INFLUENCE OF CLIMATIC FACTORS ON EXTREMELY/VERY LOW YIELDS OF SPRING BARLEY AND WINTER WHEAT IN SOUTHERN MORAVIA, CZECH REPUBLIC IN THE 1961–2012 PERIOD

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INTRODUCTION

It is frequently argued that intensive farming systems in Western and Central Europe have comparatively lower sensitivity to climate change, because of modest impact of a given change in temperature or precipitation (e.g. Chloupek et al., 2004), when farmers have resources to adapt and compensate negative effects by changing management (Olesen et al., 2011). These systems may therefore respond favourably to a modest warming (Olesen and Bindi, 2002). However, these studies do not consider in the full extent potential increase in drought or heat stress severity as well as possibility of frost damage that could alter substantially the final overall productivity (and its stability).

Number of recent studies have analysed the role of past climate variability in varying crop yields (e.g. Lobell et al., 2011; Peltonen-Sanio et al., 2010) while others focused on the effects of future climate changes on food production (e.g. Fischer et al., 2005; Lavalle et al., 2009). Most of these studies, however, compared the variation of individual climate predictors (e.g. maximum monthly temperature) and not examined the interplay of various climate phenomena during the growing season. Recent studies showed that climate conditions influence the yield of field crops in the Czech Republic the most during the period from April to June (e.g. Hlavinka et al., 2009).

The goal of this study is analysis of the variability of spring barley and winter wheat yields with respect to variability of weather and climatic factors in Southern Moravia (south-eastern Czech Republic) in the 1961–2012 period. Spring barley and winter wheat belongs to the traditional and most important crops in this region.

DATA AND METHODS

The studied area of Southern Moravia is located in the south-eastern part of the Czech Republic in Central Europe (Fig. 1). It covers 14 791 km^2 of land, of which 551 km^2 and 7 252 km^2 are agricultural and arable lands. The region includes 14 districts (Fig. 1, Tab. 1) out of which 13 had data about spring barley and winter wheat yields (Fig. 2) collected for the 1961–2012 period over the representative area. The area studied has a range of various agro-climatic patterns from the dry Pannonian lowland at the very south to the comparatively wet lowlands in the north and the wet and cold highlands in the west and partly in the east. As agro-climatic conditions within individual districts are relatively uniform (considering only the arable land), we were able to explore the climate-crop relationships across a set of districts with varying agro-climatic conditions. The entire region belongs to a traditional farming area with rain-fed grain production of winter wheat, spring barley and winter rape dominating the present cropping systems but with substantial production of wine and grain maize in the south and sugar beet in the central part. The proportions of particular land-use categories in Southern Moravia did not change dramatically between the 1960s and the present. Tiny changes occurred during whole period. However authors assume that none of these land-use changes would be in itself capable of significantly altering the climate-crop yield relationship assessed by this study.

Series of barley and wheat yields are based on the reports of the Czech Statistical Office (CSO). This dataset ends in 2007, when yield data acquisition at the district level (NUTS4) was terminated because of the overall reform of the administrative units in the Czech Republic. Data for period 2008-2012 (district Prostějov) were obtained through Agricultural Chamber of the Czech Republic that continues to collect data with almost identical results as done by CSO. Homogenous series of mean daily temperatures and precipitation totals were collected from 13 stations of the Czech Hydrometeorological Institute (CHMI) for the 1961–2012 period (Fig. 1). Winter conditions affecting predominantly winter wheat yields were represented by daily temperature and precipitation datasets which served as an input for snow cover model snowMAUS (Trnka et al., 2010). For each individual south-Moravian district there was selected only one station that was believed to most representative of the region. The nearest meteorological stations from neighboring districts were chosen in the case of rare situation when no appropriate station was present inside the district area. The study takes into account several key meteorological characteristics were employed in the study: daily air temperature maxima and minima, daily precipitation totals, daily evaporation. From these characteristics agro climatic indicators were calculated and used to analyze their relationship with the spring barley and winter wheat yields.

