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The influence of mineral fertilisers, farmyard manure, liming and sowing rate on winter wheat grain yields

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ABSTRACT

Madaras M., Mayerová M., Kumhálová J., Lipavský J. (2018): The influence of mineral fertilisers, farmyard manure, liming and sowing rate on winter wheat grain yields. Plant Soil Environ., 64: 38–46.

The influence of mineral fertilisers, liming, farmyard manure and sowing rate on the winter wheat grain yields was studied in a long-term field experiment at 4 sites under different soil and climatic conditions in the Czech Republic. A total of 135 partial fraction-factorial experiments were performed between 1980 and 2013 and evaluated using a statistical model with linear and quadratic terms for each factor. Yield trends demonstrated remarkable influence of fertilisation at two sites of lower starting productivity. Here, grain yields increased by 50% and 25% since the trial commencement, while the rate of yield increase was low at more productive sites. Yields were the most frequently influenced by nitrogen (N) fertilisation, uniformly at all sites. N response curves were strongly curvilinear, but these differed between sites and were affected by preceding crops. The relative frequency of statistically significant influences decreased in the following order: N (significant at $\alpha < 0.05$ in 89% of all partial trials) > sowing rate (29%) > phosphorus (22%) > farmyard manure (15%) > potassium (12%) > liming (8%). This order and the frequencies of these influences are discussed with regard to relevant site and soil conditions.

Keywords: *Triticum aestivum*; long-term field trials; seeding density; soil productivity; nutrients

Gradual changes in soil productivity can only be measured by long-term monitoring or field experiments. Long-term agro-ecosystem experiments help evaluation of the cropping system effects on soil quality, sustainability of these systems and provide early warning indication of threats to future crop production (Richter et al. 2007). Fertilisation is one of the most important intensification factors significantly effecting crop yield and quality (Černý et al. 2010). Edmeades (2003) contended that nutrient inputs can increase crop production by 300–400% and are essential in maintaining long-term sustainability. A long-term Broadbalk wheat experiment confirmed a strong yield response to nitrogen fertilisation with the curvilinear character of nitrogen (N) response curve (Brentrup et al. 2004). Jaakkola and Yli-Halla (2008) reported a significant decrease in cereal yields after 30 years with N fertilisation not balanced with phosphorus (P) and potassium (K) fertilisers. Moreover, yield and its response to fertilisers depend on preceding crops, and the results from a Hungarian long-term experiment (Berzsenyi et al. 2000) showed that yields of wheat cropped in monoculture were always lower than in crop rotation. Simultaneously, significantly higher yields were obtained at high NPK fertilisation rates, especially in rotations with a high proportion of cereals. The combined application of organic manure and inorganic fertiliser was an

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efficient way of fertilising (Berzsenyi et al. 2000). Fertiliser effectiveness may differ due to locally – specific conditions of field trials (Černý et al. 2010). Therefore, it is difficult to draw general conclusions and recommendations concerning effective fertilisation. Long-term yield records from the experiments performed at diverse sites can improve the fertilisation recommendations. The objective of this study is to use robust long-term field data to evaluate the effect of basic agronomic measures on the winter wheat grain yields in different soil and climatic conditions.

MATERIAL AND METHODS

Field trials. Fraction-factorial field fertilisation experiments (FFFE) were established in 1979 at 10 sites. Winter wheat grain yield data used for this study were recorded from trials active until 2013 at the Czech Republic Hněvčeves, Kostelec nad Orlicí, Humpolec and Pernolec sites (Table 1).

