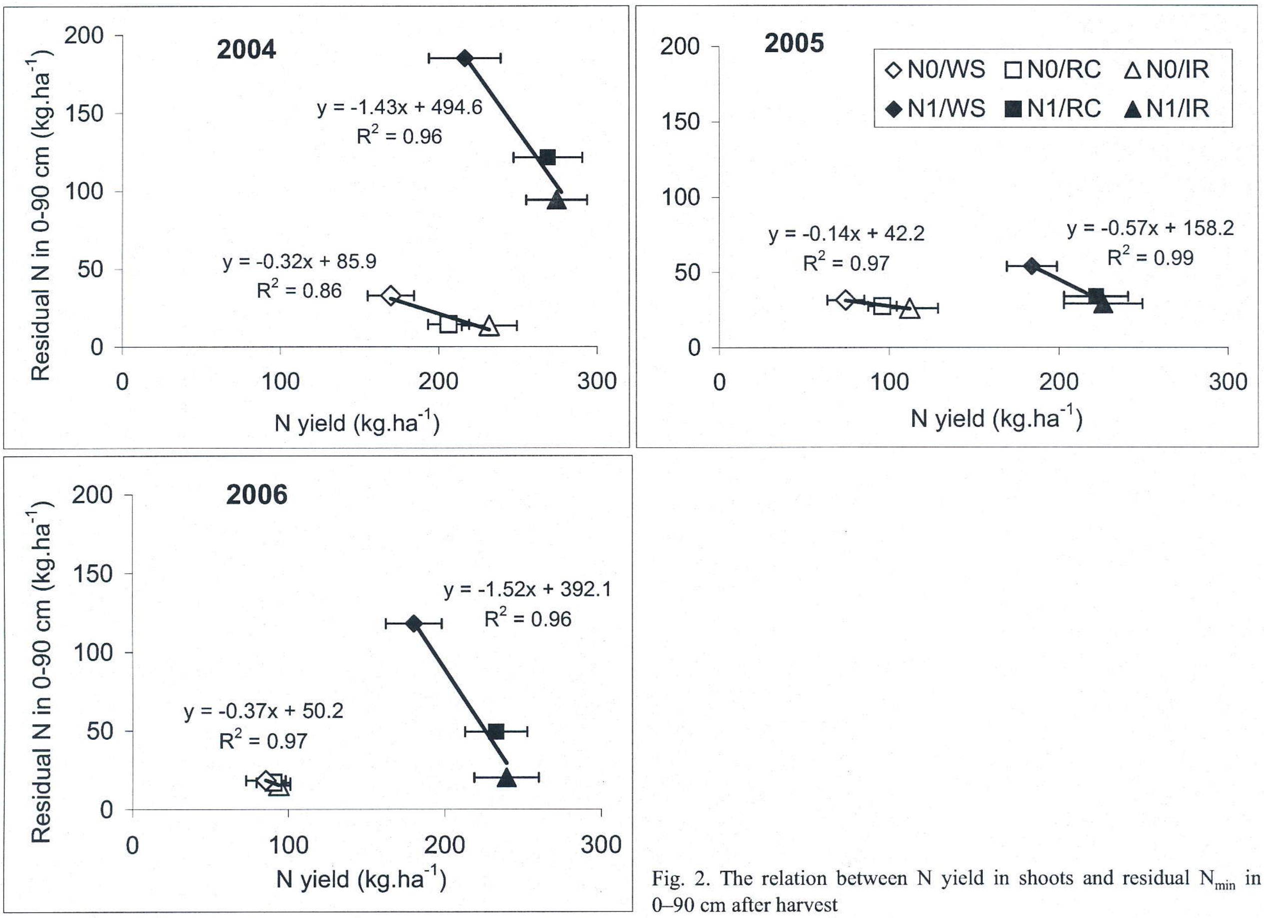

Fig. 2. The relation between N yield in shoots and residual N_{min} in 0–90 cm after harvest

content increased towards maturity, while in irrigated treatment in the subsoil N_{min} mostly decreases suggesting late N uptake due to longer growth and vitality of leaves.

