Impacts of drought at various time scales on the productivity of agricultural crops grown in the Czech Republic

Vera Potop[1], Martin Možný[2], Luboš Türkott [1]

[1]Czech University of Life Sciences Prague, Faculty of Agrobiology, Food and Natural Resources, Department of Agroecology and Biometeorology, Prague, Czech Republic; [2]Czech Hydrometeorological Institute, Czech Republic

Abstract. This study evaluated the effect of moisture conditions at various lags on the eleven agricultural crops mainly growing in the Czech Republic and in Central Bohemian region. The agro-databases contain yearly region-level logs of spring wheat, winter wheat, spring barley, winter barley, winter rye, oats, oilseed rape, maize, sugar beet, potatoes and grapevine as reported by the Czech Statistical Office for the period 1961-2012.Various lags that might be considered for the Standardized Precipitation Evapotranspiration Index (SPEI) calculation can be related to different drought types in a region. The SPEI was used to quantify the moisture conditions for each month of the year and 12 accumulated lags during the period 1961-2012 (from January 1961 to December 2012). In this study, the SPEIbase is based on the FAO-56 Penman-Monteith estimation of potential evapotranspiration from CRU with spatial resolution of 0.5ºlat x 0.5ºlon. The gridded data of the SPEI time series have been downloaded to climatological station coordinates from the Czech Republic and over Central Bohemian domain. The impact of the SPEI interannual variability on yield of agricultural crops was evaluated by means of parametric correlations using the Pearson coefficient with a significance threshold of $p < 0.05$.

Key words

SPEIbase, yield, cereals, sugar beet, potatoes, grapevine

Introduction

In the Czech Republic, drought brings about huge losses to agriculture. There are several strategies to ameliorate the effects of drought: agronomic strategies, trait-based strategies, cellular and molecular strategies. Agronomic strategies include: (1) adjusting planting time such that critical growth stages do not coincide with stressful conditions; (2) resource-conserving technologies that apply growth inputs, especially water, as optimally as possible; and (3) good farming to avoid weeds, pests and diseases from exacerbating stress (McMaster et al. 2005).

The impacts of droughts depend on how long droughts persist and the reasons why droughts extend to different time scales may be different. For example, the soil moisture–drought relationship has a strong dependence on the time scale of droughts. The Standardized Precipitation Evapotranspiration Index (SPEI) associated with a specific time scale is a useful tool for monitoring drought (Vicente-Serrano et al., 2010). Different SPEI series were obtained for different time-scales representing the cumulative water balance over the previous *n* months. Short lag time scales display a strong relationship with variations in soil moisture that determine water availability for agriculture, whereas water resources in reservoirs are mostly related to longer time scales. The SPEI calculated for various lags contain the *memory* of moisture conditions prior to the current month (Potop et al., 2013; Potop and Možný, 2013). The SPEI uses monthly precipitation and average monthly temperature in its calculation and was developed to help overcome some limitations of the SPI. With the temperature input potential evapotranspiration (PET) is calculated and a historical time series of the simple water balance (precipitation – PET) is used in place of the precipitation only time series used in the Standardized Precipitation Index (SPI). The standardization procedure for SPEI follows the same steps as SPI, however the developers of SPEI recommend using the three parameter log-logistic theoretical distribution to account for common negative values which are found in the time series (precipitation – PET). According to previous study (Potop et al., 2012 a), the comparison between the SPEI and SPI in the Czech Republic indicated differences in representative severe drought records during the decades for 1) the lowest summer negative temperature anomalies combined with the lowest negative precipitation anomalies (cold and dry; during the first two decades of the 20th century), 2) the highest summer positive temperature anomalies (at the end of the 20th century), 3) both high spring positive temperature and precipitation anomalies (warm and wet, at the beginning of the 20th century), and 4) the highest deficits of water balance. Our objectives are to determine the influence of SPEIbase series based on the FAO-56 Penman-Monteith estimation of potential evapotranspiration on crop productivity and, in particular, the drought time-scales that are affecting growth of eleven agricultural crops in the Czech Republic and Central Bohemian region.