FFFE's were designed to specify the influences of six independent agronomy measures – nitrogen, phosphorus and potassium mineral fertilisation, farmyard manure (FYM), liming and sowing rate on the growth of common field crops. FFFEs are based on the fraction-factorial experimental design of a central scheme of the second order in incomplete blocks (Cochran and Cox 1957). Medium levels of all factors reflected standard (optimal) crop-specific cropping practice and excess levels were expected to limit crop growth by excess nutrient or very high stand density. Fertilising and liming had five levels: zero (0%) – lower (58%) – medium (100%) – higher (142%) and excess (200%). Sowing rate was utilised as a factor until 1990 in a modified range from basal 40–75% of the medium level depending on crop type to the 140–200% excess range. Medium levels of fertiliser and sowing rates are shown in Table 2. Ammonium nitrate and sulphate, superphosphate and potassium chloride were used as N, P and K mineral fertilisers. Wheat was usually sown between September 24th and October 10th and the sowing rate ranged from 200 to 700 germinated seeds per m^2. Lime was applied each 4 to 8 years in the medium rate calculated to reach the optimal soil reaction, which was 7.0 for Hněvčeves and Kostelec, 6.5 for Pernolec and 6.0 for Humpolec.

At each site, the trial comprised 4 fields with 56 plots (5 × 12 m) per field and 47 treatments were employed. Details of the FFFE design are described in Madaras and Lipavský (2009). Crops were grown in an 8-year crop rotation (Table 2). The crop rotation was phased in four fields at individual sites so that the same crop appeared in the same crop sequence on each site in the two-year period. Conventional tillage up to 25 cm depth was used for soil cultivation and 12 winter wheat cultivars were grown during the evaluated period; each for approximately 5–7 years. After two complete rotations, alternative crops such as oilseed rape and pea were also included and crop rotation was changed in some fields. The sowing

Table 1. Characteristics of the experimental sites and soil properties at the experiment commencement

Site	Location		Altitude (m a.s.l.)	Temperature (°C)	Precipitation (mm)	Soil	C_{ox} (%)	pH	Available nutrient (mg/kg)	
	latitude	longitude							P_{Egner}	$K_{Schachschabel}$
Hněvčeves	50.31	15.72	265	8.2	573	Orthic Luvisol on loess, clay-loam	1.0	6.4	73	120
Kostelec	50.12	16.19	290	7.6	681	Orthic Luvisol on loess, sandy-loam	1.1	6.3	62	119
Humpolec	49.55	15.35	525	6.5	667	Stagno-gleyic Cambisol on paragneiss, sandy-loam	1.7	6.1	27	212
Pernolec	49.77	12.68	530	7.1	559	Stagno-gleyic Cambisol on orthogneiss, sandy-loam	1.1	6.0	71	185

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Table 2. Crop rotation in experiments and application rates (medium factor levels) for crop-plants

Year	Crop – plant	N*	P	K	Farmyard manure (10^3 kg/ha)	Sowing rate (seeds/ha)
		(kg/ha)				
1	Clover + oat/alfalfa + oat#	40	60	100	–	16 kg + 2.0 × 10^6
2	Clover/alfalfa#	–	–	–	–	–
3	Winter wheat	100	40	70	–	4.5 × 10^6
4	Silage maize	175	50	150	40	8.0 × 10^4
5	Winter wheat	125	40	70	–	4.5 × 10^6
6	Spring barley	90	40	50	–	4.5 × 10^6
7	Potato/sugar beet#	150	50	150	40	8.5 × 10^4
8	Spring barley	60	40	50	–	4.5 × 10^6

*the total amount of nitrogen (N). N application was divided into 3 doses for winter wheat (50% before sowing, 17% in early spring, 33% in spring). – factor not used. #Potato and clover were planted in Humpolec and Pernolec

rate factor was not used after 1995 and a uniform sowing rate of 4.5 × 10^6 germinated seeds/ha was applied to follow the previous medium level. The factorial fertilisation scheme for the remaining five factors continued until 2013. Therefore, the yield records were not excluded from our evaluation.

