available at www.sciencedirect.com
ScienceDirect
journal homepage: www.elsevier.com/locate/agrformet

Effect of drought on yield variability of key crops in Czech Republic

Petr Hlavinka[a,*], *Miroslav Trnka*[a], *Daniela Semerádová*[a], *Martin Dubrovský*[a,b], *Zdeněk Žalud*[a], *Martin Možný*[c]

[a] *Institute of Agrosystems and Bioclimatology, Mendel University of Agriculture and Forestry Brno, Zemědělská 1, 613 00 Brno, Czech Republic*
[b] *Institute of Atmospheric Physics, Academy of Sciences CR, Boční II/1401, 14131 Prague, Czech Republic*
[c] *Agrometeorological Observatory in Doksany, Czech Hydrometeorological Institute, 411 82 Doksany, Czech Republic*

ARTICLE INFO

Article history:
Received 1 April 2008
Received in revised form
14 September 2008
Accepted 19 September 2008

Keywords:
Palmer Z-index
Soil water holding capacity

ABSTRACT

The relationship between seasonal agricultural drought and detrended yields (within a period from 1961 to 2000) of selected crops was assessed in the conditions of the Czech Republic, which are to some extent representative of a wider area of Central Europe. Impact of water stress was analyzed using time series of yields for 8 crops (spring barley, winter wheat, grain maize, potato, winter rape, oats, winter rye and hay from permanent meadows) for 77 districts in the Czech Republic (average district area is 1025 km^2). Relative version of Palmer's Z-index (rZ-index or rZ-i) was used as a tool for quantification of agricultural drought. The monthly values of the rZ-index for each individual district were calculated as the spatial average (only for the grids of arable land). The study showed that severe droughts (e.g., in 1981 and 2000) are linked with significant reduction in yields of the main cereals and majority of other crops through the most drought prone regions. We found a statistically significant correlation ($p \leq 0.05$) between the sum of the rZ-index for the main growing period of each crop and the yield departures of spring barley within 81% (winter wheat in 57%, maize in 48%, potato in 89%, oats in 79%, winter rye in 52%, rape in 39%, hay in 79%) of the analyzed districts. This study also defined the crop-specific thresholds under which a soil moisture deficit (expressed in terms of rZ-index) leads to severe impact at the district level. This can be expressed as the sum of the monthly rZ-index during the period of high crop sensitivity to drought; for spring barley it is −5, winter wheat −5, maize −9, rape −12, winter rye −10, oat −4, potato −6 and for hay −3. The length of the sensitive period is also crop-specific and includes the months that are important for the yield formation. The results show that yields of spring barley (and spring crops in general) are significantly more affected by seasonal water stress than yields of winter crops and hay from permanent meadows. The study proved that a severe drought spell during the sensitive period of vegetative season does have a quantifiable negative effect, even within more humid regions. These results demonstrate that, at least in some areas of the CR (and probably most of Central Europe), drought is one of the key causes of interannual yield variability.

* *Corresponding author*. Tel.: +420 545 133 090; fax: +420 545 133 083.
E-mail addresses: phlavinka@centrum.cz (P. Hlavinka), mirek_trnka@yahoo.com (M. Trnka), dany357@yahoo.com (D. Semerádová), dub@ufa.cas.cz (M. Dubrovský), zalud@mendelu.cz (Z. Žalud), martin.mozny@chmi.cz (M. Možný).
0168-1923/$ – see front matter
doi:10.1016/j.agrformet.2008.09.004

1. Introduction

Water deficit during drought spells is one of the most significant stress factors in crop production worldwide (e.g., Sivakumar et al., 2005; Narasimhan and Srinivasan, 2005; Lobell and Field, 2007). It can lead to significant yield reduction or even crop failure. Beside the negative effects of water stress on the yield quantity, the quality can also be influenced (e.g., Jensen et al., 1996; Ozturk and Aydin, 2004). Even though the Czech Republic is not generally characterized as a drought prone region of Europe, drought (and flooding) still occurs (Brázdil et al., 2005, 2007) and is one of the most important climatic extremes in terms of economic damage. This is demonstrated by the examples of severe droughts recorded in 1935, 1976 and especially in 1947 (Možný, 2004). Within recent years, this region of Central Europe experienced droughts in 2000, 2001 and 2003, with the first of these being particularly damaging. Detailed climatological analysis of the past drought events can be found in a number of contemporary studies (e.g., Blinka, 2005; Dubrovský et al., 2006; Trnka et al., 2008 or Brázdil et al., 2008).

Despite the often catastrophic impact of drought, there is no simple and generally valid definition of this phenomenon. This paradox is mainly due to the complexity of the phenomenon and its spatial specificity. In contrast to most other stress factors, the impact of drought on crops creeps in relatively slowly (Svoboda et al., 2002) and quite often increases in intensity with longer duration. According to dominant impacts and timescales, we predominantly distinguish four types of drought: meteorological, agricultural, hydrological and socio-economic (e.g., Heim, 2002). This study is focused mainly on agricultural drought that could be defined as a situation where the soil moisture of a region is consistently below the climatically appropriate moisture supply required for crop production (Palmer, 1965 or Quiring and Papakryiakou, 2003) for one or more months in a row. According to Earl and Davis (2003), drought stress reduces the yield of grain crops through three main mechanisms: (i) reducing canopy absorption of incident photosynthetically active radiation (PAR) (e.g., by limitation of leaf area expansion, leaf rolling or early leaf senescence), (ii) reducing radiation use efficiency, and (iii) reducing harvest index (i.e., the fraction of crop dry matter allocated to the grain).

The main objective of this study was to find whether an occurrence of seasonal agricultural drought has any quantifiable influence on the production of 8 selected crops grown in the Czech Republic. As an indicator of soil moisture anomaly, we selected the Palmer's relative Z-index (rZ-index or rZ-i) introduced by Dubrovský et al. (2008). It is based on the modified version of the self-calibrated Palmer's Z-index as defined by Wells et al. (2004). We also compared vulnerability of crops and tried to determine a susceptible period (to the water stress occurrence) within the growing season of individual crops.

2. Materials and methods

2.1. Weather data

The study used a climatological dataset consisting primarily of mean air temperature and precipitation data recorded during the period 1961–2000 at the 233 Czech Republic stations. The same set of stations was also used in the atlas of the climate of Czechia (Tolasz et al., 2007). The database arose as a result of co-operation between the Czech Hydrometeorological Institute and the National Climatic Program of the Czech Republic. The spatial density equals one station per 335 km^2 on average, while the stations were located within a range of 157–1490 m a.s.l. with the mean altitude of the stations being 435 m a.s.l. (mean country altitude is 430 m). Mean annual temperature and sum of precipitation are almost identical to the mean climatological values for the Czech Republic (i.e., 7.5 °C and 674 mm). The data were homogenized and checked for consistency prior to use. The average precipitation and air temperature during the main growing season (April–September) in the analyzed districts (average district area is 1025 km^2) are listed in Table 1. Presented values are spatial means derived only for arable land.

2.2. Soil data

The study required prior knowledge about the spatial distribution of soil properties within the region of interest in order to determine the ‘‘maximum soil water holding capacity’’ (MSWHC) in the rooting zone. This parameter was estimated using a combination of digitized maps of soil types (Tomášek, 2000) and detailed data about soil physics from 1073 soil pits compiled during the Czech National Soil Survey. For each of the 25 soil types of the basic soil classification used by Tomášek (2000), the mean value of MSWHC was defined as the average of the maximum water holding capacities of all soil pits of specific soil type from the database. The MSWHC of all soil types was determined as a weighted value from soil water holding capacities of considered soil horizons (up to maximum rooting depths). Spatial distribution of MSWHC and the range of values are presented in Fig. 1.

