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Winter wheat yields under different soil-climatic conditions in a long-term field trial

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Abstract: The impact of precipitations and air temperatures on winter wheat yields was evaluated in a 34-year long-term field trial with mineral and organic fertilization established at two experimental sites with different soil-climatic conditions: Ivanovice na Hané with well fertile soils (degraded Chernozem), higher average year temperatures and lower precipitations; Lukavec situated in Bohemian-Moravian highlands with less fertile soils (Cambisol), lower temperatures and higher precipitations. At both sites, a significant positive effect of used fertilizers was noted from the dose of 80 kg N/ha; the best yields were generally obtained at 120 kg N/ha and 160 kg N/ha. The wheat yields at the Ivanovice site were negatively affected by the decrease of precipitations, namely in more fertilized treatments, particularly farmyard manure + mineral nitrogen, from the dose of 80 kg N/ha. A different trend was obtained at the Lukavec site where better winter wheat yields were obtained under lower precipitations. The air temperatures played a positive role at the Lukavec site, but no significant effect of temperature was observed at the Ivanovice site. The less productive areas in highlands can become more interesting for agriculture production with changing climate. However, the soils generally having lower quality and nutrient content can be a limiting factor for obtaining high yields.

Keywords: weather; *Triticum aestivum* L.; climate change; straw; water deficit; drought

The scale of results collected during decades from long-term field trials can help in understanding the possible effects of changing climate on yields as well as other parameters (Urruty et al. 2017). The long-term field trials bring a key response of the effects of long-term soil fertilization with different types of fertilizers on crop yields and contribute to the understanding of nutrient availability (Rasmussen et al. 1998). Optimal fertilization based on scientific understanding can contribute to improved soil quality and sustainable soil use (Yadav et al. 2000, Li et al. 2018).

The winter wheat represents the main crop grown in the Czech Republic and is grown in localities differing in their soil-climatic conditions including less and more fertile soils and also by the efficiency of organic and mineral fertilizers. Results of more than 60-year long-term trials with mineral and organic fertilization in the Czech Republic described by Hejcman and Kunzová (2010), Hejcman et al. (2012), Kunzová and Hejcman (2009) showed an important and positive role of soil fertilization on crop yields and also the fact that wheat in the Czech Republic is frequently planted even in areas less suitable for wheat production.

The climatic changes are already visible globally and as an independent factor can affect seriously the crop yields (Sun et al. 2018). Winter wheat yield is affected not only by extreme climatic events like long-term drought or large-scale flood but also by less severe unfavourable weather conditions that are liable to increase with future climate change (Urruty et al. 2017). The effect of temperatures, increasing since the 1980's, has been several times reported. The shortening of the growth period, grain filling, aggravation of heat-related water stress, acceleration of phenological development was reported, i.e. by Lobell et al. (2013), Xiao et al. (2013) and Sun et al. (2018). Climate change is also associated with the increase of CO_2 fluxes from agricultural soils that can

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modify the functions of agroecosystems by changing nutrient cycling and the decomposition of organic matter in soils (Gelaw et al. 2015, Zhang et al. 2016). Herbst et al. (2017) showed that in 140 long-term trials with eternal rye yields increased since 1920, which was caused by the cultivation of new higher yielding cultivars, regular use of plant protection products and perhaps also by elevated atmospheric CO_2 concentration.

The drought is an important problem in last years in the Czech Republic; it significantly reduces yields of the main cereals and majority of other crops through the most drought-prone regions in some areas of the Czech Republic (and probably most of Central Europe) and is one of the key causes of interannual yield variability (Hlavinka et al. 2009).

The research aimed at evaluating: (i) the effect of mineral or organic fertilization; (ii) effects of temperature and precipitations on the yields of winter wheat grown in the long-term field trial.