Data processing and statistics. The winter wheat grain yields at standard 86% dry matter moisture recorded from 1980 to 2013 were used, and the database for analysis comprised 135 partial trials, which provided 7560 individual plot records. Yield time trends were evaluated by simple linear regression. Each field trial was evaluated separately to determine the experimental factor effects. The method proposed by Cochran and Cox (1957) was employed; briefly, the statistical evaluation of the data was based on the model, which enables estimation of linear and quadratic effects and the interactions between factor pairs. The statistical significance of each factor or each factor pair interaction was tested at $\alpha < 0.05$ and only statistically significant equation members were used in the final model equation. When a particular model did not prove the factor's statistical significance, either alone or in an interaction, the factor's influence on yields in that model was regarded as zero. Models lacking significance were discarded and yield prediction curves were generated from each of the remaining models. The obtained values were then averaged according to the preceding crop and the experimental site, and final results were graphed for visual assessment. Results on factor pair interactions are not shown here; they will be reported and discussed in the separate paper.

RESULTS AND DISCUSSION

Yield trends. A remarkable increase in winter wheat grain yields was recorded in Kostelec and Humpolec, i.e. at lower productivity sites (Figure 1). Mean yields increased by 50% in Kostelec and by 25% in Humpolec between the first and the last crop rotation. Fertilisation clearly gradually enhanced soil fertility by increasing soil quality, and this was supported by the research results from Christensen (1997), Johnston (1997) and Edmeades (2003). During the experimental period, the fertiliser effect was combined with the introduction of new more productive wheat cultivars with better nutrient use efficiency and/or better structure and higher component yield capacity (Mladenov et al. 2011, Sanchez-Garcia et al. 2012, Cormier et al. 2016). This resulted in an increasing difference between non-fertilised controls and the most productive treatments. The rate of yield increase was only 13% in Hněvčeves. Even excess N did not bring substantial additional yield increase. Hejcman and Kunzová (2010) and Černý et al. (2010) recorded that the N yield effect is often lower at sites with higher natural soil fertility. Specific decreasing trends were recorded in Pernolec, where mean yields dropped by 9% after the first rotation. Only the most intensive fertilisation maintained yields at the starting level and the yields at unfertilised treatments decreased immediately after the experiment set-up. These experimental fields were most likely intensively fertilised before 1979, as the starting yields were quite high for these climatic and soil conditions.

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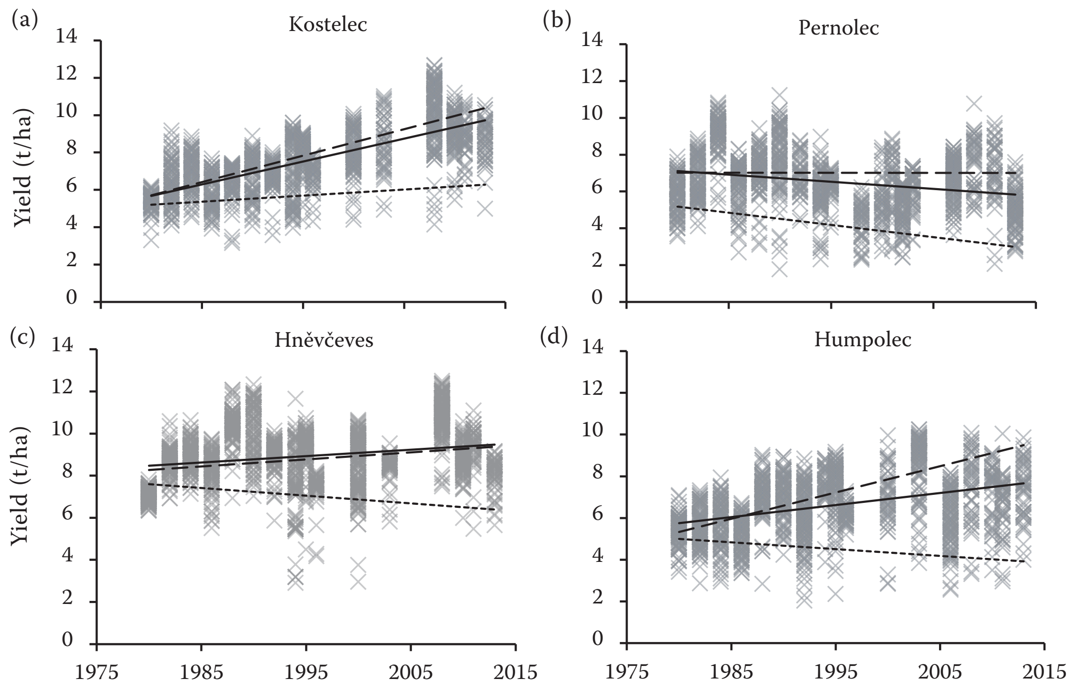

