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Effect of N, P and K fertilisers and their interactions in a long-term experiment on winter barley (*Hordeum vulgare* L.)

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SUMMARY

The aim of this work was to analyse the effect of K, P and N supplies on the yield of winter barley in a long-term mineral fertilisation experiment with clearly distinct soil nutrient supply levels in order to develop fertilisation guidelines for winter barley growers. The experiment was set up in 1989 on a chernozem meadow soil calcareous in the deeper layers, applying all possible combinations of 4 levels each of N, P and K fertiliser, giving a total of 64 treatments.

The results of analyses performed in 2011 and 2012 can be summarised as follows:

1. *In 2011, when rainfall supplies were deficient in the shooting phase, improved K supplies (324 mg kg^{-1} AL-K_2O) increased the grain yield, but in 2012, when rainfall supplies were more evenly distributed, K supply levels in the range 210–335 mg kg^{-1} AL-K_2O had no significant influence on the yield of winter barley.*
2. *An analysis of the P treatments revealed that, compared to the 119–133 mg kg^{-1} AL-P_2O_5 level (P_0), better P supplies (186–251 mg kg^{-1}) led to a significant increase in the grain yield.*
3. *In both years rising N rates significantly increased the yield up to an annual N rate of 160 kg ha^{-1}.*
4. *A K×N interaction could only be detected in the nutrient supplies of winter barley in 2011. The yield-increasing effect of N fertiliser was more pronounced at better K supply levels, while K fertiliser led to higher yields in the case of better N supplies.*

Keywords: *nitrogen, phosphorus, potassium, winter barley, yield quantity*

ÖSSZEFOGLALÁS

Az őszi árpa trágyázási szaktanácsadásának fejlesztéséhez kísérleti munkák célja az volt, hogy jól elkülönülő talaj tápelem-ellátottsági szinteken, műtrágyázási tartamkísérletben vizsgáljuk K-, P- és N-ellátottság hatását az őszi árpa terméshozamára. A műtrágyázási tartamkísérlet 1989-ben lett beállítva, mélyben karbonátos csernozjom réti talajon, 4–4 N-, P és K-ellátottsági szinteken, teljes kezelés kombinációban, 64 kezeléssel.

A 2011 és 2012-ben elvégzett kísérlet eredményei az alábbiakban foglalható össze:

1. *A szárbaindulás fázisában hiányos vízellátottságú tenyészidőszakban (2011) a jobb K-ellátottság (324 mg/kg AL-K_2O) növelte a szemtermést, azonban a kiegyenlítettebb csapadékeloszlású tenyészévben (2012) a talaj 210–335 mg/kg AL-K_2O ellátottságának intervallumában a K-ellátottság szintje az őszi árpa terméshozamát szignifikánsan nem befolyásolta.*
2. *A P-kezeléseket vizsgálva megállapítható, hogy a talaj 118–133 mg/kg AL-P_2O_5-ellátottságához (P_0) képest a jobb P-ellátottság (186–251 mg/kg) a szemtermést megbízhatóan növelte.*
3. *Mindkét vizsgálati évben a növekvő N-dózisok megbízhatóan emelték a termést 160 kg N/ha/év ellátásig.*
4. *Az őszi árpa tápanyag-ellátottságában csak 2011-ben tudunk K×N kölcsönhatást kimutatni. A N-trágyázás termésnövelő hatása kifejezettebb volt jobb K-ellátottsági szinteken, a K-trágyázás pedig jobb N-ellátás esetében eredményezett magasabb hozamot.*