Phenological observation is limited by the dependence on each individual observer, despite such subjectivity it may improve consciousness about the process of yield formation. Data from the Czech Hydrometeorological Institute (CHMI) for the period of 1961–2012 was employed to analyze individual growing seasons with low yields. 12 phenological stations in the region were able to cover the period with its datasets (Fig. 1). Incomplete series were filled in according to results of regression analysis among the stations. In terms of the overall grain yield most important phenophases are tillering, flowering and full ripeness. These phases usually occur during April-July period. Final yield is affected not only by the calendar day of phenophase onset but also by the duration of period in between. For each phenological station the default onset and phenophase duration respectively were calculated from its long-term mean.

To distinguish low-yielding years for the study of relations between yields and climate, series of spring barley and winter wheat cannot be used in original form. To avoid various trends and influences yield series were detrended using polynomial function of the 5th order (Fig. 3) as a most suitable method according to results of residual analysis and minimal mean absolute percentage error (MAPE).

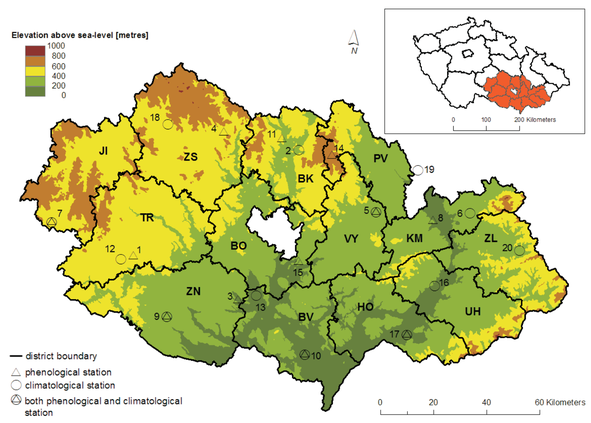

Fig. 1. Districts of Southern Moravia, climatological and phenological stations used in the study (1 – Blatnice, 2 – Boskovice, 3 – Branišovice, 4 – Bystřice nad Pernštejnem, 5 – Ivanovice na Hané, 6 – Holešov, 7 – Kostelní Myslová, 8 – Kroměříž, 9 – Kuchařovice, 10 – Lednice, 11 – Lysice, 12 – Moravské Budějovice, 13 – Pohořelice, 14 – Protivanov, 15 – Sokolnice, 16 – Staré Město, 17 – Strážnice, 18 – Valtín, 19 – Věrovany, 20 – Vizovice); white letters represent abbreviations of districts (BK – Blansko, BO – Brno-venkov, BV – Břeclav, HO – Hodonín, JI – Jihlava, KM – Kroměříž, PV – Prostějov, TR – Třebíč, UH – Uherské Hradiště, VY – Vyškov, ZL – Zlín, ZN – Znojmo, ZS – Žďár nad Sázavou)

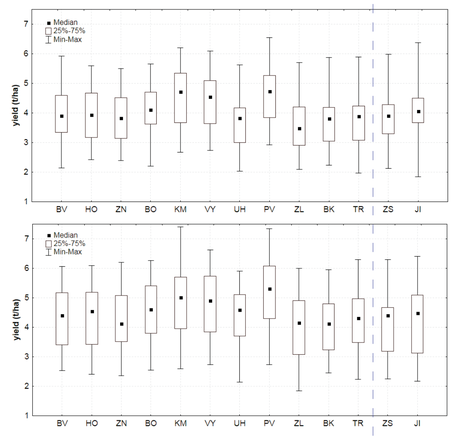

Fig. 2. Box-plots of yields of spring barley (above) and winter wheat (below) according to particular districts (ordered according their increasing altitude) in the 1961–2007 period; abbreviations of districts see Fig. 1

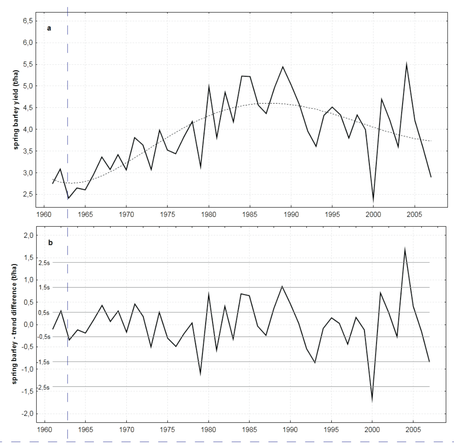

Fig. 3. Example of detrending of yield series of spring barley for Znojmo district in 1961–2007: a) original series, b) detrended series; s – standard deviation