Figure 1. Winter wheat grain yields over the experimental period, with trends for average annual yields (solid), non-fertilised control (dotted) and the most productive treatment (dashed)

The average influence of experimental factors on wheat grain yields is quantitatively expressed in Figure 2; Figure 3 highlights the influence only for the partial trials where factors were significant. These graph curves are therefore steeper because they not flattened by a large number of

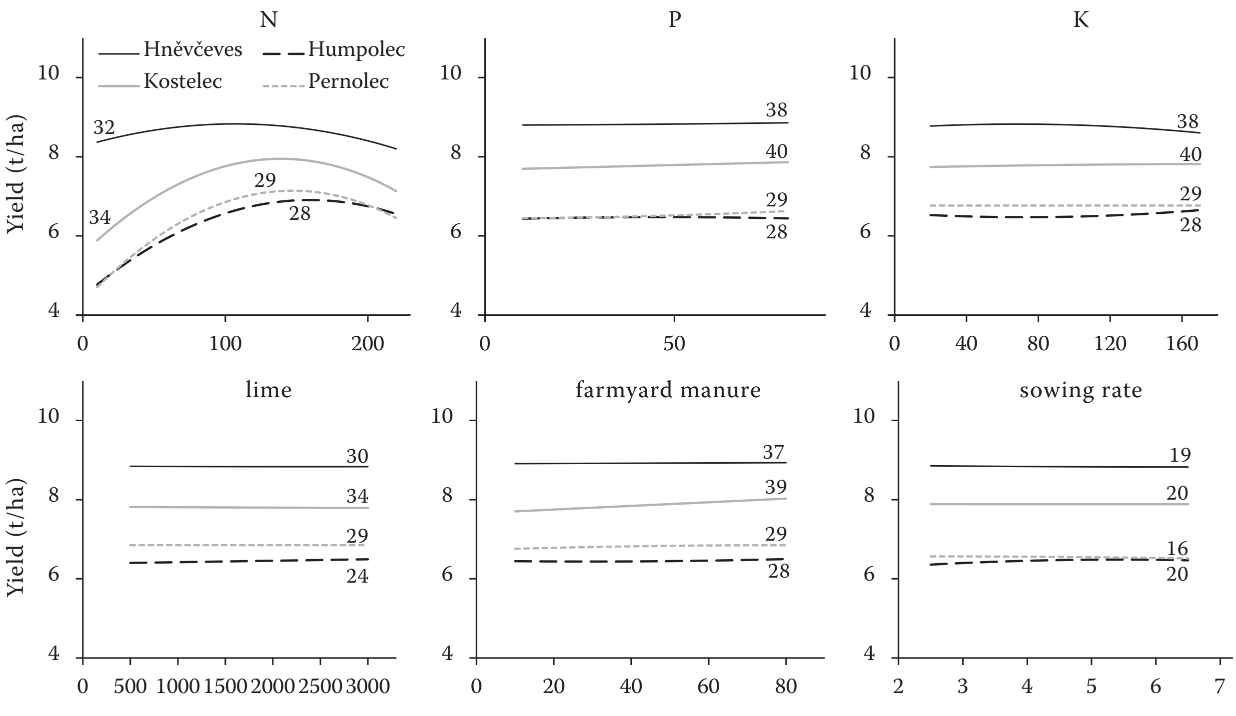

Figure 2. Average influence of N, P, K and lime (kg/ha), farmyard manure (t/ha) and sowing rate (10^6 germinated seeds) on winter wheat grain yields in the whole dataset. Numbers next to curves show number of partial trials participating at the average model curve calculation. For each factor graph, other factors were set to their medium values in the model