Kulcsszavak: *nitrogén, foszfor, kálium, őszi árpa, termésmennyiség*

INTRODUCTION

Plants contain almost all the elements occurring in nature, but not all of these are required for their growth and physiological functions (Johnston, 2005). Among the 16 nutrients essential for plants, nitrogen plays the most important role in increasing yields and in improving the value of plant products for human and animal nutrition (Aulakh and Malhi, 2004). According to Zeļonka et al. (2005) the second most limiting element for plants is phosphorus. A similar opinion was reported by Kádár (2014), who also found phosphorus to be the second most important macroelement after nitrogen in nutrient management in Hungary. Zörb et al. (2014), on the other hand, emphasised the importance of potassium. Balasubramanian et al. (2004) drew attention to the interactions between nitrogen and other nutrients, including the synergistic interactions of nitrogen with P, K, S and various microelements, which may lead to substantial increases in yield. On soils with deficient supplies of phosphorus and potassium, plants give a poor response to nitrogen, which may even be negative. Many authors have reported that on soils with severe P deficiency the application of nitrogen alone had a negligible effect on the yield, while the joint application of nitrogen and phosphorus resulted in a significant rise in yields (Aulakh and Malhi, 2004). When winter barley was used as test plant on Ramann's brown forest soil, Berhanu et al. (2013) found that increasing N supplies improved the yield of barley when the humus content (1.6–1.7%) and P supplies (60–80 mg kg^{-1}) were low and the K supplies moderate (140–160 mg kg^{-1}).

On calcareous chernozem soil with nutrient supplies of 128 mg kg^{-1} AL-P_2O_5, 243 mg kg^{-1} AL-K_2O and 21 mg kg^{-1} N (NH_4^+- and NO_3^--N), Kádár and Csathó (2015) reported a significant increase in winter barley yields at N rates of 100 kg ha^{-1} year^{-1}, while higher rates (200–300 kg ha^{-1} year^{-1}) caused yield depression. According to Grezebisz et al. (2012) the nitrogen and water supplies are the basic factors determining the maximum yields that can be achieved in the rainfall-dependent agriculture characteristic of Eastern Central Europe. Both Kádár (1992) and Balasubramanian et al. (2004) mention the temperature and the rainfall quantity as factors influencing the growth and nutrient use efficiency of crops. One reason why nitrogen fertiliser attracts so much attention is that plants only take up 30–65% of the nitrogen fertiliser applied (Roberts, 2008; Sebilo et al., 2013), which means that the superfluous quantity of nitrogen (NO_3^--N) leaches from the root zone and accumulates in the deeper layers, or may migrate as a function of rainfall conditions. The quantity of N accumulated depends greatly on the rate of N fertiliser applied (Izsáki, 2010). Shejbalová et al. (2014) suggested that efficient nitrogen fertilisation is essential for both profitable crop production and environment protection. The practice of sustainable agriculture promotes a system of soil fertility management in which rational mineral fertiliser use aims not only to achieve high quality and a profitable yield level, but also to cause the least possible pollution of the environment. Increasingly frequently, climate change is likely to result in dry springs followed by wet summers in Northern Europe and in longer dry periods in the south (Zörb et al., 2014). Barley production may gain greater importance in the future, so more information will be required on the mineral fertilisation of barley in terms of soil types, the nutrient-supplying ability of the soil and climatic conditions. The most suitable method for investigating these factors is the analysis of the results achieved in long-term field experiments. According to Blake et al. (2000) long-term field experiments are rarely performed, but are invaluable for the study of nutrient cycles in agriculture. Kádár (1992) also expressed the opinion that a large proportion of the agrochemical and plant nutrition knowledge available on the soil–plant system is obtained in field experiments.

The aim of this paper was to report the effect of N, P and K supply levels on the yield of winter barley on chernozem meadow soil and to expand the database of results from long-term experiments available for improving fertilisation recommendations for winter barley.

MATERIAL AND METHODS

The long-term mineral fertilisation experiment was set up in 1989 in the experimental nursery of the Faculty of Economic, Agricultural and Health Sciences of Szent István University in Szarvas.