MATERIAL AND METHODS

Field trial. The long-term field trial with organic, mineral and combined fertilization IOSDV (Internationaler Organische Stickstoffdüngungsdauerversuche) was established in 1984 according to the unified methodology (Körschens et al. 2012) at two different sites: Lukavec near Pacov [altitude 620 m a.s.l., Cambisol, loamy-sandy soil, average (1985–2014) precipitations and temperature – 708 mm; 7.4°C, pH_{CaCl_2} 5.9, available nutrient contents according to Mehlich 3: 118 mg P/kg, 237 mg K/kg, 144 mg Mg/kg, 1537 mg Ca/kg] and Ivanovice na Hané [altitude 225 m a.s.l., degraded Chernozem, loamy soil, average precipitations and temperature – 558 mm; 9.3°C, pH_{CaCl_2} 6.3, available nutrient contents according to Mehlich 3: 117 mg P/kg, 452 mg K/kg, 245 mg Mg/kg, 3564 mg Ca/kg]. The crop rotation was following: (i) 1st year: potatoes (Lukavec) or sugar beet (Ivanovice); (ii) 2nd year: winter wheat; (iii) 3rd year: winter barley-intercrop.

Three basic fertilization systems were adopted: (i) only mineral fertilization; (ii) 30 t/ha of farmyard manure once in 3 years to potatoes or sugar beet; (iii) straw remaining in the field after the cereals harvest plus 20 kg of N to/for postharvest residues decomposition and grown intercrop. The mineral fertilization was 35 kg P/ha, 83 kg K/ha and 40-80-120-160 kg N/ha in the relevant treatments. The nitrogen was applied in four terms: before sowing; regeneration dose at BBCH 12; productive dose at BBCH 31 and qualitative N dose (only to the highest N dose) at BBCH 51. N fertilization rates were divided into 20 + 20 kg N/ha in the lowest dose 40 kg N/ha. Higher N doses were divided by 40 kg N/ha. 4 million germinating seeds of winter wheat per hectare were sown. The sowing period was between 23/9–30/9 at the Lukavec site and between 25/10–5/11 at the Ivanovice site. The yield characteristics (yield of grains, the weight of one thousand grains (WTG) and spikes density) of winter wheat were determined.

Statistical analysis. The results from the overall period 1985–2017 were statistically analysed using the Statistica 13.0 software (TIBCO Software, California, USA). The one-way ANOVA and the Tukey's test was used to determine significant differences among treatments indicated by letters given to relevant data in tables. The correlation coefficients (*r*) based on the Spearman's equations between yield characteristics, precipitations and temperatures were calculated.

RESULTS AND DISCUSSION

Effect of fertilization. According to expectations, wheat yields achieved in the control treatments without any nitrogen (N) fertilization were lower at both experimental sites irrespective if the crops were fertilized with phosphorus and potassium or not and were comparable with corresponding straw treatments (Table 1). At both experimental sites, farmyard manure (FYM) treatments significantly increased yields in comparison with control, in combination with low doses of mineral N also in comparison with relevant treatments without organic fertilization. No significant influence of the only mineral fertilization was noted at higher N treatments. The effect of FYM at no or low mineral N doses on obtained winter wheat yields was given by the fact that FYM contained the considerable amount of nutrients and also served as an important source of the organic matter regularly added into the soil. The straw amendment caused lower wheat yields in comparison with FYM treatments at both experimental sites. Positive effects of the straw amendments were significant only in comparison with no or lower doses of mineral treatments. Merbach et al. (2000) reported that in a long-term field trial in Halle founded in 1949, the yields were not directly influenced by straw if optimal fertilizers were applied. In our present IOSDV trial, the straw and FYM treatments increased wheat yields at the Ivanovice site of 10% and 19%, respectively.

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Table 1. Yield parameters at Ivanovice and Lukavec sites (average 1985–2017)