2.3. Crop data

The study applied the newly acquired and homogenized database of annual mean district yields of spring barley (*Hordeum vulgare conv. Distichon var. nici*), winter wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), rape (*Brassica napus* L. *arvensis Lam.*), oats (*Avena sativa* L.), winter rye (*Secale cereale* L.), potato (*Lycopersicon tuberosum* L.) and hay from permanent grasslands and meadows. Each of these crops is rain-fed throughout the whole country. These crops were selected because they represent key crops in the Czech Republic's plant production in terms of acreage and volume. The planting area of each crop is presented in Fig. 2 with regard to the entire extent of total agricultural area, which is about 4.3 million ha (3.3 million ha of arable land included) in the Czech Republic. There was a noticeable increase of winter wheat production area after 1960 and its extent more than doubled within 15 years. On the contrary winter rye, oat and potato planting acreage decreased continuously during the whole period. Fig. 2 also reveals apparent growing interest in oil seed rape production after 1990. Area of hay production was decreasing, with a clear comeback during the 1990s. Total area occupied by 8 selected crops remained stable at about 2.5 million ha. Seven of these

Table 1 – Overview of the 77 Czech Republic districts with average air temperature and precipitation during the vegetative season (April–September). Mean maximum soil water holding capacity (MSWHC) is also listed. All average values (including air temperature and precipitation) are related only to arable lands.

District	Abbreviation	T (°C)	Precipitation (mm)	MSWHC (mm)	District	Abbreviation	T (°C)	Precipitation (mm)	MSWHC (mm)
Břeclav	BV	15.8	314.8	171.2	Plzeň-město	PM	13.7	348.2	190.6
Nymburk	NB	15.2	356.0	161.4	Šumperk	SU	13.8	409.2	184.8
Mělník	ME	15.0	332.8	172.3	Beroun	BE	14.1	364.7	205.8
Hodonín	HO	15.4	343.2	177.9	Děčín	DC	14.1	392.0	153.5
Litoměřice	LT	14.5	315.1	163.2	Vsetín	VS	14.0	494.0	209.7
Pardubice	PA	14.5	377.4	181.5	Náchod	NA	13.4	415.4	166.3
Karviná	KI	14.6	508.3	218.1	Chrudim	CR	13.8	438.4	139.9
Ostrava-město	OV	14.5	482.9	235.3	Ústí nad Orlicí	UO	13.6	438.3	147.8
Hradec Králové	HK	14.6	358.6	181.7	Rakovník	RA	14.0	340.1	155.4
Brno-město	BM	15.3	325.1	172.1	Trutnov	TU	13.2	417.2	225.3
Mladá Boleslav	MB	14.8	360.8	161.4	Bruntál	BR	13.3	456.4	206.5
Kroměříž	KM	15.0	398.0	197.8	Rokycany	RO	13.5	371.4	205.5
Uherské Hradiště	UH	14.9	389.3	180.4	Plzeň-jih	PJ	13.6	368.1	178.3
Most	MO	14.5	300.6	144.0	Benešov	BN	13.6	415.8	110.1
Kolín	KO	14.8	373.8	166.3	Plzeň-sever	PS	13.5	333.5	156.0
Olomouc	OC	14.5	382.3	204.5	Domažlice	DO	13.6	392.3	123.5
Přerov	PR	14.7	416.7	195.0	Semily	SE	13.0	431.1	200.1
Brno-venkov	BI	15.1	327.2	172.4	Písek	PI	13.7	368.9	114.4
Znojmo	ZN	15.1	317.5	158.5	Příbram	PB	13.7	373.6	126.4
Praha-východ	PY	14.8	373.1	162.4	České Budějovice	CB	13.7	418.2	149.3
Praha	PH	14.9	358.5	169.4	Blansko	BK	13.8	386.8	191.5
Vyškov	VY	15.1	345.0	166.0	Svitavy	SY	13.4	421.9	139.4
Louny	LN	14.4	311.7	163.4	Strakonice	ST	13.6	386.6	124.4
Teplice	TP	13.9	318.7	154.3	Třebíč	TR	13.8	356.3	112.7
Jičín	JC	14.3	367.9	206.8	Tábor	TA	13.5	392.3	113.9
Kladno	KD	14.4	335.4	187.9	Klatovy	KT	13.4	422.6	131.4
Chomutov	CV	14.3	300.9	157.5	Havlíčkův Brod	HB	13.5	433.2	101.7
Zlín	ZL	14.6	442.5	165.6	Sokolov	SO	12.6	390.4	125.4
Ústí nad Labem	UL	14.4	338.1	159.6	Cheb	CH	12.6	376.8	143.4
Česká Lípa	CL	14.0	372.8	180.6	Jablonec nad Nisou	JN	12.7	478.4	203.0
Nový Jičín	NJ	14.2	478.5	243.5	Tachov	TC	12.8	362.4	131.4
Prostějov	PV	14.5	371.0	196.3	Jindřichův Hradec	JH	13.4	416.1	111.6
Jeseník	JE	13.5	519.1	124.7	Prachatice	PT	13.2	433.5	130.6
Frýdek-Místek	FM	13.9	579.9	233.7	Žďár nad Sázavou	ZR	13.1	398.7	111.2
Opava	OP	14.2	429.7	243.0	Pelhřimov	PE	13.0	432.1	104.3
Praha-západ	PZ	14.5	359.7	187.2	Jihlava	JI	13.0	397.6	114.6
Liberec	LI	13.4	455.9	179.2	Karlovy Vary	KV	12.8	351.1	142.4
Kutná Hora	KH	14.4	386.3	160.1	Český Krumlov	CK	13.0	447.7	121.9
Rychnov nad Kn.	RK	13.7	434.4	133.7					

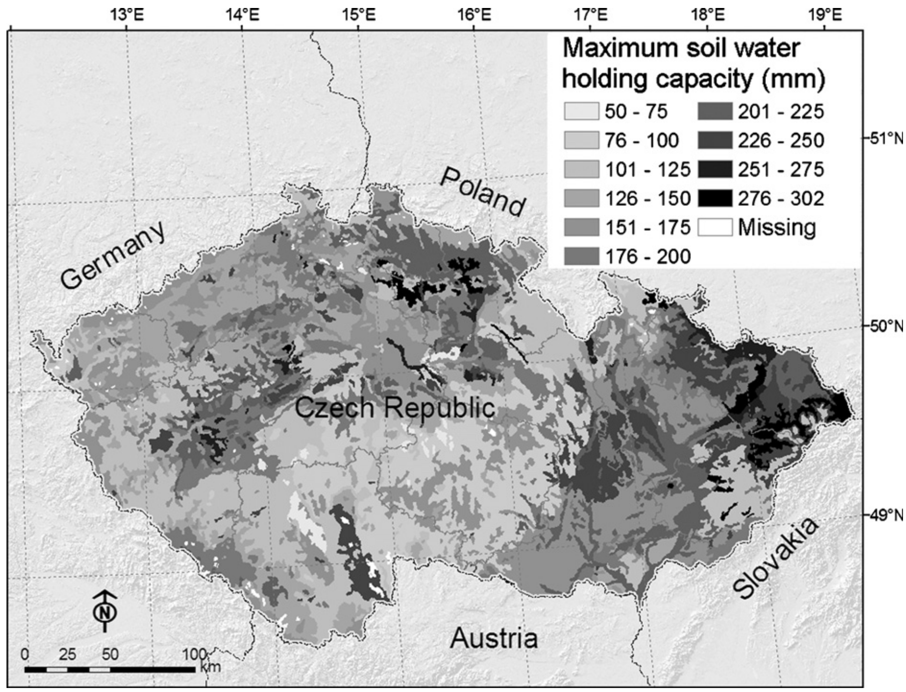

Fig. 1 – The maximum soil water holding capacity (MSWHC) (in millimeters) across the Czech Republic as it was used for calculation of rZ-index.