The chernozem meadow soil, which was calcareous in the deeper layers, had an 85–100 cm humus-containing layer. Properties of the ploughed layer: pH_{KCl} 5.0–5.2, humus 2.8–3.2%, no $CaCO_3$, plasticity index according to Arany (K_A) 50, clay content 32%. The groundwater was located at a mean depth of 300–350 cm. In autumn 1989, before the experiment was set up, mean values of AL-P_2O_5 156 mg kg^{-1} and AL-K_2O 322 mg kg^{-1} were recorded in the plots, which was equivalent to high quality on the basis of the standard methods and limit values used in Hungary (MÉM NAK, 1979). The long-term mineral fertilisation experiment involved all possible combinations of four levels each of three factors (N, P and K fertilisation), giving a total of 4^3=64 treatments, arranged in a split-split plot design with three replications. Within the three true replications, there were 48 internal replications for the N fertiliser treatments and 16 for the P fertiliser treatments. The experimental factors and treatments were as follows:
Factor "A" was K fertilisation, applied at the following rates:
K_0 = no K fertiliser,
K_1 = 300 kg ha^{-1} year^{-1} K_2O between 1989 and 1992, 100 kg ha^{-1} year^{-1} from 1993 onwards,
K_2 = 600 kg ha^{-1} K_2O in 1989, 1000 kg ha^{-1} in 1993 and 600 kg ha^{-1} in 2001,
K_3 = 1200 kg ha^{-1} K_2O in 1989, 1500 kg ha^{-1} in 1993 and 1200 kg ha^{-1} in 2001.
Factor "B" was P fertilisation, applied at the following rates:
P_0 = no P fertiliser,
P_1 = 100 kg ha^{-1} year^{-1} P_2O_5,
P_2 = 500 kg ha^{-1} P_2O_5 in 1989, 1993 and 2001,
P_3 = 1000 kg ha^{-1} P_2O_5 in 1989, 1993 and 2001.
Factor "C" was N fertilisation, applied at the following rates:
N_0 = no N fertiliser,
N_1 = 80 kg ha^{-1} year^{-1} N,
N_2 = 160 kg ha^{-1} year^{-1} N,
N_3 = 240 kg ha^{-1} year^{-1} N.

The aim of the periodic application of replenishment rates of P and K fertiliser was to achieve clearly distinct supply levels in the soil for the investigation of plant nutrition situations and to determine threshold values for the nutrient-supplying capacity of the soil. Nitrogen was applied in the form of ammonium nitrate (34%), phosphorus as superphosphate (18%) and potassium as potassium chloride (40 or 60%). Four crops were sown each year in a full crop rotation on 4×192 plots, where the main plots measured 320 m², the subplots 80 m² and the sub-subplots 4×5=20 m².

The pre-crop of winter barley was canary grass (*Phalaris canariensis* L.) and the winter barley was the two-row cultivar GK Stramm.

The results obtained in the 22nd (2010/2011) and 23rd (2011/2012) years of the long-term experiment are discussed in this paper. Winter barley was sown on 14 October in 2010 and on 3 November in 2011 with a row distance of 12 cm and a seed norm of 5 million seeds ha^{-1}. No chemical weed control was required in the experiment, and other plant protection treatments were applied as necessary. The barley was harvested at full maturity using a plot combine at the end of June.

In the 2010/2011 growing season there was a total rainfall of 435 mm, which exceeded the long-term mean (396 mm), but the rainfall distribution deviated from the mean (*Figure 1*). The mean annual temperature during the winter barley growing season was 8.2 °C, which was higher than the long-term mean (7.5 °C) (*Figure 2*). In autumn 2010 the rainfall quantity (31 mm) available for germination was somewhat lower than the long-term mean (43 mm) and this was also true of the temperature (8.4 °C), but this had no negative effect on the uniform emergence of the stand. During the shooting phase, however, in which water supplies are critical, the rainfall quantity (8 mm) was well below the long-term mean (44 mm). During the second critical period for rainfall, at flowering, both the rainfall quantity (72 mm) and the temperature (17.1 °C) were higher than the long-term values (59 mm, 16.5 °C). In autumn 2011 emergence was somewhat protracted due to the rainfall deficiency, but during the critical shooting phase the rainfall quantity was equivalent to the long-term mean (46 mm). In later phenophases, such as heading, flowering and ripening, the rainfall quantity was lower than the 75-year mean. The weather in 2012 was drier than in 2011 during the growing period, but the temperature was similar to the long-term mean.

Figure 1: **Rainfall quantity during the period tested (Szarvas, 1901–1975, 2010–2012)**