Table 1. Overview of land-use, soil conditions and basic climate parameters in 13 selected districts ordered according their increasing altitude. For each district mean available water holding capacity of agriculture soils in the district (AWC), mean slope of arable land and overall mean temperatures and precipitation totals for the year and April–June (AMJ)

District	Total area	Arable land	Altitude and properties of arable land					Air temperature		Precipitation	
			Mean	Maximum	Minimum	Slope	AWC	annual	AMJ	annual	AMJ
	(km^2)	(%)	(m asl)	(m asl)	(m asl)	(degree)	(mm)	(°C)	(°C)	(mm)	(mm)
Břeclav	1173	53	197	393	146	3.6	171	9.4	15.8	476	319
Hodonín	1086	49	222	606	152	3.6	178	9.1	15.3	532	343
Znojmo	1638	63	286	516	163	1.7	162	8.8	15.0	487	328
Brno–venkov	1109	47	281	548	170	2.9	172	8.7	15.0	512	336
Kroměříž	798	53	260	659	180	2.9	197	8.6	14.9	619	409
Vyškov	888	50	287	646	188	2.5	166	8.5	14.8	546	351
Uh. Hradiště	989	42	264	722	165	2.1	192	8.6	14.7	651	402
Prostějov	770	51	327	697	192	2.2	195	8.7	14.4	580	371
Zlín	1032	24	319	700	175	5.0	196	8.3	14.4	726	449
Blansko	942	39	464	723	271	4.1	204	7.7	13.8	605	379
Třebíč	1516	56	477	687	290	2.7	151	7.7	13.8	562	355
Žďár n. Sáz.	1672	47	562	822	264	3.8	149	7.0	13.0	651	391
Jihlava	1178	52	573	753	427	3.4	147	7.0	12.9	641	386

Climatic factors diminishing overall yields were divided into two groups. First group includes factors principally occurring in winter months or winter half-year occasionally. These factors affect predominantly winter crops, such as winter wheat. In case of extreme conditions spring crops may also be negatively affected. There are two major risks during winter:

(1) unusually long duration of snow cover contributing to crop exhaustion and resistance decreasing;
(2) occurrence of severe frosts without satisfactory snow cover protecting crop stand from freezing (Petr, 1987).

Both risks can be quantified in reference to snowMAUS calculations and afterwards analysed in relation to yield datasets. SC – days factor represent the overall number of days when snow cover was simulated at each station. FR1 – FR4 factors project specific days with simulated occurrence of hard frosts (FR1 – number of days when daily T_{min} was lower than -10 degrees Celsius and snow cover concurrently lower than 2 mm of water equivalent, FR2 – number of days when daily T_{min} was lower than -15 degrees Celsius and snow cover concurrently lower than 2 mm of water equivalent, FR3 – number of days when daily T_{min} was lower than -20 degrees Celsius and snow cover concurrently lower than 2 mm of water equivalent, FR4 – number of days when daily T_{min} was lower than -5 degrees Celsius and snow cover concurrently lower than 2 mm of water equivalent).

Second group of factors includes those ones realizing in spring and early summer months (April, May, June) when both winter and spring crops are passing through most important phenological phases in connection with overall yields. From the list of potential risks long periods with high temperatures (heat waves) and long term lack of available water (droughts) are of furthest concern (e.g. Soja et al., 2005, Rajala et al., 2009). T_{max} sums factor is defined as a sum of daily T_{max} over various temperatures ranging from 22 to 28 degrees Celsius. Drought intensity was assessed through Palmer's drought severity index or PDSI (Palmer, 1965) using its self-calibrated version (Wells et al., 2004).

Simple regression analysis was applied to examine significance of individual factors. Considering complicated interactions among the factors and chain effects of multiple factors impacts multiple linear regression was also utilized in the study.