Treatment	Yield grain (86% dry mass) (t/ha)		Weight of one thousand grains (g)		Number of spikes (spikes/m²)	
	Ivanovice	Lukavec	Ivanovice	Lukavec	Ivanovice	Lukavec
Control	5.0[a]	3.24[ab]	46.3[de]	43.43[a]	459[a]	365[a]
PK	4.9[a]	3.13[a]	46.3[de]	43.60[ab]	491[ab]	383[ab]
N40-PK	5.9[bcd]	4.60[de]	46.5[de]	45.15[abc]	492[abcd]	409[abcd]
N80-PK	6.6[cdef]	6.01[gh]	45.5[de]	45.64[abc]	540[abcd]	451[abcde]
N120-PK	7.0[f]	7.06[ijk]	44.1[abcde]	44.37[abc]	551[abcd]	477[defg]
N160-PK	6.9[f]	7.39[l]	43.6[abcd]	44.36[abc]	558[abcd]	485[ef]
Straw	5.5[ab]	3.73[abc]	45.9[de]	44.41[abc]	509[abcd]	382[ab]
Straw-PK	5.5[ab]	3.83[bc]	46.4[de]	44.92[abc]	493[abc]	400[abcd]
Straw-N40-PK	6.4[cdef]	5.19[ef]	45.8[bcde]	45.69[abc]	540[abcd]	422[abcde]
Straw-N80-PK	6.7[def]	6.55[hi]	44.5[abcde]	45.69[abc]	574[bcd]	463[cdef]
Straw-N120-PK	6.7[ef]	7.24[kl]	43.2[abc]	43.43[a]	584[bcd]	469[cdef]
Straw-N160-PK	6.6[cdef]	7.40[l]	43.0[ab]	43.60[ab]	586[bcd]	488[ef]
FYM	5.9[bc]	4.01[cd]	46.4[de]	44.92[abc]	519[abcd]	390[ab]
FYM-PK	6.0[bcde]	4.07[cd]	46.4[e]	45.29[abc]	520[abcd]	406[abcd]
FYM-N40-PK	6.7[ef]	5.40[fg]	45.8[cde]	46.38[c]	549[abcd]	422[abcde]
FYM-N80-PK	6.9[f]	6.63[ij]	44.3[abcde]	45.88[bc]	561[bcd]	474[defg]
FYM-N120-PK	6.9[f]	7.41[l]	42.9[abc]	44.21[abc]	596[d]	477[defg]
FYM-N160-PK	6.7[ef]	7.50[l]	42.6[a]	44.11[abc]	592[cd]	501[g]

Different letters indicate significant differences among treatments. FYM – farmyard manure

The IOSDV field trials in other countries (Spiegel et al. 2010, Körschens et al. 2012, Kismányoky and Tóth (2012) showed yield benefits for winter wheat in combined mineral and organic fertilization up to 6% after 20 years of trial. Zavattaro et al. (2017) showed that the fertilization with manure led in an average of 80 long-term European field trials to about 9.5% higher yields of winter wheat and combined manure with mineral fertilizers increased the yields of 11.3%. On the other hand, Hijbeek et al. (2017), using the data from 20 European field trials, concluded that organic matter given into soil did not necessarily increase the yields as the nutrients were mainly supplied by mineral fertilizers. Also, Schmidt et al. (2000) reported that the soil enrichment with organic matter in FYM together with mineral nitrogen caused that a major part of the FYM-N was not available for crops.

Significant differences in wheat yields were found among the N treatments starting with the dose of 80 kg N/ha. Fertilization with mineral N increased the wheat yields in all mineral and organic treatments up to 120 kg N/ha. At the Ivanovice site, as compared to the Lukavec site, the highest dose of nitrogen (160 kg N/ha) did not increase the yields more. One of the possible reasons can be the last N dose given at heading, when particularly in drier conditions they could not be used by plants. Merbach et al. (2000) showed that the combination with FYM and moderate inorganic fertilization allowed yields higher about 10%, but increasing inorganic N supply led to a decrease or even complete lack of FYM effects. The average wheat yields obtained under lower doses of fertilizers at the Lukavec site were up to 80 kg N/h lower in comparison with that at the Ivanovice site. The wheat yields at the Lukavec site showed lower variability than at the Ivanovice site where in the years with good water supply and adequate temperatures, high yields (up to 10 t/ha) were obtained under higher N doses, but very low yields were obtained under unfavourable conditions which were the most visible in 1996 (freezing and long winter) and in 1993, 2012 and 2017 (drought) (Figure 1).

The important effect on the wheat yields had the number of spikes, which in correspondence to the fertilization dose, correlated well with grain yields (Ivanovice: r = 0.880, $P \leq 0.001$; Lukavec: r = 0.983,