crops (without hay) occupied approximately 59% of arable land in the Czech Republic. During this period, the investigated crops were also significantly represented within the agriculture of a wider region of Central European territory. For example, a set of seven field crops (area of hay is not considered) covered 69% of arable land in Germany (on the average) and 67% in Poland during 1961–2000 (FAO, 2008).

The database used in the study was provided by the Czech Statistical Office (CSO) and included information from all 77 districts collected over the period from 1961 to 2000 (Table 1). Yields were analyzed separately for each crop. During the first step, districts with a sowing area less than 0.5% of the total national acreage (of the given crop) in more than 2/3 of years were excluded from further analysis. In this way, districts of minor importance for the production of a given crop where uneven distribution of the crop over the arable land was more likely were not considered in further analysis.

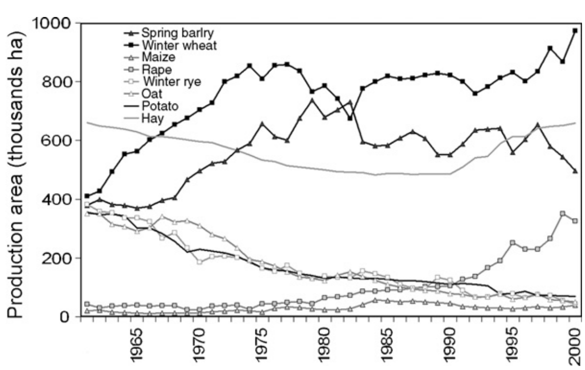

Fig. 2 – Production area of selected crops within the Czech Republic during the period 1961–2000.

The continual innovation of agricultural technology and introduction of new cultivars combined with dynamical changes in fertilization resulted in a prominent trend that dominates the long-term variability of the yield data series (Chloupek et al., 2004). In order to account for the existence of the trend, the original yield data was detrended separately in each district. It was conducted using the procedure proposed by Quiring and Papakryiakou (2003) or Trnka et al. (2007), who excluded the yields in the two driest and the two wettest vegetative seasons (according to rZ-i) (Fig. 3) in order to decrease influence of exceptional years (from soil moisture point of view) within trend calculation. In the next step the derived function was applied for detrending of the whole time series. Positive trends in annual yield up to 1990 could mostly be explained by increasing fertilization, plant breeding and farm innovation (Chloupek et al., 2004). The apparent yield decline within 1990s was a direct consequence of socio-economic transformation of the farming industry in the Czech Republic after 1989, and possibly also due to recent temperature increases as suggested by Lobell and Field (2007). During this period large-scale changes in the composition of the farming community were combined with efforts to decrease overall production intensity (e.g., lower fertilization and plant protection). The applied method of detrending using second order polynomials effectively captures the long-term component of the crop yield fluctuation. The outputs of the process are values of residuals (hereafter introduced as yield departures) that describe interannual yield variability over a 40-year period in the given district.

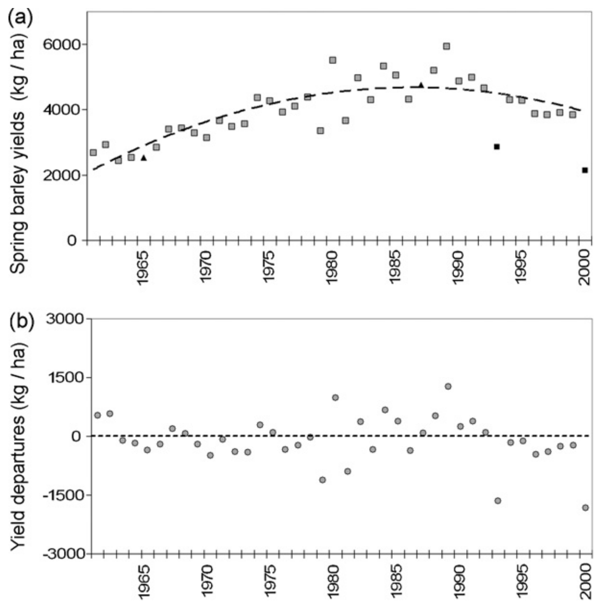

Fig. 3 – Average spring barley yields (kg/ha) for Břeclav district (BV) during 1961–2000 depicted by squares and triangles (a). For trend construction 36 years were used (without the yields in the two wettest and the two driest vegetative periods—depicted by black triangles and squares respectively). The trend is represented by dotted curve (r = 0.83). The detrended yield departures (spring barley for the same district) used for further analyses are represented by the grey circles (b).

2.4. *Definition and determination of drought condition*

Drought is a multifaceted natural disaster that leads to serious socio-economic impacts that have long-term implications (Das, 2005), and thus the present study focused only on the agricultural impacts of drought. Based on the results of previous studies (e.g., Quiring and Papakryiakou, 2003; Trnka et al., 2007) the variety of Palmer's Z-index (Palmer, 1965; van der Schrier et al., 2006) was selected as a tool that could describe agricultural drought. This parameter has been widely used within various regions of the world (e.g., Alley, 1984; Karl, 1986) and for depiction of drought climatology within the Czech Republic territory as well (e.g., Tolasz et al., 2007). The Z-index is derived from the soil moisture/water balance algorithm that requires a time series of monthly air temperature and precipitation. Information about parameter MSWHC is also necessary. The soil profile is divided into two layers with the top layer being set at the retention capacity of 25 mm. Soil water is not transferred to the second layer until the saturation of upper one. Runoff occurs when both layers are saturated. For estimation of the potential evapotranspiration (PE) the method of Thornthwaite (1948) was used, and water loss from soil by this method was assumed when PE > P (where P is monthly precipitation sum). The Z-index is an instrument for the description of the soil monthly moisture anomaly and reflects the departure of moisture conditions in a particular month from climatological optimum (CO or climatically appropriate) (Heim, 2002). The CO is derived for each locality based on at least a 30-year time series, and the Z-index is a weighted difference between expected CO and actual soil moisture in the given month. In this study, the so-called relative version of the Z-index (rZ-index or rZ-i) proposed by Dubrovský et al. (2008) was applied. It is designed for comparison of drought conditions between locations or at the same sites between different periods. The reference data series that were used for the determination of regional CO in this particular case were created by aggregating data from the whole set of 233 stations, which comprised 9320 years of data. The value of the relative Z-index was consequently calculated for all months (480 months) at each station. Because the drought impacts were assessed on the district level, at first the rZ-index was interpolated for the whole territory of the Czech Republic using a co-krigging interpolation technique (with altitude and MSWHC as additional co-variables). Then the monthly value of the rZ-index for each district (but only for the grids with arable land) was calculated as the spatial average. The data regarding extension of arable land were obtained from the Corine land cover 2000 (EEA, 2005) and assumed fixed during 1961–2000. The spatial distribution of drought conditions through the analyzed region was depicted in detail by Tolasz et al. (2007), who focused also on the changes in the rZ-index during the growing time (April–September) within the same period as in the present study (1961–2000).