RESULTS - SPRING BARLEY

According to the results of low-yields analysis there are 10 situations with at least one district with very low yield category for spring from the period 1961–2007. Spatial variability appears to be high in most cases which supports hypothesis about different vulnerability to climatic factors among individual south-Moravian districts. This statement can be supported by the fact that districts with similar conditions) usually tend to have corresponding fluctuations in yields. But in contrast yields of 1981, 2000 and 2007 for spring barley were demonstrably lower in whole region which may probably indicate strong impact of the same climatic factor (or group of factors). Considering timescales of such extreme situations there is certain evidence towards higher occurrence of lowered yields in the second half of the 1961–2007 period (50 % of cases occurred after 1990).

Ten years with extremely or very low yields of spring barley in at least one district studied were analyzed more in detail (Table 2). As the most extreme was the year of 2000 (Fig. 5) in which extremely low yields occurred in seven districts (located in lowlands southwards from the city of Brno) and very low yields in four districts and mean yield was about 30% lower.

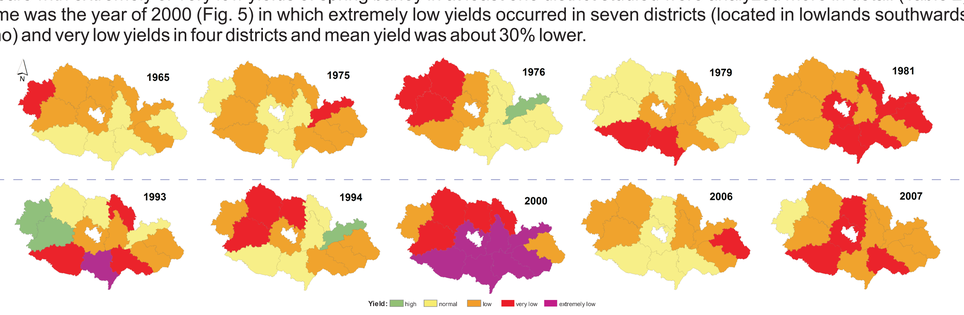

Fig. 4. Spatial variability of selected years with extremely/very low spring barley yields for individual Southern Moravian districts in the 1961–2007 period. Barley yields are classified in seven-degree scale according intervals given by mean and multiples of standard deviation.

Table 2. Low spring barley yields and its phenological aspects in Southern Moravia during 1961–2007; Δq – yield deviations for all 13 districts (mean), the lowest (min) and the highest (max) yields of particular districts; proportion of districts with various yields; phenophase responses (the reference period of 1961–2007): shifts in periods from tillering to flowering (I) and from flowering to full ripeness (III) from their mean duration, and in the beginning of flowering (II) and full ripeness (IV) – completed by highest and lowest deviations in the area (extreme deviations from the mean value are in brackets; positive values mean later onset of phenophases as well as longer interval between them, negative values oppositely)

Year	Δq				Districts in yield categories (%)			Phenophase responses (days)			
	mean(t/ha)	(%)	min (t/ha)	max (t/ha)	Ex. L.	Very Low	Low	I	II	III	IV
1965	-0.35	87.2	-0.76	-0.13	0	8	54	1 (17;-13)	7 (20;1)	2(11;-9)	8 (13;3)
1975	-0.35	91.2	-0.87	0.20	0	8	62	3 (14;0)	-2 (3;-7)	0 (4;-9)	-3 (2;-7)
1976	-0.32	92.3	-0.91	0.52	0	23	23	2 (30;-6)	-1 (10;-7)	-1 (2;-11)	-3 (0;-5)
1979	-0.41	90.6	-1.09	0.07	0	15	38	2 (9;-6)	3 (15;-5)	4 (16;-6)	6 (14;-1)
1981	-0.65	85.7	-0.97	-0.31	0	46	54	-3 (2;-12)	-4 (2;-10)	0 (13;-10)	-5 (3;-12)
1993	-0.45	90.1	-1.53	0.39	8	23	31	-6 (4;-15)	-1 (5;-8)	1 (14;-10)	-1 (6;-11)
1994	-0.37	91.8	-1.01	0.49	0	23	38	0 (9;-14)	0 (11;-9)	-4 (5;-15)	-6 (0;-9)
2000	-1.24	69.9	-1.95	-0.61	54	31	15	-5 (-1;-12)	-4 (-2;-9)	1 (9;-5)	-4 (7;-10)
2006	-0.36	91.3	-0.81	0.24	0	8	54	-1 (9;-6)	11 (18;-1)	-8 (-3;-15)	2 (7;-12)
2007	-0.61	85.5	-1.08	-0.16	0	31	62	-2 (11;-10)	-7 (0;-17)	-2 (4;-13)	-10 (0;-18)