Our results showed that under variable, unpredictable precipitation during grain growth the calculation of optimal N rates (Chen et al., 2006) ensuring a high yield and quality, and also leaving low residual N content after harvest is not an easy task (Semenov et al., 2007). Also, the results confirm that late application of N fertilizers (e.g. Gooding et al., 2007) to soil under the climate conditions may be ineffective in some years.

Plant growth and N uptake

Water shortage (WS) reduced growth and grain yield in comparison with ample water supply (IR) and rain-fed control (RC) (not-shown). The differences between IR and RC were less pronounced and mostly insignificant due to relatively high soil water supply and precipitation in experimental years. The residual N left in soil after maturity corresponded with N yields in above-ground parts of fertilized crop (correlation coefficient > 0.93 and 0.97 in N0 and N1, resp.), however the slope of regression was different in experimental years and N0 and N1 treatments (Fig. 2). The evaluation of treatment N0 was not reliable as the range of values was too narrow in 2005 and 2006.

In fertilized wheat crop the differences of residual N_{min} among treatments were higher by 1.40 and 1.52 times than corresponding N yields in shoots in 2004 and 2006, resp. In 2005 the relation was opposite, 0.57, i.e. the differences of N yield among treatments were higher than suggested by differences in residual N_{min}. In N0 the differences of N yields among water treatments were also higher than those of N_{min} in all years. Nitrogen content of roots could not probably account for the differences – unlike years 2004 and 2006 we found significantly lower root mass in stress treatment in 2005 in comparison with irrigated wheat crop (not shown), but the difference represented only about 5 kg N.ha^{-1} that could not substantially modify the regression coefficients. Year variable growth of roots and depletion of deep subsoil under 90 cm (Haberle et al., 2006; Svoboda, Haberle, 2006; Herrera et al., 2007) may alter the ratio between N yield and apparent soil N depletion from 0–90 cm, but in the season 2005 the N_{min} content in 90–130 cm at spring was low (not shown).

It should be mentioned that precipitation in July 2005 was extremely high, 126 mm (42 mm on 5th July), in comparison with 52 mm and 21 mm in 2004 and 2006. However, leaching of nitrate out of rooted zone was not possible due to a low N_{min} content and a high evapotranspiration. The results suggest that dynamics of soil nitrogen (mineralization, immobilization, denitrification) contributed differentially to amount of residual N_{min} in years. It is supported by the fact that in 2004 and 2006 the N_{min} content was significantly higher than in 2005 in stressed crop. Thus, both reduced uptake of N due to water shortage and soil nitrogen dynamics due to rewetting of a dry soil was responsible for a higher residual N in stressed wheat crop. The shift in development rate complicated the comparison of treatments – water stress in interaction with low N supply shortened development up to by 14 days in comparison with irrigated and fertilized wheat plants.

CONCLUSIONS

The results of three-year field experiment showed that water stress during grain development of winter wheat reduced utilization of available soil mineral nitrogen in comparison with irrigated and rain-fed treatments. There was a negative correlation between N yield of shoots and amount of residual N_{min} in 0–90 cm, however different regression coefficients in experimental years suggest that the amount of residual N was affected both, by reduction of N uptake and processes of soil N dynamic at the end of wheat growth.

The reduced utilization of mineral nitrogen under water shortage should be taken in account in management of nitrogen during wheat growth and also in following crop. Further, introduction of catch crops after main growing season with drought occurrence may reduce risk of nitrate losses during subsequent winter period.

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Vliv zásobení vodou v průběhu růstu zrna na využití půdního minerálního dusíku ozimou pšenicí.