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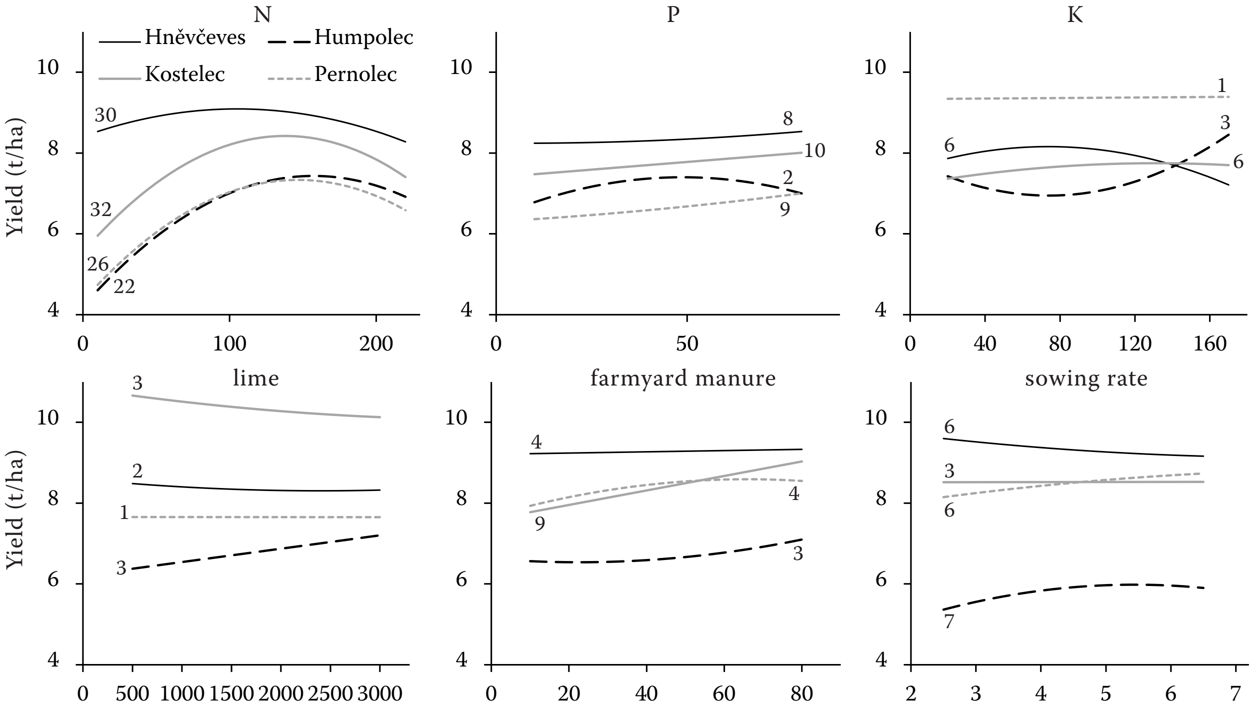

Figure 3. Influence of N, P, K and lime (kg/ha), farmyard manure (t/ha) and sowing rate (10^6 germinated seeds) on winter wheat grain yields in cases when factor effects were statistically significant at $P > 0.05$. Numbers next to curves show number of partial trials participating at the average model curve calculation. For each factor graph, other factors were set to their medium values

non-significant cases. Within the partial trials performed, each factor was used from 16 to 40 times at each site, while the statistical significance was confirmed from 1 to 32 times at each factor and site combination (Table 3). These numbers are important for the relevance of the quantitative results presented in Figures 2 and 3. The higher is the percentage of significant cases, the higher is the result relevance.