Material and methods

We evaluated the effect of moisture conditions at various lags on eleven of the main agricultural crops grown in the Czech Republic and in Central Bohemian region. The agro-databases contain yearly region-level logs of spring wheat (SW), winter wheat (WW), spring barley (SB), winter barley (WB), winter rye (WR), oats (O), maize (M), oilseed rape (OR), sugar beet (SB), potatoes (P) and grapes (G) as reported by the Czech Statistical Office for the period 1961-2012 (Table 1). The SPEI was used to quantify the moisture conditions for each month of the year and 12 accumulated lags during the period 1961-2012 (from January 1961 to December 2012). The SPEI is calculated monthly by considering the cumulative precipitation minus cumulative PET, respectively, over the past number of months relative to historical conditions. For example, the 6-month SPEI for June would require the difference of precipitation minus PET accumulated from January through June.

In this study, the SPEIbase is based on the FAO-56 Penman-Monteith estimation of potential evapotranspiration from CRU (the Climatic Research Unit of the University of East Anglia) with spatial resolution of 0.5°lat x 0.5°lon (Beguería et al., 2010). In our study, gridded data of SPEIbase have been downloaded to climatological station coordinates as a *.csv* files (*comma-separated values*) and over Bohemian Central domain as a *netCDF* files by using the Grid Analysis and Display System (openGrADS) software (http://sac.csic.es/spei).

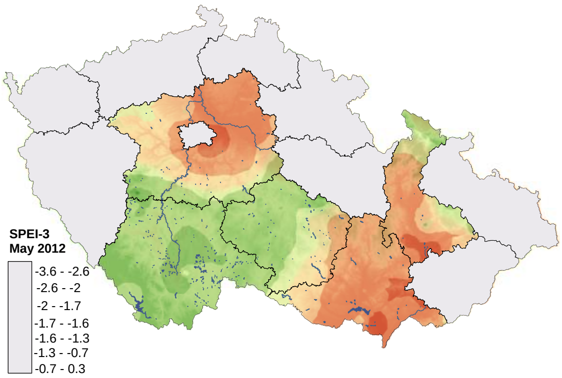

Figure 1. *Spatial distribution of gridded SPEIbase at 3 time scales with resolution of 0.5°lat x 0.5°lon on May 2012 over the Czech Republic.*

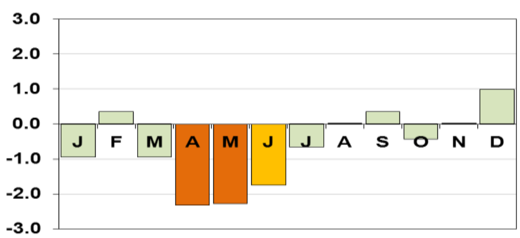

Figure 2. *Temporal evolution of the SPEIbase at 3-month lag during the year of 2012 at grid-point of 50.19°N;14.66°E, h=179 (Brandýs nad Labem-St.B station).*

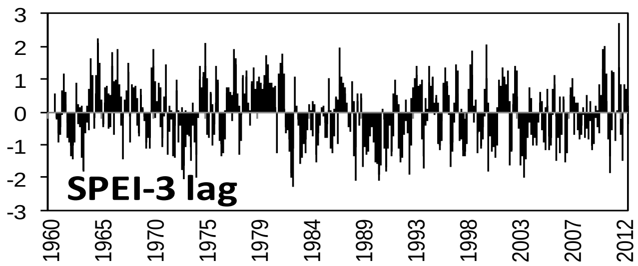

Figure 3. *The evolution of moisture characteristics quantified by the 0.5° SPEIbase at 3-month lag from January 1961 to December 2012 at Central Bohemian domain (http://sac.csic.es/spei).*

The Figure 1 shows spatial distribution of gridded SPEI at 3 time scales with resolution of 0.5°lat x 0.5°lon on May 2012 over the Czech Republic. The Figure 2 shows the temporal evolution the SPEI at 3-month lag from January to December 2012 downloaded at Brandýs nad Labem station as an example for the station situated in Central Bohemian region. Figure 3 displays the evolution of moisture characteristics quantified by the 0.5° SPEIbase at 3-month lag for the period 1961-2012 downloaded at Central Bohemian region.