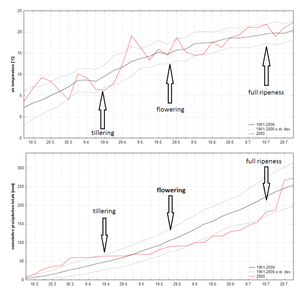

Fig. 5. Five-days mean daily air temperatures (above) and cumulated five-days precipitation totals during March–July at the Lednice station in 2000 compared to the 1961–2006 mean (levels of mean ± standard deviation are expressed). Beginnings of phenophases are highlighted by arrows.

RESULTS - WINTER WHEAT

As for spring barley also for winter wheat ten situations with extremely or very low yields were realized (Fig. 6). Yields of 1979, 1986 and 2003 were demonstrably lower in whole region which may probably indicate strong impact of the same climatic factor (or group of factors). Extraordinary low yields of 1979 involved whole region with focal spot southwesterly from Brno. Mean yield reached only 75 % of long term mean (Table 3) but without considering resown areas that have usually not been a part of statistic evaluation. Moreover rate of extremity of 1979 yields can also be supported by the fact this is the last time when all districts belonged entirely to categories of very low or extremely low yields.

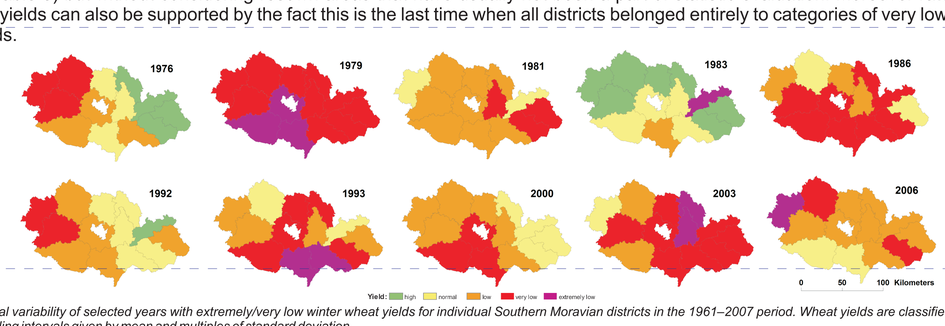

Fig. 6. Spatial variability of selected years with extremely/very low winter wheat yields for individual Southern Moravian districts in the 1961–2007 period. Wheat yields are classified in seven-degree scale according intervals given by mean and multiples of standard deviation.

There is worth mentioning that for the lowest yields in major part of districts not solely negative winter or April–June conditions can lead to most extreme events (Table 4). Consecution of at least two groups of factors constitutes typical and most significant causes of extraordinary low yields. These merits fully correspond to 1979, 1993 and 2003 yields when combination of severe winter hard frosts and April–June high temperatures and low precipitation occurred. Those districts situated in highlands (Jihlava, Žďár nad Sázavou) were affected less significantly when comparing with 2006 yields that were influenced predominantly by long duration of winter conditions remaining till the beginning of April. Under permanent snow cover crop suffered a lot and considerable part of winter wheat did not over winter. Somehow analogous situation arose in 1986 when low yields were preponderantly concentrated in lowlands where abnormally wet winter with long duration of snow cover was recorded. Solitary inappropriate April–June conditions (1981, 2000) tended to became evident less pronounced than on the example of spring barley. Similarly same districts (Brno-venkov, Břeclav and Znojmo) belonged to categories with lowest yields even though the rate of extremity remained one order lower.