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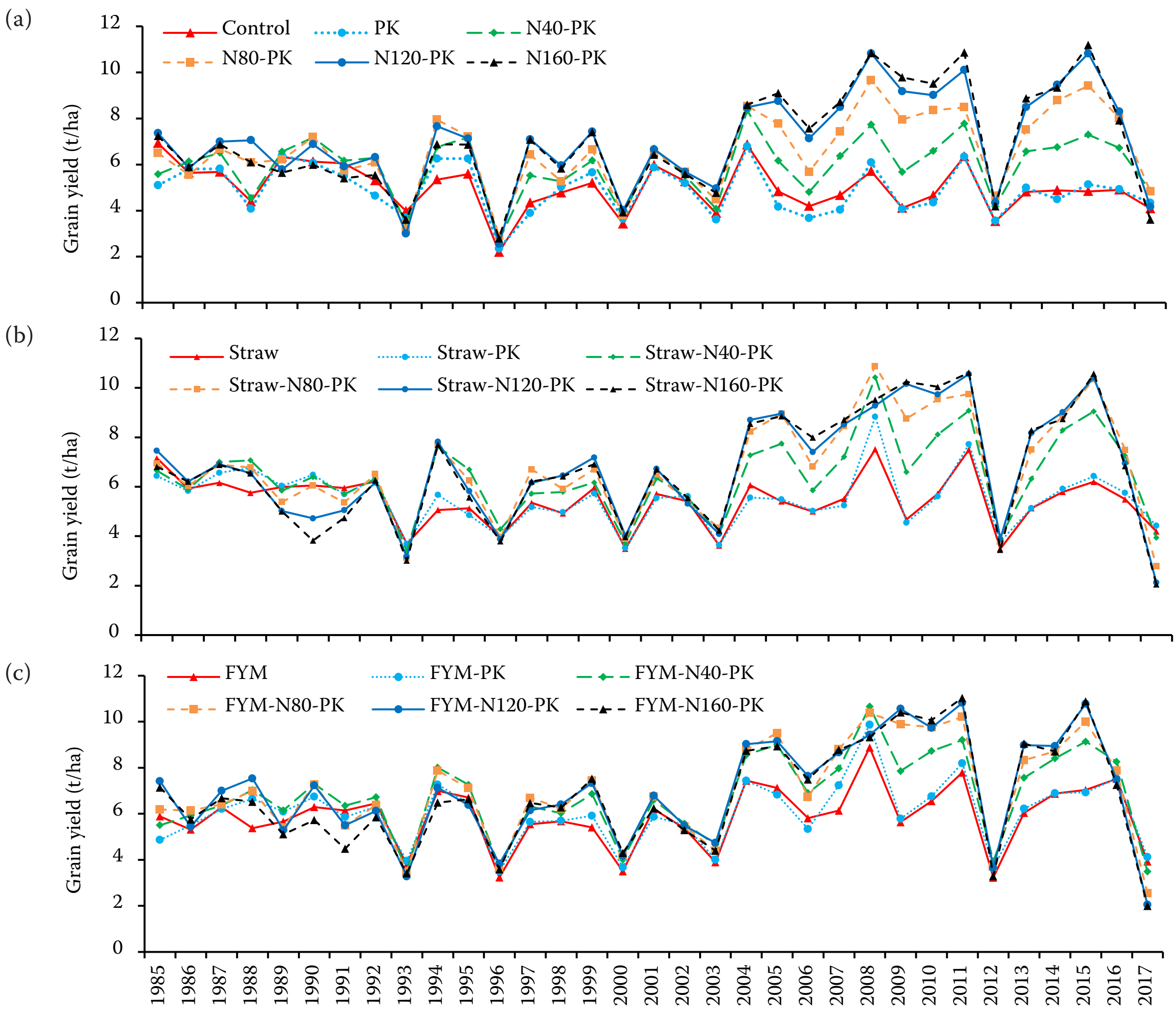

Figure 1. Grain yields of winter wheat at the Ivanovice site in 1985–2017: (a) mineral treatments; (b) straw treatments; and (c) farmyard manure (FYM) treatments

$P \leq 0.001$) and contributed to obtained yields. On the other hand, WTG at the Ivanovice site showed a negative correlation in relation to the obtained yields ($r = -0.734$, $P \leq 0.001$) and also to number of spikes ($r = -0.859$, $P \leq 0.001$), which indicates that high spikes density could be achieved by high off-shooting of plants and therefore smaller grains. No correlation was found between WTG and wheat yields at the Lukavec site. The number of spikes was, therefore, an important parameter for obtaining grain yields. In fact, the lower number of spikes (52–65% of average) was found at the Ivanovice site in 2012 and 2017 with low precipitations corresponding with very low wheat yields, particularly in well-fertilized treatments.