Nitrogen. N was statistically significant in 89.4% of all partial trials and in 100% of trials performed in last 8 years (Table 3). A quadratic member was significant for 66% of all calculated yield models, resulting in a strongly curvilinear N response curves. N fertilisation can increase yields by an average of 2 t/ha; however N effect was strongly site-dependent with the curve rather flat for Hněvčeves and steeper for other sites. Site yield potential was in the order: Hněvčeves > Kostelec > Pernolec ≈ Humpolec, but the maximum yields obtained were in the reverse order – at 110 kg N/ha for Hněvčeves, 130 kg N/ha for Kostelec, 145 kg N/ha for Pernolec and 170 kg N/ha for Humpolec. High N application rates caused occasional wheat lodging, resulting in lower grain yields. The shift in curve peaks can be explained by increased nitrate leaching in the climatic gradient from warmer to colder sites. Results obtained from international long-term experiments showed different optimum N application rates, highlighting the strong effect of local soil and climate conditions (Brentrup et al. 2004). N leaching strongly depends on N supply, crop type and soil and climatic conditions (Heumann et al. 2013). N losses are also connected with autumn and winter precipitation, and are higher on light-textured soils (Cameron et al. 2013). Results from other Czech long-term experiments by Kunzová and Hejcman (2009) and Hejcman and Kunzová (2010) confirmed that grain yields on less productive soils were strongly dependent on N application rates. In addition, Sieling et al. (2005) and Hejcman and Kunzová (2010) recorded a statistically significant influence of the preceding crop on grain yield, and Rahimizadeh et al. (2010) reported that the preceding crop affects wheat N uptake and use efficiency. This research supports our finding that the preceding crops have a substantial effect on the N response curve (Figure 4).

Sowing rate. The next most important factor was sowing rate, and its statistical significance

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Table 3. Overview of the influence of six experimental factors on winter wheat grain yields at experimental sites

Site	Period	Nitrogen		Phosphorus		Potassium		Liming		FYM		Sowing rate	
		n_{total}	$n_{\alpha<0.05}$ / x (x^2)	n_{total}	$n_{\alpha<0.05}$ / x (x^2)	n_{total}	$n_{\alpha<0.05}$ / x (x^2)	n_{total}	$n_{\alpha<0.05}$ / x (x^2)	n_{total}	$n_{\alpha<0.05}$ / x (x^2)	n_{total}	$n_{\alpha<0.05}$ / x (x^2)
Kostelec	1980–2013	34	32 (21)	40	10 (0)	40	6 (1)	34	3 (1)	39	9 (0)	20	3 (0)
Hněvčeves	1980–2013	32	30 (18)	38	8 (4)	38	6 (5)	30	2 (1)	37	4 (0)	19	6 (2)
Humpolec	1980–2013	28	22 (14)	28	2 (2)	28	3 (3)	24	3 (0)	28	3 (1)	20	7 (2)
Pernolec	1980–2013	29	26 (20)	29	9 (1)	29	1 (0)	29	1 (0)	29	4 (2)	16	6 (1)
All sites	1980–2013	123	110 (73)	135	29 (7)	135	16 (9)	117	9 (2)	133	20 (3)	75	22 (5)
Kostelec	2007–2013	9	9 (6)	9	2 (0)	9	1 (0)	9	1 (0)	9	2 (0)	–	–
Hněvčeves	2007–2013	9	9 (5)	9	2 (1)	9	1 (0)	8	0 (0)	9	2 (0)	–	–
Humpolec	2007–2013	4	4 (2)	4	2 (2)	4	2 (2)	4	2 (0)	4	1 (0)	–	–
Pernolec	2007–2013	6	6 (3)	6	1 (0)	6	0 (0)	6	1 (0)	6	0 (0)	–	–
All sites	2007–2013	28	28 (17)	28	7 (3)	28	4 (2)	27	4 (0)	28	5 (0)	–	–

n_{total} – number of partial trials including the factor; $n_{\alpha<0.05}$ – number of partial trials in which the factor significantly influenced yields; x^2 – number of partial trials in which a quadratic member was statistically significant; FYM – farmyard manure

was observed in 29.3% of cases. Sowing rate influence was less frequently noted in Kostelec than at other sites and it increased yields on average by 0.2 t/ha in the experimental range applied. In addition, while the effect of increasing sowing rate was positive in colder sites providing + 0.5 t/ha in significant cases, and slightly negative in Hněvčeves, the most consistent results were es-