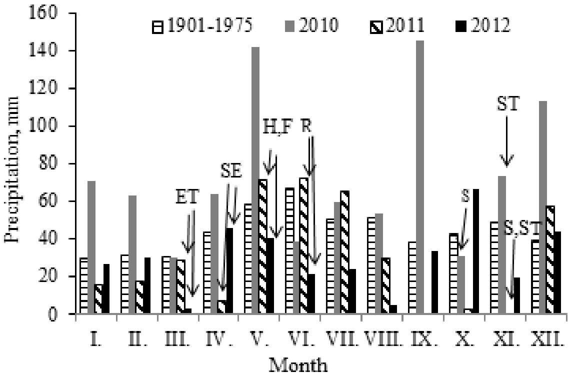
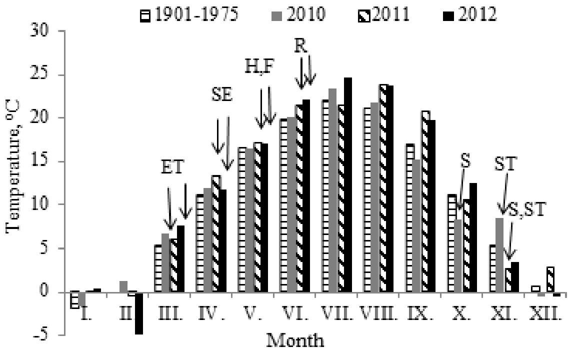


Figure 2: **Temperature during the period tested (Szarvas, 1901–1975, 2010–2012)**



The K_2O and P_2O_5 contents of the ploughed layer (0–30 cm) were analysed prior to the sowing of winter barley using the AL (ammonium lactate acetate) method in order to determine the P- and K-supplying ability of the soil. The results of the analysis in the individual years are presented in *Table 1*.

The analysis of individual main effects uses the concept of relative yield, i.e. the percentage of the maximum yield that can be achieved without fertilisation. Statistical analysis was performed using three-factor analysis of variance (UNIANOVA) and Student's t-test for a split-split plot design, with the help of the SPSS statistical program, version 15.

Table 1.

P- and K-supplying ability of the soil in each fertilisation treatment (Szarvas, 2010–2011)

Treatment	Years of experiment	
	2010	2011
	AL- K_2O in ploughed layer (mg kg^{-1})	
K_0	218	210
K_1	324	320
K_2	294	286
K_3	346	335
	AL-P_2O_5 in ploughed layer (mg kg^{-1})	
P_0	133	118
P_1	206	224
P_2	194	186
P_3	251	233

RESULTS AND DISCUSSION

Main effect of K supplies

When the long-term experiment was set up in 1989 the AL-K_2O content of the ploughed layer was 322 mg kg^{-1}, which dropped to 218 mg kg^{-1} by autumn 2010 and to 210 mg kg^{-1} by autumn 2011 in plots given no K fertiliser (*Table 1*). Without K fertilisation the grain yield of winter barley was 3.07 t ha^{-1} in 2011, representing a relative yield of 85%, while in 2012 the grain yield was 4.62 t ha^{-1} and the relative yield 96%. As the movement of potassium in the soil is mostly due to mass flow and diffusion (Zeļonka et al., 2005), soil moisture is decisive for nutrient uptake and yield formation. In 2011 the weather was dry (8 mm) and warm (13.3 °C) in April, during the shooting phase when water supplies are critical, so the dry soil inhibited K uptake. Zörb et al. (2014) emphasised the fact that K plays an outstanding role in the tolerance of drought stress, while Černý et al. (2010) suggested that balanced nutrition could compensate for weather anomalies in barley. The AL-K_2O supply level in the soil was almost the same in both years in the K_1 treatment. In 2011, compared to the K_0 treatment, the grain yield of winter barley was significantly enhanced by soil AL-K_2O supplies of 346 mg kg^{-1} and was equivalent to the maximum yield (3.62 t ha^{-1}). At the K_2 and K_3 levels the yield did not differ significantly from that obtained in the K_0 treatment, and an AL-K_2O supply level of 346 mg kg^{-1} (K_3) resulted in a substantial yield decline compared with the maximum yield. In the 2012 season, when rainfall distribution was more favourable, differences in the K supplies did not lead to significant changes in the yield over a soil AL-K_2O level range of 210–335 mg kg^{-1} (*Table 2*). According to Kádár (2012) cereals exhibit little response to K fertilisation on heavy soils.

Main effect of P supplies

When the long-term experiment was set up in 1989 the AL-P_2O_5 content of the ploughed layer was 156 mg kg^{-1}, which dropped to 133 and 118 mg kg^{-1} by the 22nd and 23rd years of the long-term experiment in plots given no P fertiliser (*Table 1*).

Table 2.