2.5. *Evaluation of drought impact on yields*

The relationship between agricultural drought and detrended yields of selected crops was assessed with the time series of soil moisture anomalies (rZ-index) being the independent variable and the series of yield residuals being the dependent variable. There was no lag autocorrelation in either data series. Firstly, we investigated the period of the highest crop sensitivity to drought (PCSD) during the vegetative period of each crop. We tested all combinations of individual months as well as longer periods with the aim of finding the best period(s) during growing season when the rZ-index could explain most of the variability in yield reduction through all the analyzed districts together within 1961–2000. The similar approach as it was presented by Lobell and Field (2007) was used. The parameter for assessment of the relationship between the rZ-index and district yields during potential PCSD was the coefficient of determination. In the next step, the degree of correlation between soil moisture deviation represented by the rZ-index during PCSD and yields was calculated for each district for the period 1961–2000. Assessed districts were divided into four bins including districts where no statistically significant relationship between the rZ-index and yield departures of the given crop was found (the criterion was $p \leq 05$), and those with a statistically significant relationship using progressively $p \leq 0.05$, $p \leq 0.01$ and $p \leq 0.01$ with coefficient of correlation higher than 0.5. Using this method, the districts susceptible to drought during 1961–2000 were determined.

3. Results and discussion

3.1. *Period of the highest crop sensitivity to drought*

As is evident in Fig. 4, the PCSD differs between crops as a consequence of different water stress sensitivities during

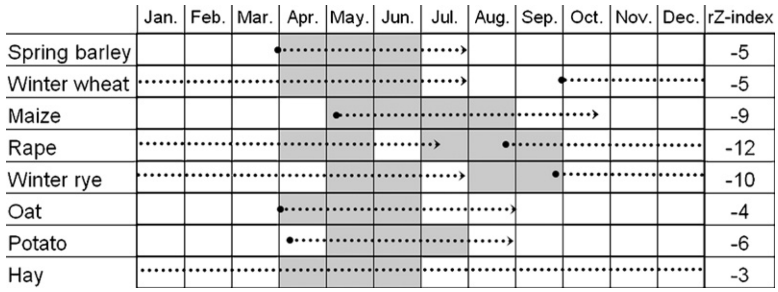

Fig. 4 – Periods of crop sensitivity to drought (PCSD) within the vegetative period of 8 selected crops (marked as shaded area). Approximate sowing date of crops within the Czech Republic is depicted by bold dots, duration of growth shown by dotted lines and harvest by arrows. In case of hay production the highest production is achieved in the first half of vegetative season in the period of 1st cut (usually mid June–early July). The values of rZ-index are thresholds when yield departures dropped under district average.

various growth stages for the investigated plants (e.g., Otegui et al., 1995; Chmielewski and Köhn, 2000; Ozturk and Aydin, 2004) with diverse vegetative periods. The results show that a majority of the investigated crops were susceptible to drought within the April–June period, which is crucial for yield quantity. The remaining crops were sensitive during other periods, which is a consequence of their different period of vegetative growth and their physiological character (e.g., maize with PCSD May–August). Rape and winter rye (winter crops) also demonstrated sensitivity to water stress within months before and during emergence in autumn. On the other side, when the PCSD of winter wheat included also autumn months it did not improve the explained variability of yield departures. This phenomenon is also due to later sowing (mainly compared to rape) with emergence during wetter and colder months.

3.2. *Relationship between the rZ-index and yield departures within districts*

Our investigation showed that the rZ-index (sum per PCSD) played a statistically significant role (assuming $p = 0.05$) in the case of spring barley yields for 81% of the analyzed districts (winter wheat in 57%, maize in 48%, potato in 89%, oats in 79%, winter rye in 52%, rape in 39%, hay in 79%) during 1961–2000. The example of results for drought impact on spring barley and winter wheat yield departures within particular districts are graphically summarized in Fig. 5a and b, while spatial pattern is influenced mostly by the combination of climate and soil conditions. This interpretation is focused on the influence of drought on yields from separate districts.

The remaining variability of yield departures that was still unexplained by the rZ-index was likely caused by a combination of factors that are beyond the scope of the rZ-index. Among these include the effect of nutrient availability, pests and diseases, moistures stress out of PCSD, and other climatic variables or extreme events such as hail, intensive rainfall combined with windstorms leading to crop lodging, frost damage and summer floods (Sivakumar et al., 2005; Brázdil et al., 2007).

The consequences of drought episodes of various intensities on the average yield departures within all analyzed districts and years are depicted in Fig. 6a–h. This analysis showed that the sum of the rZ-index (April–June) when below −10 (severe drought) caused a spring barley yield departure of about −1500 kg/ha (Fig. 6a). If the rZ-index for the same period was in the interval −9 to −8 (more frequent) the average yield departure was around 500 kg/ha and the negative influence of dry conditions was apparent when the rZ-index dropped below −5. Drought had a practically identical impact on reducing the average oat (spring crop with the same PCSD) yield (Fig. 6f). Fig. 6g indicates that potatoes (PCSD May–July) were also drought sensitive when the rZ-index threshold was −6, and for the rZ-index lower than −10 the average yield was reduced from the mean district harvest by about 3000 kg/ha on the average (there were 28 years with the rZ-index less than −10). Schittenhelm et al. (2006) investigated drought resistance of potato cultivars (near Braunschweig, Germany) and revealed that during the year 2003 (severe and persistent drought), tuber dry weight decreased by 49–67% (according to cultivar). The average maize yield reduction as a result of water deficit during PCSD was not as substantial (Fig. 6c); for example, when the rZ-index was below −12, average departure was slightly more than −500 kg/ha. The relatively low sensitivity of maize to drought in comparison with other spring crops is most likely a consequence of the different physiological make up of this C4 plant (Polley, 2002; Nayyar and Gupta, 2006) with higher water use efficiency (WUE) (Larcher, 2003) and longer vegetative period compared to most other spring crops. The consequences of a dry PCSD (also April–June) on winter wheat average yield was about −800 kg/ha for an rZ-index lower than −10, and more than −400 kg/ha for an rZ-index from −9 to −8. The negative influence of a soil moisture anomaly was still observed when the rZ-index dropped below −5. Winter rape (PCSD July–September and April–May) was affected by drought occurrence before sowing, at the beginning of vegetative period and also during the spring months April and May. When the sum of the rZ-index for PCSD dropped below −15, the departure from average yield was about −550 kg/ha and a negative influence is apparent from threshold of rZ-i −12 and below. This is consistent with the findings of Jensen et al. (1996) who showed a 17% decrease (against irrigated variant) of seed yield on sandy soil as a consequence of soil drying (caused by higher evaporation