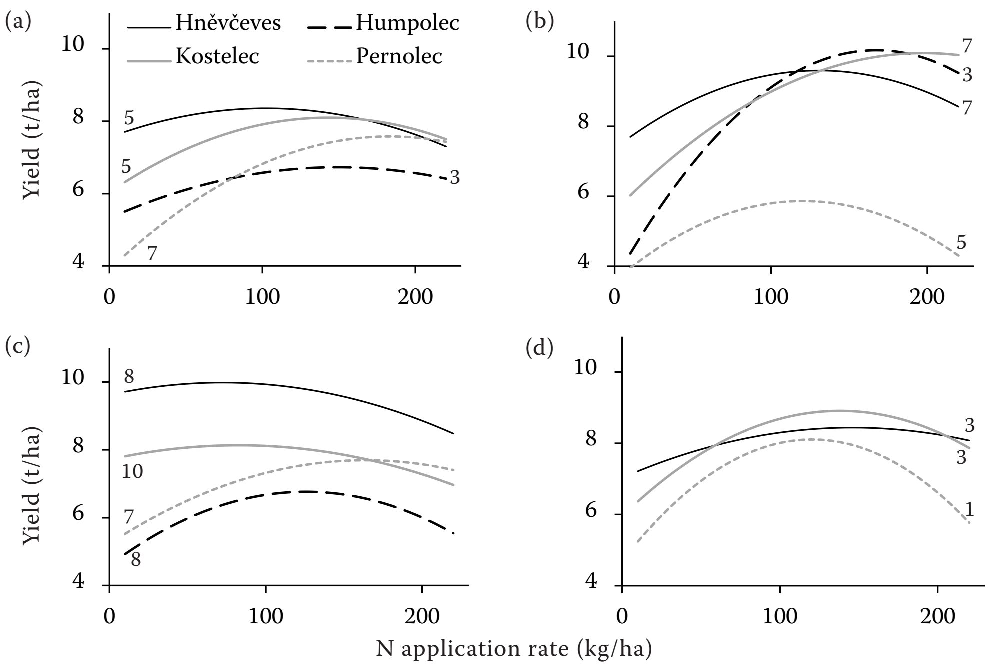

Figure 4. Average influence of nitrogen (N) fertilisation on winter wheat grain yields for different preceding crops ((a) silage maize; (b) oilseed rape; (c) alfalfa/clover; (d) pea). Numbers next to curves show number of partial trials participating at the average model curve calculation. For each factor graph, factors other than N were set to their medium values

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tablished in Humpolec where 6 of 7 significant cases achieved a positive effect. At other sites, positive and negative cases were equally recorded, thus confirming that the effect of sowing rate differs in different environments and conditions (Geleta et al. 2002). Compensatory mechanisms for yield components usually lead to yields being unaffected in the range of 300 to 500 germinated seeds/m^2 (Gaile et al. 2017). The mutual compensation of yield-forming components produces equal final stand density (Stephen et al. 2005) and the lower plant number per m^2 is compensated by a higher number of offshoots. Goodling et al. (2002) reported a low-sowing-rate effect in N-deficient wheat cropping, and this may also be relevant for other nutrients. The Kostelec soil nutrient limitation recorded in our research is confirmed by a steep yield increase when fertilisation began and this could have initiated conditions where the sowing rate did not affect yields in the tested range.