Table 3. Low winter wheat yields in Southern Moravia during 1961–2007; Δq – yield deviations for all 13 districts (mean), the lowest (min) and the highest (max) yields of particular districts; proportion of districts with various yields

Year	Δq				Districts in yield categories (%)		
	mean (t/ha)	(%)	min (t/ha)	max (t/ha)	Ex. Low	Very Low	Low
1976	-0,19	95,4	-1,02	0,77	0	23	23
1979	-1,14	75,5	-2,09	-0,67	23	77	0
1981	-0,54	89	-1,22	-0,1	0	23	62
1983	0,11	102,2	-1,35	0,69	8	0	8
1986	-0,69	86,8	-1,15	-0,05	0	62	23
1992	-0,25	95,1	-0,89	0,37	0	15	38
1993	-0,74	85,5	-1,78	0,13	15	38	31
2000	-0,5	89,6	-1,17	0,14	0	23	46
2003	-0,85	82,4	-1,38	0	15	62	15
2006	-0,54	89,7	-1,26	-0,2	8	15	62

Table 4. Standardized regression parameters of selected climatic factors affecting winter wheat yields in individual south-Moravian districts during 1961–2007; statistically significant parameters are highlighted (p = 0,05, p = 0,01)

District	AMJ factors									winter factors			
	T_{max} sums						monthly PDSI						
	≥ 22	≥ 23	≥ 24	≥ 25	≥ 26	≥ 27	April	May	June	SC - days	FR1	FR2	FR3
BK	-	-	-	**0,51**	-	-	-	-	0,16	0,18	-	0,16	-
BO	-	-	**0,57**	-	-	-	0,11	-	-	0,22	0,23	-	-
BV	**0,62**	-	-	-	-	-	-	-	0,09	0,08	-	*0,31*	-
HO	-	**0,62**	-	-	-	-	0,09	-	-	0,19	*0,24*	-	-
JI	-	-	*0,29*	-	-	-	-	-	0,03	**0,42**	-	0,14	-
KM	-	-	-	-	**0,40**	-	-	*0,28*	-	0,02	-	-	0,22
PV	-	-	-	**0,42**	-	-	0,14	-	-	0,17	-	0,24	-
TR	**0,60**	-	-	-	-	-	0,15	-	-	0,10	-	*0,30*	-
UH	-	-	-	-	-	**0,42**	-	-	*0,28*	*0,30*	-	0,15	-
VY	**0,54**	-	-	-	-	-	0,17	-	-	0,24	-	0,17	-
ZL	-	-	-	-	**0,51**	-	*0,34*	-	-	0,01	-	0,13	-
ZN	**0,58**	-	-	-	-	-	-	-	0,17	0,06	-	**0,33**	-
ZS	-	**0,47**	-	-	-	-	0,14	-	-	**0,47**	-	0,01	-

CONCLUSIONS

Climate-crop relationship documented on the example of spring barley and winter wheat is complicated by its time and spatial variability. Several events of extremely low yields in the region of southern Moravia during 1961–2012 improved our understanding of the most important climatic factors realizing by means of phenophase anomalies. There has been recorded increase in inter-annual yield variability particularly since 1980s. Higher occurrence of negative climatic factors and its elevated intensity serve as dominating argument of this change. The strongest yield penalties can be attributed to accelerated or insufficient crop development caused by abnormally high temperatures and droughts actuating during April-June (AMJ) period (2000, 2003, and 2007). Winter wheat is much more resistant towards negative AMJ conditions than spring barley (90% of long-term mean yield for winter wheat in 2000, 70% for spring barley respectively). The AMJ season of 2000 belongs to the warmest and driest in southern Moravia of the past 200 years. Winter wheat yields are subjected also to winter conditions and in the case of accumulation of negative winter and AMJ climatic factors (chain effect), overall yield can significantly decrease (e.g. in 1979, 2003).

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ACKNOLEDGEMENTS

This poster is supported by the Operational Programme of Education for Competitiveness of Ministry of Education, Youth and Sports of the Czech Republic (Project: Building up a multidisciplinary scientific team focused on drought, No. CZ.1.07/2.3.00/20.0248).This poster is an output of the Global Change Research Centre AS CR, that is being developed within OP RDI and co-financed from EU funds and state budget of the Czech Republic (Project: CzechGlobe - Centre for Global Climate Change Impact Studies, Reg.No. CZ.1.05/1.1.00/02.0073.

INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