Prior to calculating the correlations between yield and SPEI series, the trend in each of the SPEI time series was removed by assuming a linear evolution in each monthly series at the different time scales. Therefore, correlation analyses were performed between de-trended yield and de-trended monthly SPEI series.

Results and discussion

The statistical analysis of crop production was conducted of the average yields derived from all districts in the Czech Republic and Central Bohemian region (Tables 1 and 2).

Table 1. *Statistical analysis of annual yield series (tha^{-1}) of crops grown in Central Bohemian region and in the Czech Republic for period of 1961-2012.*

	Average yield (tha^{-1})		Minimum (tha^{-1})		Maximum (tha^{-1})	
	CR	CB	CR	CB	CR	CB
WW	4.25	4.32	2.44	2.33	5.96	6.09
SW	3.46	3.57	2.15	1.95	5.10	5.12
WB	3.80	3.91	1.70	1.93	6.06	6.29
SB	3.71	3.73	2.24	2.27	5.44	5.26
R	3.40	3.41	2.03	2.09	5.29	5.36
O	3.02	2.98	1.83	1.70	4.70	4.25
M	4.83	4.93	2.42	2.05	8.79	9.19
P	19.68	18.44	9.99	8.08	32.52	29.80
SB	39.67	37.91	23.53	19.66	66.84	67.83
OR	2.33	2.29	0.97	0.95	3.60	3.73
G	5.36	3.66	0.34	0.00	9.29	7.47

Table 2. *Tendency of changes in annual yield (tha^{-1}) of crops grown in the Central Bohemian region and in the Czech Republic from 1961 to 2012.*

	t_1 (tha^{-1})		t_2 (tha^{-1})		Growth trend (%)	
	CR	CB	CR	CB	CR	CB
WW	2.37	2.71	4.91	5.14	207.5	189.7
SW	2.18	2.51	3.43	3.69	157.0	147.0
WB	1.76	1.94	4.13	4.17	234.4	214.5
SB	2.51	2.83	3.83	4.06	152.8	143.4
R	2.04	2.11	4.26	4.26	208.5	202.3
O	1.81	2.12	2.77	2.76	152.9	129.9
M	3.20	2.55	8.02	7.92	250.3	310.5
P	14.45	13.24	26.39	24.86	182.6	187.8
SB	33.38	33.10	58.93	56.83	176.5	171.7
OR	1.28	1.26	2.78	2.83	217.7	224.9
G	3.89	3.84	3.90	4.31	100.1	112.3

t_1- predicted values of starting period of trend;
t_2- predicted values of ending period of trend.

All the crops monitored for the period 1961 - 2012 in the Czech Republic and Central Bohemian region show an increasing growth trends (Table 2). The majority of agricultural crops have been pronounced increasing trend of yields in the Czech Republic, only for demanding crops to temperature (maize, grapes and oilseed rape) had a higher rate of yield growth in Central Bohemian region.

If evaluating the trend growth rate as the percentage from an initial trend value (t_1) to a final trend value (t_2), the largest growth rate had maize (*Zea mays* L.) both in Central Bohemian region (310.5%) and over the Czech Republic (250.3%). This is mainly due to breeding performance of hybrids and since 1970s putting them into practice. In this period, however, the yield of grain maize showed a large inter-annual variability. A further significant increase of maize yields and simultaneously reducing inter-annual variability occurs since 1994 (year with a significant yield losses), when in subsequent years already yield of grain maize in Central Bohemian region does not drop below 5.0 tha^{-1}.