Phosphorus. P influence was significant in 21.5% of all partial trials; however only in 7% in Humpolec. P effect was positive for all sites except Humpolec over the rate of 50 kg P/ha, where it was curvilinear and negative. On average, P fertilisation increased yields by approximately 0.5 t/ha. Humpolec soil had the lowest starting available P content of all sites. The only two significant results recorded for this site are therefore rather surprising although available P level of 27 mg/kg may still be sufficient to supply wheat plants. These two cases were recorded in last 8 years of the evaluated period (Table 3), indicating that soil available P at underbalanced treatments might have fallen enough to increase P effect on yields. Guggenberger et al. (2000) reported that clay fraction is important in short-term P turnover, and while the low clay content in Humpolec soil may be positive for P release, P may also be adsorbed more readily in soils with higher clay content. Thus, differences in soil type significantly influence P dynamics (Blake et al. 2000). The meta-analysis reported by Valkama et al. (2009) highlighted that P fertilisation significantly increased crop yields by 11%, but this depended strongly on soil texture and organic matter content and its beneficial effect decreased in the following order: organic soils > coarse-textured mineral soils > clay soils.

Farmyard manure. FYM influence was significant in 15.0% of cases, and its fertilisation effect was linear. FYM increased yields by approximately 0.75 t/ha in the range of applied rates; with the most frequent influence of 23.1% of trials observed in Kostelec. The effect there was the most intensive, with expected yield increase by 1.5 t/ha. Nutrients released from manure had a beneficial effect for Kostelec plant growth because of its low initial soil fertility, and the nutrient effect was therefore much higher than in soils with higher available nutrients. Černý et al. (2010) and Berzsenyi et al. (2000) reported that FYM application had a lower effect on yield increase than NPK fertilisation. On the contrary, Johnston's (1997) Rothamsted results recorded the greatest crop yields on plots treated with manure, but FYM was applied here annually and at a higher rate than in our experiment. Results from 14 international field trials indicated no significant differences between manures and mineral fertilisers in their long-term effects on crop productivity; even the lower bulk density and higher porosity, hydraulic conductivity and aggregate stability relative to fertilised soils were reported in manured soils (Edmeades 2003).

Potassium. In most cases, potassium (K) fertilisation had no significant effect on yield, and this finding is supported by Khan et al. (2014). The significant effect of K fertilisation was more frequent at Kostelec and Hněvčeves, with their loess-derived soils and 15.4% of statistically significant cases, than at the remaining two sites with gneiss-derived soils. The gneiss at our sites contains a high percentage of K-bearing micas, resulting in higher soil K content, while the total K in the loess-derived soils is much lower (Madaras et al. 2010). The quantitative effects of K fertilisation are inconsistent in some significant cases (Figure 3); K fertilization increased yields in Kostelec by approximately 0.5 t/ha also in the excess rates while in Hněvčeves rates over 70 kg N/ha exerted a strong negative effect. The yield reduction due to KCl application is explained by both KCl's high salt index (Khan et al. 2014) and Mg deficiency induced by high K supply (Römheld and Kirkby 2010). In contrast to these two sites, Humpolec high K rates had occasional clearly positive effect on yields (N = 3), more frequently in last 8 years of the experiment.

Liming. Haynes and Naidu (1998) and Kisić et al. (2004) reported that liming of acid soils improves crop growth and yields. However, soil pH at our experimental sites is within the 5.5–6.5 optimum wheat range, which ensures both crop growth and

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optimum nutrient availability (Islam et al. 1980). The pH very rarely fell under 6.0 at untreated control plots, and therefore slightly acidic pH range is most likely the reason that the effect of soil reaction control by lime was rarely observed; only in 7.7% of trials. Although soil acidification with pH levels less than 5.0 can occur due to the long-term use of N fertilisers, there was no reduction in winter wheat yield (Schroder et al. 2011).

Yields were most frequently influenced by N and much less responsive to other factors. The effect of N was much stronger than for other factors and it had a parabolic shape in contrast to the linear and very flat effects of the other factors, which signals weak or negligible influence. Fertiliser doses at or above the tested excess levels therefore did not affect higher yields but they might have contributed to water and soil pollution due to leaching. Finally, our results confirmed the profound role of climatic and edaphic site characteristics and the effects of preceding crops on the shape of response curves.

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