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V polním pokusu s ozimou pšenicí byl v letech 2004–2006 sledován vliv odlišného vodního režimu na využití minerálního dusíku z vrstev půdního profilu do hloubky 90 cm. Dostupnost vody byla diferencována v období růstu zrna zakrýváním porostu při dešti a kapkovou závlahou. Pokus měl dvě úrovně zásobení dusíkem, bez hnojení (N0) a 200 kg N.ha^{-1} (N1) aplikovaných na podzim (100 kg N.ha^{-1}) a na jaře (40 kg a 60 kg N.ha^{-1}). Odběr dusíku z různých vrstev půdy byl určen bilančně, na základě postupných odběrů vzorků půdy. Současně byl zjišťován odběr N nadzemními orgány rostlin pšenice, aby bylo možné odlišit vliv odběru N porostem a vliv dynamiky N v půdě v období zrání na pozorovaný obsah N_{min} v půdním profilu.

Vliv vodního režimu na obsah reziduálního N_{min} (po dosažení zralosti) v podorniční vrstvě 50–90 cm u nehnojené varianty (obr. 1) byl na hranici průkaznosti (P = 0,011); ve vrstvě 0–50 cm a 0–90 cm byl vliv neprůkazný (P = 0,65 a 0,054). Obdobně byl vliv ročníku a interakce ročníku a vrstvy půdy průkazný pouze v podorničí. U hnojeného porostu byl vliv vodního režimu průkazný ve vrstvě 0–50 cm a 0–90 cm ($P \leq$ 0,01), v 50–90 cm byl vliv na hranici průkaznosti (P = 0,042), průkazně ($P \leq$ 0,05) se lišil obsah N_{min} v 0–50 cm u varianty WS oproti RC a IR, a obsah N_{min} v 0–90 cm u varianty WS oproti IR. Vliv ročníku byl vysoce průkazný v podorničí a v celé vrstvě 0–90 cm ($P \leq$ 0,001). Nedostatek vody v průběhu růstu zrna zvyšoval množství reziduálního N_{min} ve vrstvě 0–90 cm, v jednotlivých letech u N0 o 18 kg, 4 kg a 3 kg.ha^{-1}, a o 64 kg, 20 kg a 68 kg.ha^{-1} u N1 ve srovnání s kontrolou. Při srovnání varianty WS se

zavlažovaným porostem dosáhly odpovídající hodnoty N_{min} v jednotlivých letech 19 kg, 5 kg, 1 kg.ha^{-1} u N0, a 91 kg, 25 kg, 98 kg.ha^{-1} u N1.

Menšímu využití dusíku z půdy u stresovaného porostu odpovídalo snížení obsahu N v nadzemních částech v jednotlivých letech u N0 o 36 kg, 22 kg a 8 kg N.ha^{-1} a 54 kg, 38 kg a 53 kg N.ha^{-1} u N1 ve srovnání s kontrolou RC. Při srovnání se zavlažovanou variantou činilo snížení výnosu N 62 kg, 38 kg, 5 kg N.ha^{-1} u N0 a 58 kg, 42 kg, 59 kg N.ha^{-1} u N1. S výjimkou varianty N0 v roce 2004 existovala ve všech letech průkazná lineární negativní korelace mezi množstvím reziduálního N po zralosti a množstvím N v nadzemních částech (korelační koeficient $r > 0,93$ a $r > 0,97$ pro N0 a N1; $P \leq 0,1$), ale koeficienty regresní rovnice se lišily jak mezi ročníky, tak mezi variantami N0 a N1 ve stejném roce (obr. 2). V roce 2004 a 2006 bylo u varianty N1 zvýšení obsahu reziduálního N v půdě na suché variantě 1,4krát a 1,5krát vyšší, než by odpovídalo sníženému odběru N v nadzemní hmotě, v roce 2005 tomu bylo naopak (koeficient 0,52).

zásoba vody; přístupný dusík; půdní profil; odběr; příjem; reziduální N; kořenový systém; pšenice

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