The year of 1994 was for growth and development of maize and other crops critical, because in the second half of June, the Czech Republic suffered by extreme drought (Potop et al., 2013b). On most of the territories an available water capacity dropped below 10% and the belt with critical level of soil moisture at wilting point spread out from NW to SE territory across Central Bohemian region. The highest yield of maize were in 2002 (8.8 tha^{-1}) and 2011 (9.2 tha^{-1}), while the lowest in 1964 and 1965 (2.1 tha^{-1}). Similar yields can be observed over the Czech Republic, with the exception of 1964, which was an above-average yield during decade 1961-1970. According to the SPEI series, 1964 had a longer dry spell in the growing season, with an average of 3.0 to 4.9 dry months over the Czech Republic (Potop et al., 2013b).

The typical cereals for Central Bohemia are wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.). Considerable growth trends of winter forms were recorded, which also is having a larger sown areas and higher long-term yields. The average yield of spring wheat and winter wheat for the period 1961 - 2012 were 3.46 tha^{-1} and 4.25 tha^{-1}, respectively (Table 1). The highest yields of winter wheat forms were achieved in 2004 and 2008 (6.09 tha^{-1} and 6.08 tha^{-1}) and for spring forms in 1990 (5.12 tha^{-1}). The lowest wheat yields were recorded at the beginning of the observation period (in the mid-1960s).

Yield series of both winter and spring barley have a very similar temporal evolution as that of wheat. The highest yield of winter and spring barley forms was achieved in 1990. This year was characterized by very early onset of spring and above-average temperatures in the beginning of the year. The cool wave occurred in the second half of April, which allowed good tillering of wheat and barley. In 1990, there were dry episodes in July and consequently, there were the optimum conditions for ripening and harvesting of cereals (Potop et al., 2013b).

Conversely, the 1990 was critical for potatoes (*Solanum tuberosum* L.) and sugar beet (*Beta vulgaris* L.), when the July drought affected these crops in the highest moisture requirements period. This year was ranked for sugar beet the sixth lowest yield (27.87 tha^{-1}) and for potatoes the fourth lowest yield (11.91 tha^{-1}) during the period 1961 - 2012.

The lowest growth trend had grapevine with only 112.3% in Central Bohemian region, while for the Czech Republic reaching 100.1%. Yields of grapevine in Central Bohemian region show a significant interannual variation and their average value (3.66 tha^{-1}) is significantly lower than national average production (5.36 tha^{-1}) (Table 1).

Despite the remarkable development of technology of the cultivation and the introduction of new no rising tendency in yields of grapevine was observed. This is due to the transition of cultivation technology on reductive way (artificial reduction shaft grapes) and increase of content of the sugar production. The critical year with zero yield of grapevine was the year of 1985, when vines has frozen up to wood and the subsequent years of 1986 and 1987 were obtained the yield strongly below-average. On the contrary, the highest yield in Bohemian Central region were reached in 1973 (7.47 tha^{-1}), 1964 (6.86 tha^{-1}) and 1976 (6.54 tha^{-1}) with a regional average yield of 3.66 tha^{-1}.

(a)