The low yields under higher fertilization rates at the Ivanovice site could also be obtained due to several factors such as late wheat sowing after sugar beet harvesting, low winter and spring temperatures (e.g. in 1996), the drought still more often observed in the most critical growth periods consequently caused that last N rates could not be used by plants. Sun et al. (2018) showed that wheat yields were hardly affected by drought and Mäkinen et al. (2018) on the basis of 2500 wheat cultivars grown from the North to South Europe (Finland, Denmark, Germany, Czech Republic, Slovakia, Belgium, France, Spain, Italy) stated that extreme weather led to marked yield penalties with the exception of some specific regions and good performance under high temperatures and southern-origin cultivars.

Effect of precipitations and temperatures on wheat yields. Wheat yields changed under different weather conditions during more than 30-year long period (Figures 1 and 2). In 2006, the wheat yields at the Lukavec site were lower in comparison with other years of trial (Figure 2). The year 2006 at the

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Lukavec site was characteristic by the long and cold winter which affected the survival of wheat plants and their late regeneration (Figure 3b).

Lower yields at the Ivanovice site were obtained in 1993, 1996, 2000, 2003, 2012 and 2017 (Figure 1). The year 1996 was characterized by long winter that affected the regeneration of plants. Lower precipitations corresponding to the yields decrease were observed in 1993, 2003, 2012 and 2017. The overall experimental period (1985–2017) at the Ivanovice site was characterized by the increase of average temperatures of 1.04°C (from 8.86°C to 9.90°C). Increasing temperatures and decreasing precipitations were observed in this period (Figure 3a). Particularly, the period in the last four years (2014–2017) was characterized by a rapid decrease of precipitations. The accumulation of water deficit caused a serious decrease of wheat yields in the year 2017 when highly fertilized treatments achieved the worst yields of the whole experimental period, achieving only about 2 t/ha (Figure 1). In China, Australia, and Argentina, warming influenced the pre-flowering growth stage of wheat (Sadras and Monzon 2006, Liu et al. 2010, Sun et al. 2018). The wheat yield decrease at the Ivanovice site was more often observed when the precipitations were low during the spring period (Figure 4a) and new cultivars bred for obtaining high yields can become more susceptible to unfavourable weather conditions.

The correlations between temperature and wheat yields under different fertilization strategies at the Ivanovice site did not show any significant effects (Table 2). The significant correlations were obtained for precipitations and yields that were positively and significantly correlated with wheat yields mostly under FYM and straw treatments from the dose of 80 kg N/ha (r = 0.362–0.494, $P \leq$ 0.05–0.01) indicating that low precipitations decreased wheat yields at higher fertilization doses. No significant effect