Effect of K supplies on the yield of winter barley, averaged over the N and P treatments (t ha^{-1}) (Szarvas, 2011–2012)

Years	Yield (t ha^{-1})				LSD$_{5\%}$	Average	Relative yield (%)
	K_0	K_1	K_2	K_3			
2011	3.07	3.62	3.26	2.95	0.24	3.23	85
2012	4.62	4.66	4.72	4.79	NS	4.70	96
Average	3.85	4.14	3.99	3.87	-	3.96	91

While a barley yield of 2.96 t ha^{-1} was achieved without P fertiliser in 2011, representing a relative yield of 89%, the grain yield was 4.50 t ha^{-1} in 2012, which was 92% of the maximum yield (*Table 3*). The fact that there was very little decline in the yield without P fertiliser is indicative of the good P-supplying capacity of the soil. It was emphasised by Csathó and Kádár (2013) that acidic soils with high clay content bind more P than lighter soils with a neutral pH. It was shown by Csathó and Kádár (2013) that the P supply gradually decreases as the result of plant P uptake and P adsorption, making its replacement essential (Draskovits, 2013). In 2011 the application of the P_1 supply level increased the AL-P_2O_5 supplies of the soil to 206 mg kg^{-1}, resulting in a significantly higher yield and maximum yield (3.33 t ha^{-1}) than in the P_0 treatment. In the P_2 treatment the AL-P_2O_5 content of the soil was 194 mg kg^{-1}, which had no significant effect on the yield. The P_3 treatment resulted in an AL-P_2O_5 level of 251 mg kg^{-1}, which again had no influence on the yield of winter barley (3.32 t ha^{-1}) compared with the P_1 treatment. The rainfall quantity has little effect on the phosphorus-supplying ability of the soil, as P is less mobile than the other nutrients (Kádár, 2014). In 2012 the application of the P_1 treatment led to an AL-P_2O_5 content of 224 mg kg^{-1}, which gave a significantly higher yield (4.78 t ha^{-1}) than the P_0 treatment. According to Draskovits (2013) satisfactory phosphorus supplies improve the tillering vigour and grain yield of cereals. As the plants chiefly take up phosphorus by means of diffusion, which is a rather slow process (Zeļonka et al., 2005), satisfactory soil moisture has a decisive influence on the phosphorus uptake, root formation and yield.

Table 3.

Effect of P supplies on the yield of winter barley, averaged over the N and K treatments (t ha^{-1}) (Szarvas, 2011–2012)

Years	Yield (t ha^{-1})				LSD$_{5\%}$	Average	Relative yield (%)
	P_0	P_1	P_2	P_3			
2011	2.96	3.33	3.30	3.32	0.23	3.23	89
2012	4.50	4.78	4.67	4.87	0.24	4.71	92
Average	3.73	4.06	3.99	4.10	-	3.97	91

Main effect of N supplies

The effect of N supplies on the yield of winter barley, averaged over the P and K treatments, was evaluated on the basis of the data given in *Table 4*. In the 22nd year of the long-term experiment the yield of winter barley was 2.22 t ha^{-1} without N fertiliser, while in the 23rd year this figure was 3.39 t ha^{-1}. Without the application of N fertiliser the natural N-supplying ability of the soil has a decisive influence on plant development and thus on the yield. Nitrogen is one of the most important mineral nutrients for plants, which take it up primarily in inorganic form, mostly as NO_3^--N (Krček et al., 2008; Manahan, 2010). The NO_3^- anion does not become bound on colloids, so the extent of leaching depends mainly on the quantity of N applied, the soil type, the plant species and the rainfall quantity.

In November and December 2010 there was more rain than the long-term mean, but this was followed by a drier period, while in the 2011/2012 season the rainfall distribution satisfied the water demands of the critical phenophases. As nitrogen is of vital importance for vegetative development, its availability during tillering, when spike differentiation takes place, is decisive for the yield. According to Alazmani (2014) good N supplies are necessary for the early tillering of barley and for the achievement of high yields. In 2011 increasing rates of N significantly enhanced the yield up to a rate of 160 kg ha^{-1}. Excessive N fertilisation (240 kg ha^{-1}), however, caused a significant yield decline compared with the maximum yield in 2011, when the relative yield was only 59%.