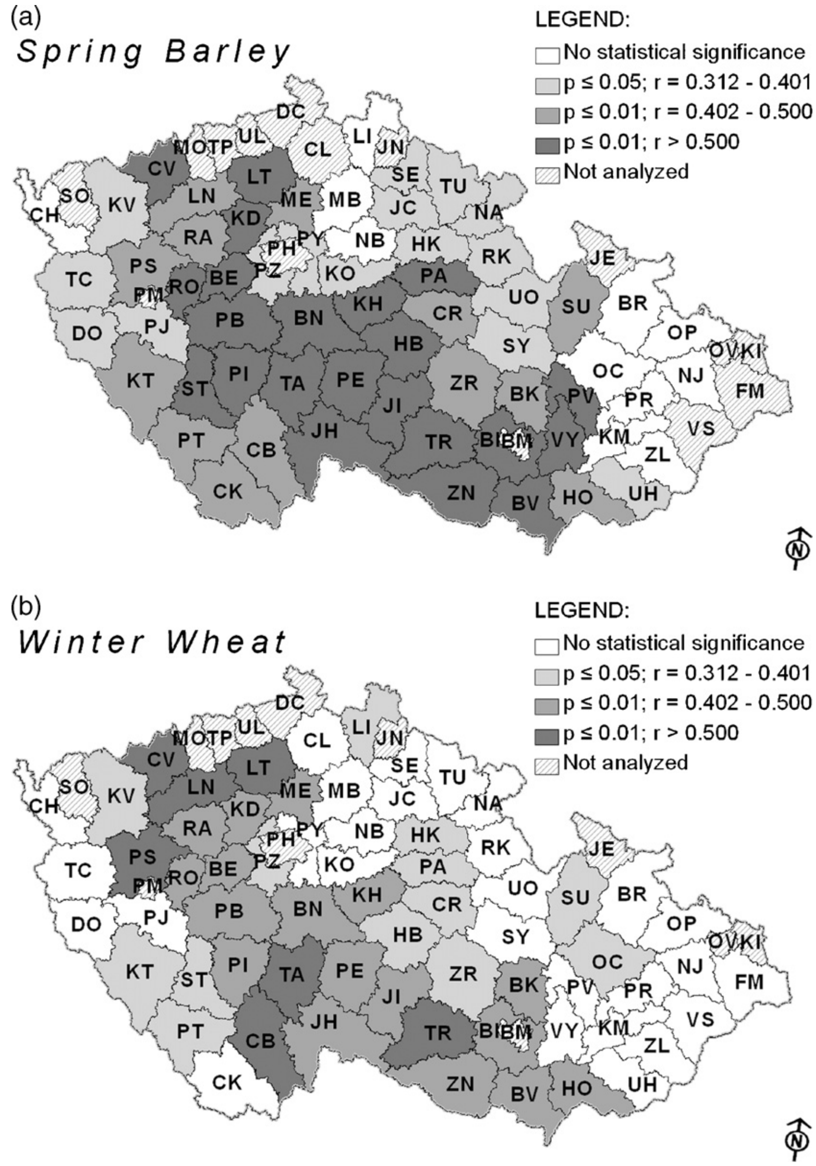

Fig. 5 – Maps represent a spatial distribution of districts in which relationship between course of rZ-index (sum per PCSD) and yields departure of spring barley (a) and winter wheat (b) is statistically significant during the period 1961–2000. Statistical significance assessed by the coefficient of correlation (*r*) increases with the tone of grey. The white color represents districts without statistically significant influence of seasonal drought variability within yields during 1961–2000. The hatched districts were excluded from analysis due to negligible planting area of analyzed crops. For the abbreviations of the districts see Table 1.

demand) within the pod filling stage of rape (spring variant). The yield of winter rye is only slightly negatively influenced during a severe drought spell within PCSD (Fig. 6e) This result for winter rye is a consequence of a relatively large proportion of roots as compared to wheat (Sheng and Hunt, 1991), and a weaker influence of weather on the yield formation of this crop than for spring cereals (Chmielewski and Köhn, 2000). In this study, drought susceptibility was also identified within hay harvests (PCSD April–June) even though hay is a perennial crop. The main cause of the high drought susceptibility of grassland production was usually a shallow rooting zone and inferior soil quality used for hay production. Notable negative implications followed when the rZ-i dropped below −3 (for rZ-i lower than −9, average yield departure was almost −900 kg/ha). For better evaluation the achieved results could be compared with average district yield during the investigated period when for spring barley it was 3410 kg/ha, for winter wheat 3780 kg/ha, for maize 4180 kg/ha, for rape 2160 kg/ha, for winter rye 3060 kg/ha, for oat 2910 kg/ha, for potato 16,880 kg/ha and for hay 3690 kg/ha.

The thresholds for the detrimental impact of drought defined by the rZ-index are also interesting in conjunction with changing variability of drought within the past, present and future climate. Before any conclusions for the expected