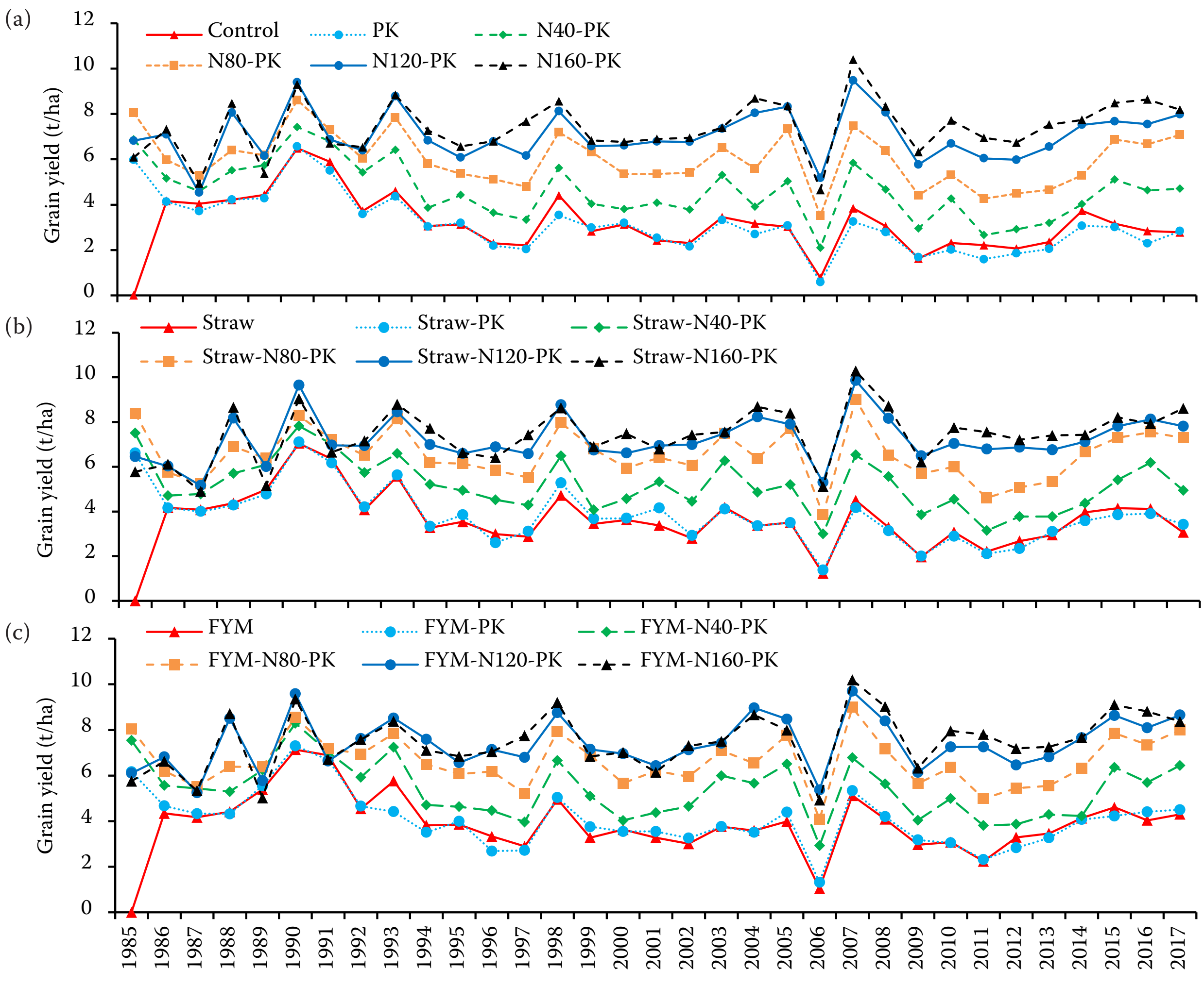

Figure 2. Grain yields of winter wheat at the Lukavec site in 1985–2017: (a) mineral treatments; (b) straw treatments; and (c) farmyard manure (FYM) treatments

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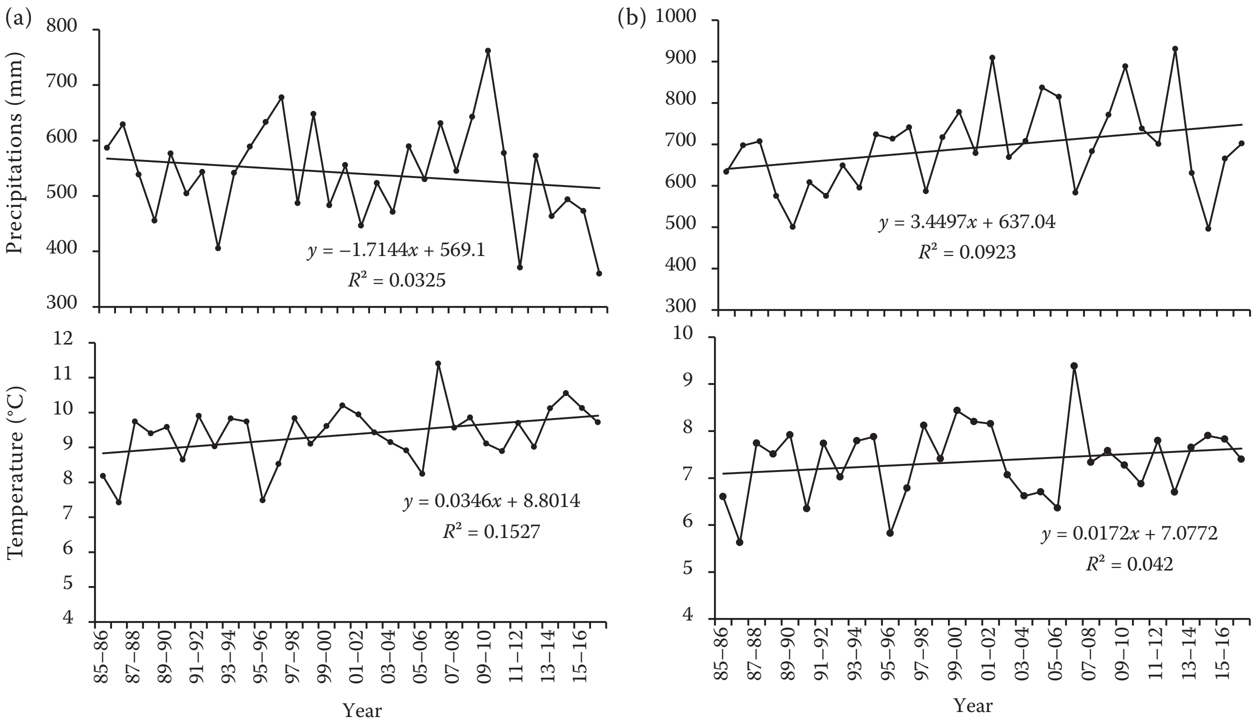