Winter-spring rye												
Dec	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	-0.3
Nov	0.2	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.2	-0.2	-0.2	-0.1
Oct	0.0	0.0	0.1	0.1	0.2	0.1	0.1	0.3	-0.3	-0.2	-0.1	-0.2
Sep	0.0	0.0	0.1	0.0	0.0	0.0	0.3	-0.2	-0.2	0.2	-0.3	-0.3
Aug	0.0	0.0	0.2	0.0	0.1	0.2	0.0	0.1	0.1	0.0	0.1	0.1
Jul	0.0	0.0	0.0	0.2	0.2	0.2	0.0	0.2	0.1	0.0	0.1	0.0
Jun	-0.3	-0.3	-0.3	-0.2	-0.4	-0.4	0.2	0.2	0.1	0.1	0.1	0.1
May	0.2	0.2	-0.4	-0.4	-0.4	-0.4	-0.3	0.0	0.0	0.0	0.0	0.0
Apr	0.0	-0.2	-0.5	-0.6	-0.6	-0.6	-0.4	-0.2	0.0	0.0	0.0	0.0
Mar	-0.2	-0.1	0.4	0.3	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Feb	0.0	0.3	0.1	-0.1	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.0
Jan	0.0	0.0	-0.2	-0.1	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0
	1	2	3	4	5	6	7	8	9	10	11	12
SPEI time-scales												

(b)

Maize												
Dec	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nov	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oct	0.2	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sep	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.2	0.0	0.1	0.2	0.2
Aug	-0.2	-0.2	-0.5	-0.6	-0.6	-0.5	0.0	0.3	0.1	0.2	0.1	0.1
Jul	-0.2	-0.2	-0.1	-0.2	-0.1	-0.2	0.0	0.1	0.1	0.1	0.1	0.1
Jun	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.2	0.0	0.0	0.1	0.1
May	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.0	0.0	0.1	0.1	0.1
Apr	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0
Mar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Feb	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	1	2	3	4	5	6	7	8	9	10	11	12
SPEI time-scales												

-0.6	-0.5	-0.4	-0.3	-0.2	-0.1	0.0	0.1	0.2	0.3	0.4	0.5	0.6

Figure 4. *Mean Pearson correlation coefficients (r) between monthly SPEI de-trended series at 1 to 12-month lag and de-trended yield of maize (a) and winter and spring rye crops (b) for the period of 1961-2012.*

However, the worldwide trends in increasing productivity (yield per hectare) of most crops over the last 40 years, primarily due to technological improvements in breeding, pest and disease control, fertilisation and mechanisation, make identifying climate-change signals difficult.

Mean Pearson correlation coefficients (r) between monthly SPEI de-trended series at 1 to 12-month lag and de-trended yield as an example for maize and winter and spring rye crops for the period of 1961-2012 are given in Figure 4.

To summarize the correlation analyses and compare to drought effect among crops, we found differences in the responses of agricultural crops to different lags of the SPEI. Positive correlations indicate that year-to-year variations in yield are related to year-to-year variation in de-trended SPEI (Figure 4). That means, higher yields are observed in moderately wet and normal years and lower yields occurred under severely and extremely dry conditions (Potop and Možný, 2013a).

The growth stages of cereal crops clearly show the negative signs of the SPEI in a given set of months when drought conditions are significant for yield formation (Figure 4). In agreement with the SPEI, winter wheat (*Triticum aestivum* L.) was affected by a severe drought in May-June (*r = -0.5 to -0.6*) at 1 to 6-month lag (cumulative moisture). In the years with the mid-term spring drought lower yields of spring wheat (*Triticum aestivum* L.) and spring barley were registered (*r =-0.37 to -0.55*). Winter barley, due to its early maturation does not have a great demand for the moisture and crops are able to obtain water from the deeper soil layers during short dry spells but spring barley (*Hordeum vulgare* L.) is susceptible to drought in May (*r = -0.6*) at short- to mid-term (1 to 7 months) lags.

Among the winter cereals, winter rye (*Secale cereale* L.) shows the highest fluctuations due to spring drought (April-May with *r = -0.2 to -0.6*) (Figure 4a). Oats (*Avena sativa* L.) is difficult to grow when there is insufficient moisture and the droughts are most damaging in its early stages (*r = -0.1 to -0.6*).