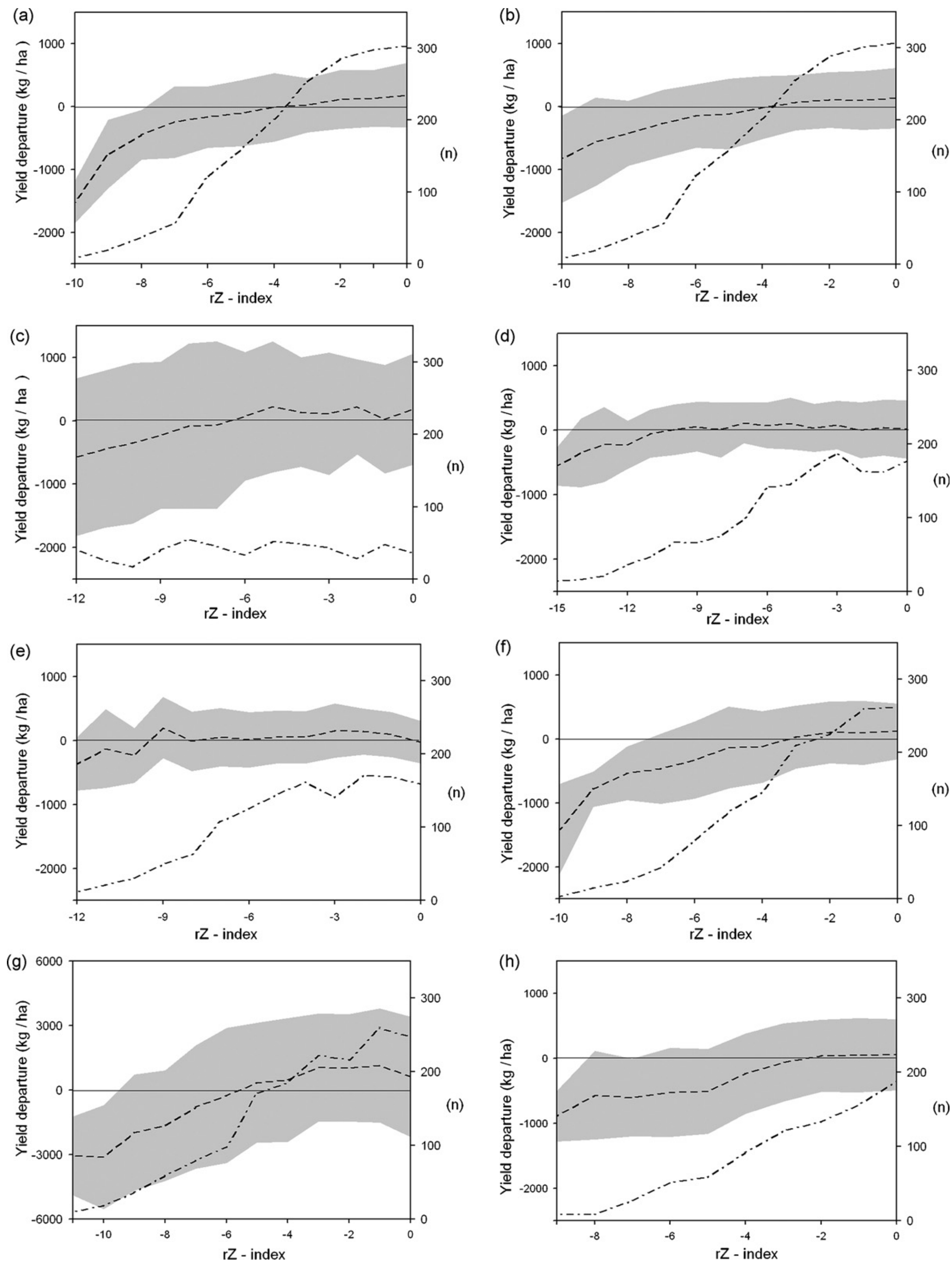

Fig. 6 – Average yield departures of spring barley (a), winter wheat (b), maize (c), rape (d), winter rye (e), oat (f), potato (g) and hay (h) within all analyzed districts for defined drought severity are depicted by broken line. Standard deviation (± from the average yield departures) is represented by the grey colored surface. Number of district–seasons (*n*) for each drought category is shown by the dot-and-dash line.

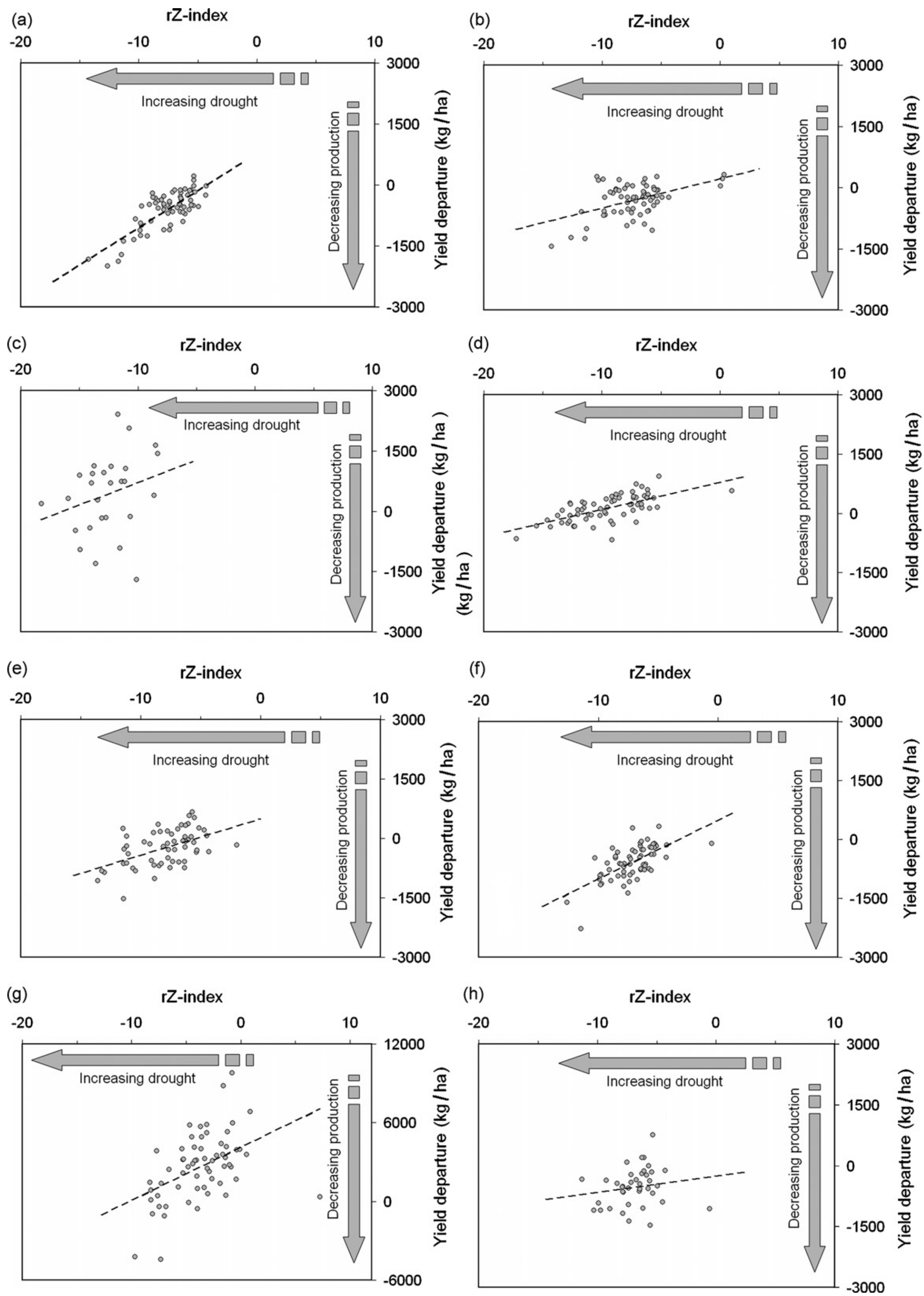

Fig. 7 – Relationship between yield departures from all included districts and appropriate rZ-index (for PCSD) for the very dry year 2000. The graphs show situations for (a) spring barley, (b) winter wheat, (c) maize, (d) rape, (e) winter rye, (f) oat, (g) potato and (h) hay.

climate are drawn based on this study result, it is necessary to understand the influence of higher atmospheric CO_2 concentrations (Houghton et al., 2001) on crop water stress resistance. The present concentration of atmospheric CO_2 for C3 plants is suboptimal (e.g., Amthor, 2001), and a rise of ambient CO_2 stimulates photosynthesis according to the given phenological stage (Mitchell et al., 1999). CO_2 simultaneously decreases transpiration due to the reduction in the duration of open pores, which would still be sufficient for accepting the necessary amount of CO_2. Therefore, water use efficiency is higher (especially during the higher air temperature) (Bunce, 2000) and delays the onset and severity of drought impact (Kimbal, 1983 or Robredo et al., 2007). Although some key interactions between elevated CO_2 and crop management (especially irrigation and fertilization) are fairly well understood, there are still some uncertainties regarding the realized effects of higher CO_2, such as changes in moisture availability, worsening air pollution, mineral nutrition or incidence of pests, diseases and weeds (Tubiello et al., 2007).

3.3. *Using the rZ-index for spatial delimitation of yield departures*

The ability of rZ-index to explain spatial variability of yield departures was assessed during the very dry vegetative season of the year 2000. Results are depicted in Fig. 7a–h separately for each investigated crop. The yield departures in all districts were analyzed using the rZ-index (for PCSD). Results showed that in the case of spring barley the difference in available soil moisture (expressed in terms of the rZ-index) was able to explain 65% of yield variability between districts, 22% for winter wheat, 43% for rape, 25% for winter rye, 41% for oat and 21% for potatoes. The explained variability in the case of grain maize and hay remained below 10%, which is consistent with lower sensitivity of C4 and perennial crops (respectively) to drought. Moreover the hay is mostly cultivated within more humid regions of the Czech Republic. The analysis showed that spring barley was negatively influenced by severe drought (as it was in 2000), even within more humid districts (e.g., Kroměříž—KM) where the relationship between yields and the rZ-i in the 40-year database was not statistically significant (e.g., Fig. 5a). It can be concluded that the rZ-index properly indicated the variability in spatial yield departures (with the exception of maize and hay) when a severe drought spell emerged within a particular district. Mavromatis (2007) also showed that Palmer's drought severity index (PDSI) (which derives from the Z-index) successfully described yield departures of durum wheat for severely dry years (R^2 was 0.83 within the Thessaloniki district, Greece), and during all the years (high and low risk together) PDSI explained 43.8% of the observed variability. The much inferior performance of the drought indices during the low-risk years may be explained by the fact that other factors (soil fertility, disease, pest, amount of fertiliser, etc.) become more important under these conditions (Quiring and Papakryiakou, 2003).