Figure 3. Precipitations and temperatures at (a) Ivanovice and (b) the Lukavec site in 1985–2017

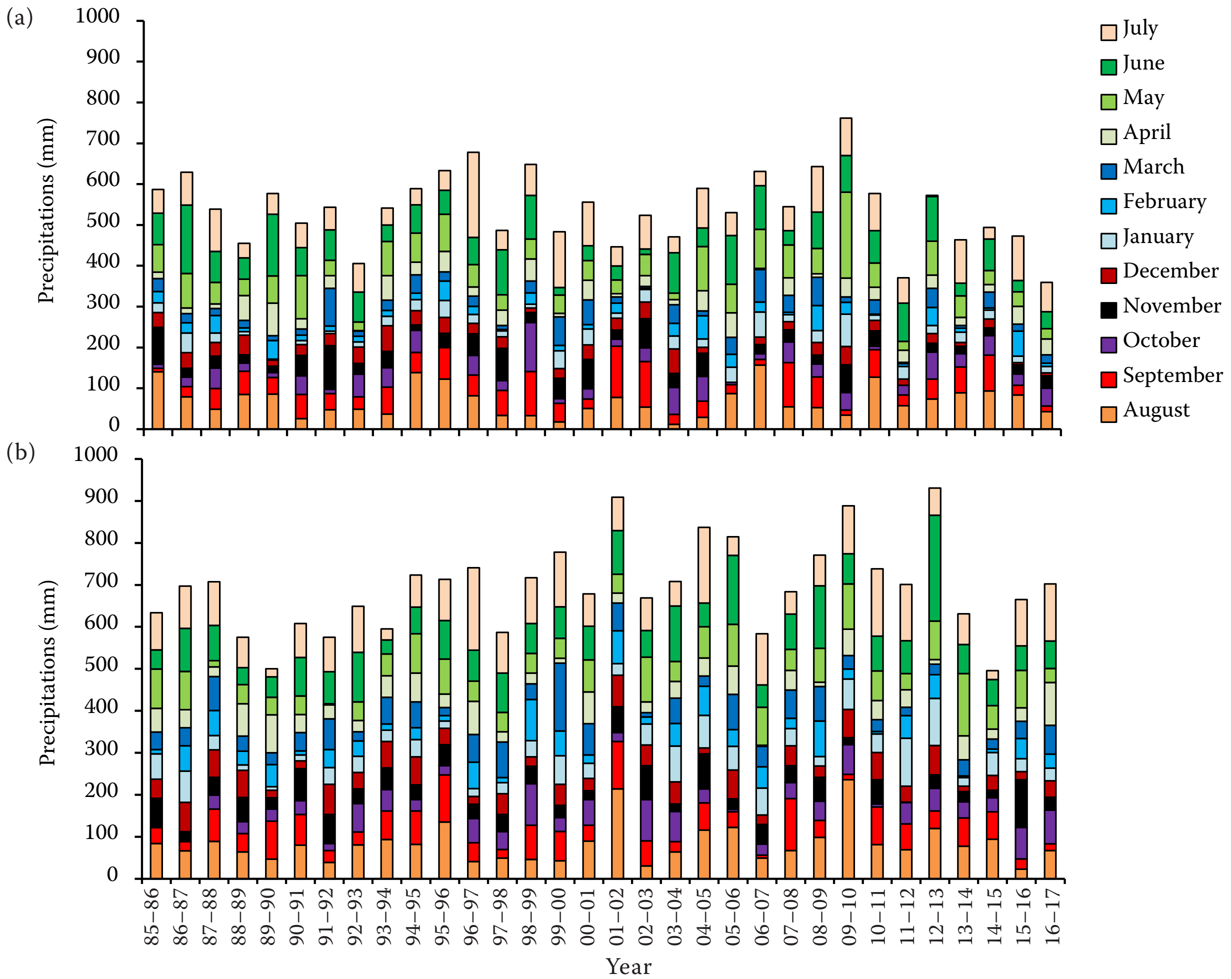

Figure 4. Month precipitations at (a) Ivanovice and (b) Lukavec sites in 1985–2017

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of temperature or precipitations on the number of spikes or WTG was noted.

The increase of average year temperatures of 0.41°C was also noted at the Lukavec site (from 7.08°C to 7.49°C). Compared to the Ivanovice site, the average precipitations at the Lukavec site showed a slight tendency to increase (Figure 3b). The different trend in correlations between winter wheat yields, temperature and precipitations were observed at the Lukavec site (Table 2). The temperature positively and significantly affected the wheat yields from 80 kg N/ha in treatments receiving straw and FYM. In this case, the increasing temperature seemed to have a positive effect on wheat yields. Higher average precipitations were noted at the Lukavec site during the experiment, however, in this case too high precipitations led to a decrease of yields. Particularly the wheat yields in treatments receiving less mineral N were negatively affected by high precipitations (r = –0.648 to –0.669, $P \leq 0.001$), no significant effect was observed for the highest fertilization dose 160 kg N/ha (Table 2). The winter wheat yields at the Lukavec and Ivanovice sites were affected by the temporal variability and particularly by precipitations as it was reported also by Ventrella et al. (2016) and Mäkinen et al. (2018).