The largest ranges of Pearson correlation coefficients (*r* = -0.16 to -0.60 and *r* = 0.13-0.50) observed for maize (*Zea mays* L.), with maximum positive correlations reached during May-June at time scales from 1 to 7 months (Figure 4b). Maize can draw water very well from deeper layers and is resistant to dry periods (Potop, 2011). It has increased demands for moisture during the flowering period (July-August). The greatest correlation was recorded for the SPEI at the 7-month lag in August (*r = -0.55*). Thus, higher yields of winter rye, maize and barley were found in the years with SPEI normal and moderately wet categories.

A negative correlation (*i.e.*, damaging effects) was observed between the de-trended yield of sugar beets (*Beta vulgaris* L.) and the SPEI at time scales from 1 to 7 months during the months of May, July, and August (*r = -0.37 to -0.55*). A positive correlation was found in April, June, September and October (*r =0.27 to 0.42*) (Potop and Türkott, 2012b). Negative correlations were found between the potatoes yield (*Solanum tuberosum* L.) and the SPEI in June (*r= -0.31*), while a positive in July (*r= 0.51*) and August (*r*= 0.38) at short-term (1 to 3-month) lags. Grapevines do not show strong associations between de-trended yield and the SPEI: only a positive moderate correlation (*r = 0.42*) observed during August-September at lags up to 6-month.

Conclusions

This study investigated the drought impact on the agricultural production system and, in particular, the drought time-scales that affect the growth of eleven agricultural crops in the Czech Republic and in Central Bohemian region. To quantify drought severity we used monthly data of the SPEI at a spatial resolution of 0.5°and time scales ranging from 1 to 12 mo obtained from the SPEIbase.

The drought influence was quantified by means of correlations between the 0.5° SPEIbase series and yield series of eleven agricultural crops growing in Central Bohemian region.

The magnitudes of the correlations between various agricultural crops and the SPEIbase series are capable to monitor agricultural drought conditions. The yield-response to drought varied among crops: the greatest yield-drought correlation was recognized for cereals; the lowest for grapes. Grapevine seems to be least affected crop by drought: the lowest grape yields were recorded in years with severe winters and late spring frosts.

Acknowledgements. This research was supported by S grant of MSMT CR and project 6046070901.

References

Beguería, S., Vicente-Serrano, S.M., Angulo, M., 2010: A multi-scalar global drought data set: the SPEIbase: a new gridded product for the analysis of drought variability and impacts. *Bulletin of the American Meteorological Society*, 91, 1351-1354

McMaster, G.S., Wilhelm, W.W., Frank, A.B., 2005: Developmental sequences for simulating crop phenology for water-limiting conditions. *Australian Journal of Agricultural Research*, 56, 1277-1288.

Potop, V., 2011: Evolution of drought severity and its impact of corn in the Republic of Moldova. *Theor. Appl. Climato*l, 105, 468-483

Potop, V., Možný, M., Soukup, J., 2012 a: Drought at various time scales in the lowland regions and their impact on vegetable crops in the Czech Republic. *Agric Forest Meteorol,* 156 (2012), 121-133

Potop, V., Türkott, L., 2012 b: Use of Standardized Precipitation Evapotranspiration Index for assessment of water deficit and/or surplus when growing sugar beet in Central Bohemia. *Sugar and Sugar Beet Journal*, 128 (12), 368-373

Potop, V., Možný, M., 2013 a: Multi-scalar indices of drought in intensively farmed regions of the Czech Republic. In: Dent David (Ed.*) Soil as World Heritage*. 450 p. ISBN 978-94-007-6186-5.

Potop, V., Boroneat, C., Možný, M., Štěpánek, Skalak, P., 2013 b: Observed spatio-temporal characteristics of drought on various time scales over the Czech Republic. *Theor. Appl. Climatol*, 112 (3-4). DOI: 10.1007/s00704-013-0908-y.

Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., 2010: A Multi-scalar drought index sensitive to global warming: The Standardized Precipitation Evapotranspiration Index – SPEI. *Journal of Climate*, 23 (7), 1696-1718.