From the present study it is apparent that plant production in the Czech Republic was influenced by drought during the investigated period, and that some sort of adaptation and prevention should be considered in the future. Some of the most effective measures limiting drought impact include plant breeding (Cattivelli et al., 2008), partial irrigation, and agronomic adaptations (e.g., shift of agriculture terms, use of cultivars, and soil water saving tillage). For instance, González et al. (1999) showed that earliness, high potential yield and presumably osmotic adjustment are traits that lead to high grain yields in barley (investigated eight genotypes) grown under conditions of water stress. The drought tolerance within winter wheat was also correlated with osmotic adjustments (e.g., Morgan, 1995). It is also evident that drought monitoring and warning systems will be very useful both for farmers and policy-makers.

4. Conclusions

This study shows that use of the relative Z-index might be helpful in the identification of drought prone areas and drought prone stages of crops within rain-fed agriculture systems. Statistically significant relationships between the sum of the rZ-index for main growing period and the yield departures for a whole range of crops were found in a substantial number of analyzed districts, although the strength of the correlation varied with the crop and district. The analyses showed that drought severely decreased yields of spring barley, oil seed rape, oat and potatoes and to lesser degree winter wheat and winter rye. The yields of hay from meadows and grain maize were negatively affected by extreme water stress. Spring cereals were found to be more vulnerable to drought than winter ones, and C3 crops more vulnerable than C4 crops (i.e., grain maize). Lower susceptibility of winter crops could be explained by the fact that these crops are usually able to establish relatively deep rooting systems that lessen the impact of spring drought. Low sensitivity of winter rye compared to other key small grain cereals (i.e., wheat and barley) might serve as another incentive for the re-introduction of the crop to the cropping schemes in the Central Europe where it dominated as late as 50 years ago. The crop-specific nature of agricultural drought is apparent from the various timings of sensitivity periods, but overall the study clearly shows that drought stress during May and June is significant for yield formation of almost all investigated crops through the country and probably a wider region. On the other hand, water deficit from October to March seemed to have no effect on the yields in the given season. The proposed methodology based on the relative Z-index allowed us to calculate a drought index that reflected available soil moisture over a relatively large territory and took into account regional differences quite well. This study showed that a big part of the spatial yield variability could be explained by this method during years with severe drought, while 65% of spring barley yield variability between districts was explained during the exceptionally dry year of 2000 (together with 22% for winter wheat, 43% for rape, 25% for winter rye, 41% for oat and 21% for potatoes, and below 10% for grain maize and hay). The results also indicated that the relative Z-index could be successfully used to estimate critical thresholds that are valid on both the regional and national level, and could therefore be used as a part of a drought monitoring and/or early warning system. As the method is not particularly data intensive (compared, e.g., to crop models) it provides a relatively attractive alternative crop-specific drought monitoring scheme.

Acknowledgements

This study was supported by project (no. 521/08/1682) of the Grant Agency of the Czech Republic and by NAZV (National Agency for Agricultural Research) project nos. QG60051 and 1G46055. The study was executed with the help of Research plan no. MSM6215648905, ''Biological and technological aspects of sustainability of controlled ecosystems and their adaptability to climate change'' financed by the Ministry of Education, Youth and Sports of the Czech Republic.

REFERENCES

Alley, W.M., 1984. The Palmer drought severity index: limitations and assumptions. Journal of Climate and Applied Meteorology 23, 1100–1109.

Amthor, J.S., 2001. Effects of atmospheric CO_2 concentration on wheat yield: review of results from experiments using various approaches to control CO_2 concentration. Field Crops Research 73, 1–34.

Blinka, P., 2005. Climatological evaluation of drought and dry periods on the territory of Czechia in years 1876–2002. Meteorological Bulletin 58 (1), 10–18.

Brázdil, R., Trnka, M., Dobrovolný, P., Chromá, K., Hlavinka, P., Žalud, Z., 2008. Variability of droughts in the Czech Republic, 1881–2006. Theoretical and Applied Climatology, in press.

Brázdil, R., Dobrovolný, P., Elleder, L., Kakos, V., Kotyza, O., Květoň, V., Macková, J., Müller, M., Štekl, J., Tolasz, R., Valášek, H., 2005. Historical and Recent Floods in the Czech Republic. Masaryk University, Czech Hydrometeorological Institute, Brno, Prague, 370 pp.

Brázdil, R., Březina, L., Dobrovolný, P., Dubrovský, M., Halásová, O., Hostýnek, J., Chromá, K., Janderková, J., Kaláb, Z., Keprtová, K., Kirchner, K., Kotyza, O., Krejčí, O., Kunc, J., Lacina, J., Lepka, Z., Létal, A., Macková, J., Máčka, Z., Mulíček, O., Roštínský, P., Řehánek, T., Seidenglanz, D., Semerádová, D., Sokol, Z., Soukalová, E., Štekl, J., Trnka, M., Valášek, H., Věžník, A., Voženílek, V., Žalud, Z., 2007. Selected natural extremes and their impacts in Moravia and Silesia. Masaryk University, Czech Hydrometerological Institute, Institute of Geonics, Academy of Science of the Czech Republic, Brno, Praha, Ostrava, 432 pp.

Bunce, J.A., 2000. Responses of stomatal conductance to light, humidity and temperature in winter wheat and barley grown at three concentrations of carbon dioxide in the field. Global Change Biology 6, 371–382.

Cattivelli, L., Rizza, F., Badeck, F.W., Mazzucotelli, E., Mastrangelo, A.M., Francia, E., Mare, C., Tondelli, A., Stanca, A.M., 2008. Drought tolerance improvement in crop plants: An integrated view from breeding to genomics. Field Crops Research 105, 1–14.

Chloupek, O., Hrstkova, P., Schweigert, P., 2004. Yield and its stability, crop diversity, adaptability and response to climate change, weather and fertilization over 75 years in the Czech Republic in comparison to some European countries. Field Crop Research 85, 167–190.

Chmielewski, F.-M., Köhn, W., 2000. Impact of weather on yield components of winter rye over 30 years. Agriculture and Forest Meteorology 102, 253–261.

Das, H.P., 2005. Agricultural drought mitigation and management of sustained Agricultural Development in India. In: Sivakumar, M.V.K., Motha, R.P., Das, H.P. (Eds.), Natural Disasters and Extreme Events in Agriculture. Springer–Verlag,, Berlin, Heidelberg, New York, p. 370.

Dubrovský, M., Svoboda, M.D., Trnka, M., Hayes, M.J., Wilhite, D.A., Žalud, Z., Hlavinka, P., 2008. Application of relative drought indices in assessing climate change impacts on drought conditions in Czechia. Theoretical and Applied Climatology (published online), doi:10.1007/s00704-008-0020-x.