In conclusion, based on our data obtained from long-term field trials, completely different strategies of fertilization, crop rotation and agrotechnics should be adopted at areas with higher temperatures and a higher risk of drought and in areas situated in regions with adequate or high precipitations. The fertilization should be adapted due to agricultural areas and possible weather excesses. The choice of crops non-demanding excess quantity of water and adequate agrotechnics at sites with high risk of drought can also play an important role in obtaining adequate yields in dry conditions. The less productive areas in highlands can become more interesting for agriculture production with changing climate; however, the soils generally having lower quality and nutrient content can be a limiting factor for obtaining high yields.

Table 2. Correlation coefficients (r) between average temperatures, precipitations and yield characteristics at Ivanovice and Lukavec sites

Mineral treatment	Organic treatment	Ivanovice		Lukavec			
		grain yield		grain yield		number of spikes	
		temperature	precipitations	temperature	precipitations	temperature	precipitations
0	0	ns	ns	ns	–0.648***	ns	ns
	straw	ns	ns	ns	–0.657***	ns	ns
	FYM	ns	ns	ns	–0.669***	–0.428*	ns
PK	0	ns	ns	ns	–0.618***	–0.230	ns
	straw	ns	ns	ns	–0.622***	ns	ns
	FYM	ns	ns	ns	–0.641***	ns	ns
N40-PK	0	ns	ns	ns	–0.628***	ns	ns
	straw	ns	ns	ns	–0.661***	–0.400*	ns
	FYM	ns	ns	ns	–0.596***	–0.416*	ns
N80-PK	0	ns	ns	ns	–0.583***	ns	ns
	straw	ns	0.449*	0.449*	–0.528**	ns	ns
	FYM	ns	0.402*	0.402*	–0.581***	–0.465*	ns
N120-PK	0	ns	0.397*	0.397*	–0.386*	–0.467*	ns
	straw	ns	0.495**	0.495**	–0.386*	–0.356	–0.417*
	FYM	ns	0.417*	0.417*	–0.382*	–0.452*	ns
N160-PK	0	ns	0.425*	0.425*	ns	–0.397*	ns
	straw	ns	0.511**	0.511**	ns	ns	ns
	FYM	ns	0.440*	0.440*	ns	–0.400*	ns

Number of spikes at the Ivanovice site was not significant in any treatment. FYM – farmyard manure; ns – not significant; *P < 0.05; **P < 0.01; ***P < 0.001

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