The yield harvested without N fertiliser in 2012 was 3.39 kg ha^{-1}, which rose significantly up to a rate of 160 kg N ha^{-1}. As in the previous year, excessive N fertiliser (240 kg ha^{-1}) led to significant yield depression compared with the maximum yield. In both years the maximum yield was obtained in the N_2 treatment (160 kg ha^{-1}), and was higher in 2012 than in 2011. It is generally agreed that drought stress has a negative effect on photosynthetic activity (Krček et al., 2008), thereby reducing the yield. In 2012 the weather was rather dry and warm at the end of tillering and during grain filling, but did not lead to lower yields. By contrast, Samarah (2005) found that drought stress at the beginning of grain filling and during ripening was unfavourable for grain development. Hall et al. (2014) reported that the day length and temperature were the most important environmental factors during flowering.

Table 4.

Effect of N supplies on the yield of winter barley, averaged over the P and K treatments (t ha^{-1}) (Szarvas, 2011–2012)

Years	Yield (t ha^{-1})				$LSD_{5\%}$	Average	Relative yield (%)
	N_0	N_1	N_2	N_3			
2011	2.22	3.33	3.77	3.58	0.15	3.23	59
2012	3.39	5.03	5.33	5.05	0.27	4.70	64
Average	2.81	4.18	4.55	4.32			62

Interactions

A K×N interaction could only be detected in the nutrient supplies of winter barley in 2011 (*Table 5*). The yield-enhancing effect of N fertilisation was more pronounced at better K supply levels, while K fertiliser resulted in higher yields in the case of better N supplies. In all the treatment combinations the maximum yield was achieved when the N rate was 160 kg ha^{-1}. Excessive N fertilisation (240 kg ha^{-1}) induced yield depression. In 2011 the yield of winter barley was lower in the K_2 and K_3 treatments, which were given replenishment rates of K fertiliser in 2001, compared to annual K fertilisation (K_1). Manahan (2010) emphasised that if N fertiliser is applied to the soil to improve productivity, the K uptake increases. Aulakh and Malhi (2004) reported synergism between N and P, but this was not confirmed in the present experiment. Kádár (2000) considered an annual rate of 100 kg N ha^{-1} to be sufficient on calcareous chernozem soil with loam texture, while the original AL-K_2O content of the soil (120–140 mg kg^{-1}) satisfied the K requirements of winter barley. In the case of the P supplies, an AL-P_2O_5 content of 150–200 mg kg^{-1} proved to be sufficient.

Table 5.

K×N interaction on the yield of winter barley (t ha^{-1}) (Szarvas, 2011)

N-supply	K-supply				$LSD_{5\%}$	Average
	K_0	K_1	K_2	K_3		
N_0	2.28	2.49	2.16	1.95	0.26	2.22
N_1	3.14	3.85	3.53	2.83		3.33
N_2	3.44	4.23	3.77	3.65		3.77
N_3	3.42	3.94	3.59	3.39		3.58
$LSD_{5\%}$	0.29					
Average	3.07	3.62	3.26	2.95		-

CONCLUSIONS

When evaluating the main effect of K fertiliser it was found that in a year with inadequate water supplies during the shooting phenophase (2011) better K supplies (324 mg kg^{-1} AL-K_2O) increased the grain yield. In a year with more balanced rainfall distribution (2012) the K supply level had no significant influence on the yield of winter barley over an AL-K_2O range of 210–335 mg kg^{-1}. The maximum grain yield was obtained in this experiment at an AL-K_2O content of 324–335 mg kg^{-1}. As regards the P treatments, in 2011 better P supplies (206–251 mg kg^{-1} AL-P_2O_5) had no significant effect on the yield compared with the P_0 treatment (133 mg kg^{-1} AL-P_2O_5), while in 2012 a soil AL-P_2O_5 content of 224 mg kg^{-1} resulted in a significantly better yield. The maximum yield was obtained with 206–233 mg kg^{-1} AL-P_2O_5. The analysis of the main effect of N fertiliser showed that in both years the maximum yield was ensured by applying 160 kg ha^{-1} N (N_2), while excessive N fertilisation (240 kg N ha^{-1} year^{-1}) caused yield depression compared to the maximum yield. Only in 2011 could a K×N interaction be detected in the nutrient supplies of winter barley. The yield-enhancing effect of N fertilisation was manifested at better K supplies, while K fertilisation resulted in higher grain yields in the case of better N supplies.

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