Dubrovský, M., Hayes, M., Trnka, M., Svoboda, M., Wilhite, D.A., Zalud, Z., Semerádová, D., 2006. Projection of future drought conditions using drought indices applied to GCM-simulated weather series. In: Vulnerable Environments: Creating a Roadmap for Change in the United States, Longmont, Colorado, September 18–20.

Earl, H.J., Davis, R.F., 2003. Effect of drought stress on leaf and whole canopy radiation use efficiency and yield of maize. Agronomy Journal 95, 688–696.

European Environmental Agency, 2005. Corine Land Cover 2000—Mapping a Decade of Change. EEA Publishing Office, Copenhagen, 16 pp.

FAO, 2008. FAOSTAT online database. http://faostat.fao.org accessed January 2008.

González, A., Martín, I., Ayerbe, L., 1999. Barley yield in water-stress conditions. The influence of precocity, osmotic adjustment and stomatal conductance. Fields Crops Research 62, 23–34.

Heim, R.R., 2002. A review of twentieth-century drought indices used in the United States. Bulletin of American Meteorological Society 83 (8), 1149–1165.

Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.), 2001. Climate Change 2001: The Scientific Basis. Cambridge University Press, Cambridge, p. 881.

Jensen, C.R., Mogensen, V.O., Mortensen, G., Fieldsend, J.K., Milford, G.F.J., Andersen, M.N., Thage, J.H., 1996. Seed glucosinolate, oil and protein contents of field-grown rape (*Brassica napus* L) affected by soil drying and evaporative demand. Field Crops Research 47, 93–105.

Karl, T.R., 1986. The sensitivity of the Palmer drought severity index and Palmer's Z index to their calibration coefficients including potential evapotranspiration. Journal of Climate and Applied Meteorology 25, 77–86.

Kimbal, B.A., 1983. Carbon dioxide and agricultural yield. An assemblage of analysis of 430 prior observations. Agronomy Journal 75, 779–788.

Larcher, W., 2003. Physiological Plant Ecology: Ecophysiology and Stress Physiology of Functional Groups, 4th ed. Springer–Verlag, Berlin, Heidelberg, New York, 513 pp.

Lobell, D.B., Field, C.B., 2007. Global scale climate-crop yield relationship and the impact of recent warming. Environmental Research Letters 2, 014002.

Mavromatis, T., 2007. Drought index evaluation for assessing future wheat production in Greece. International Journal of Climatology 27, 911–924.

Mitchell, R.A.C., Black, C.R., Burkart, S., Burke, J.I., Donnelly, A., Temmmerman, L.de, Fangmeier, A., Mulholland, B.J., Theobald, J.C., van Oijen, M., 1999. Photosynthetic responses in spring wheat grown under elevated CO_2 concentrations and stress conditions in the European, multiple-site experiment 'ESPACE-wheat'. European Journal of Agronomy 10, 205–214.

Morgan, J.M., 1995. Growth and yield of wheat lines with differing osmoregulative capacity at high soil water deficit in seasons of varying evaporative demand. Field Crops Research 40, 143–152.

Možný, M., 2004. Definition and intensity of drought on the territory of the Czech Republic in the period 1891–2003. ČHMÚ, p. 88.

Narasimhan, B., Srinivasan, R., 2005. Development and evaluation of soil moisture deficit index (SMDI) and evapotranspiration deficit index (ETDI) for agricultural drought monitor. Agricultural and Forest Meteorology 133, 69–88.

Nayyar, H., Gupta, D., 2006. Differential sensitivity of C_3 and C_4 plants to water deficit stress: association with oxidative stress and antioxidants. Environmental and Experimental Botany 58, 106–113.

Otegui, M.E., Andrade, F.H., Suero, E.E., 1995. Growth, water use, and kernel abortion of maize subjected to drought at silking. Field Crops Research 40, 87–94.

Quiring, S.M., Papakryiakou, T.N., 2003. An evaluation of agricultural drought indices for the Canadian prairies. Agriculture and Forest Meteorology 118, 49–62.

Ozturk, A., Aydin, F., 2004. Effect of water stress at various growth stages on some quality characteristics of winter wheat. Journal of Agronomy and Crop Science 190, 93–99.

Palmer, W.C., 1965. Meteorological Drought. Office of Climatology Research Paper 45. U.S. Weather Bureau, Washington, 58 pp.

Polley, H.W., 2002. Implications of atmosphere and climatic change for crop yield and water use efficiency. Crop Science 42, 131–140.

Robredo, A., Pérez-López, U., de la Maza, H.S., González-Moro, B., Lacuesta, M., Mena-Petite, A., Munõz-Rueda, A., 2007. Elevated CO_2 alleviates the impact of drought on barley improving water status by lowering stomatal conductance and delaying its effects on photosynthesis. Environmental and Experimental Botany 59 (3), 252–263.

Schittenhelm, S., Sourell, H., Löpmeier, F.-J., 2006. Drought resistance of potato cultivars with contrasting canopy architecture. European Journal of Agronomy 24, 193–202.

Sheng, G., Hunt, L.A., 1991. Shoot and root dry-weight and soil-water in wheat, triticale and rye. Canadian Journal of Plant Science 71 (1), 41–49.

Sivakumar, M.V.K., Motha, R.P., Das, H.P., 2005. Natural Disasters and Extreme Events in Agriculture. Springer-Verlag, Berlin, Heidelberg, New York, 370 pp.

Svoboda, M.D., LeComte, D., Hayes, M.J., Heim, R., Gleason, K., Angel, J., Rippey, B., Tinker, R., Palecki, M., Stooksbury, D., Miskus, D., Stevens, S., 2002. The drought monitor. Bulletin of the American Meteorological Society 1181–1190.

Thornthwaite, C.W., 1948. An approach towards a rational classification of climate. Geographical Review 38, 55–94.

Tolasz, R., Míková, T., Valeriánová, A., Voženílek, V. (Eds.), 2007. Climate atlas of Czechia. Czech Hydrometerological Institute, Olomouc, Praha, ISBN 978-80-86690-26-1, 256 pp.

Tomášek, M., 2000. Soils of the Czech Republic, 2nd ed. Czech Geological Service, Pratur, 68 pp.

Trnka, M., Dubrovský, M., Svoboda, M.D., Semerádová, D., Hayes, M.J., Žalud, Z., Wilhite, D.A., 2008. Developing a regional drought climatology for the Czech Republic. International Journal of Climatology (published online), doi:10.1002/joc.1745.

Trnka, M., Hlavinka, P., Semerádová, D., Dubrovský, M., Žalud, Z., Možný, M., 2007. Agricultural drought and spring barley yields in the Czech Republic. Plant Soil and Environment 53, 306–316.

Tubiello, F.N., Amthor, J.S., Boote, K.J., Donatelli, M., Easterling, W., Fischer, G., Gifford, R.M., Howden, M., Reilly, J., Rosenzweig, C., 2007. Crop response to elevated CO_2 and world food supply A comment on ''Food for Thought ('' by Long et al.), Science 312: 1918–1921. European Journal of Agronomy 26, 215–223.

Wells, N., Goddard, S., Hayes, M.J., 2004. A self-calibrating Palmer drought severity index. Journal of Climate 17, 2335–2351.

van der Schrier, G., Briffa, K.R., Jones, P.D., Osborn, T.J., 2006. Summer moisture variability across Europe. Journal of Climate 19, 2818–2834.