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DROUGHT STRESS IMPACT ON VEGETABLE CROP YIELDS IN THE ELBE RIVER LOWLAND BETWEEN 1961 AND 2014

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ABSTRACT. *The study is focused on drought stress that is detrimental to yield formation of field-grown vegetables in the lowland regions of the Czech Republic. Extensive vegetable yield losses are attributed to drought, often in combination with heat or other stresses. The objective of this research was to investigate, under field conditions, the effect of drought stress quantified by the Standardized Precipitation Evapotranspiration Index (SPEI) on yield variability of key vegetable crops growing in the Elbe River lowland, representing central European agriculture conditions. Additionally, we also tried to determine the period of crop with the highest sensitivity to drought (PCSD) of vegetable crops over the Elbe River lowland. Historical climate datasets for a regular gridded network with a high horizontal resolution of 10 km (CZGRIDS) and 305 climatological stations from the Czech Hydrometeorological Institute were applied. The SPEI at 1-, 3-, and 6-month lags was calculated for the period 1961-2014 based on precipitation and input dataset for the reference evapotranspiration (ET_r) by the Penman-Monteith (PM) method. Moreover, the differences between daily precipitation and crop evapotranspiration (ETc) have been used to calculate the mean crop water balance (D) per main growth stages, as an indicator of plant stress. This improvement increased the applicability of the SPEI in agriculture drought impact on rainfed and/or irrigated field crops grown under various agronomic management systems. To understand how the SPEI, over the period 1989-2014, controlled the yield variation, we calculated the percentage of yield losses and gains for each crop. When the value of the SPEI at 3-month lag –as a measure of the balance between the water availability and the atmospheric water demand– for PCSD was between -1.49 and 0.99, the yield moderately increased for Fruiting vegetables (e.g. tomatoes, cucumber). Conversely, when the SPEI-3 in the key development stage dropped below -3.0, the yield losses were about -30% and a negative influence is apparent from threshold of the*

SPEI≤-1.5. The effect of the SPEI on yield formation of vegetable cultivars grown under filed conditions was achieved up to 62% in the study region.

Impacto de las sequías en la producción de los cultivos en el bajo Río Elba entre 1961 y 2014

RESUMEN. *El estudio se centra en los perjuicios causados por las sequías sobre los cultivos en las regiones bajas de la República Checa. Grandes pérdidas en los cultivos se han atribuido a las sequías, a menudo en combinación con el calor y otros tipos de estress. El objetivo de este trabajo fue investigar el efecto de las sequías cuantificado mediante el Índice de Precipitación Evapotranspiración estandarizada (SPEI) sobre la variabilidad de la producción de cultivos clave en las tierras bajas del río Elba. Se utilizaron bases climáticas históricas para una cuadrícula de alta resolución horizontal de 10 km y 305 estaciones climatológicas del Instituto Hidrometeorológico Checo. Se calculó el SPEI para intervalos de 1, 3 y 6 meses en el periodo 1961-2014, basado en la precipitación y en la evapotranspiración de referencia (ET) utilizando el método de Penman-Monteith. Además, la diferencia entre la precipitación diaria y la evapotranspiración del cultivo se ha utilizado para calcular el balance medio del cultivo (D) para los principales estadios del crecimiento, como un indicador de estress de las plantas. Esta mejora metodológica aumentó la aplicabilidad del SPEI en el impacto agrícola de la sequía sobre cultivos de secano y/o regadío bajo diferentes sistemas de gestión agronómica. Para comprender cómo controla el SPEI la variación de la producción, calculamos el porcentaje de pérdidas y ganancias para cada cultivo. Cuando el valor del SPEI en un plazo de tres meses (como medida del balance entre la disponibilidad de aguay la demanda atmosférica de agua) estaba entre 1,49 y 0,99, la producción aumentaba moderadamente en el caso de las plantas de fruto (por ej., tomates, pepinos). Por el contrario, cuando el SPEI-3 descendió por debajo de -3,0 en un estadio clave de desarrollo, las pérdidas de producción fueron de alrededor del 30%, y una influencia negativa fue apreciable a partir de un umbral de SPEI<1,5.*

Key words: Standardized Precipitation Evapotranspiration Index, drought stress, reference evapotranspiration, crop evapotranspiration, crop coefficient, Czech Republic.

Palabras clave: Índice de Precipitación Evapotranspiración Estandarizada, estrés de sequía, evapotranspiración de referencia, evapotranspiración de cultivos, coeficiente de cultivo, República Checa.

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1. Introduction

Even though the Czech Republic is not generally characterized as a drought prone region of Europe, drought still occurs (Trnka *et al*., 2015a; Brazdíl *et al*., 2015; Zahradníček *et al*., 2015) and is one of the most important climatic extremes in terms of agriculture losses (e.g., Hlavinka *et al*., 2009; Potopová *et al*., 2015a). This is demonstrated by the example of the last most persistent dryness recorded in 2014 and 2015. As Trnka *et al*. (2015b), Potopová *et al*. (2015b) have shown, the negative anomalous snow characteristics in conjunction with winter and early summer drought amplify lingering impacts on the depletion of soil moisture in the later summer, and consequently, reduce the latent heat flux and its ability to cool the soil surface. For instance, a large part of the territory of the Czech Republic (CR) was affected by a severe winter-spring-summer drought in 2015, as a consequence of the extremely poor snow season in conjunction with high evapotranspiration and a lack of summer precipitation result in declining available soil water from April until September. The soil water content fell under 10 % of available water holding capacity (the wilting point was reached in some localities) in large areas of Moravia, East, South, and West Bohemia. In terms of precipitation, 2015 is the second lowest rainfall total since 1961 (the lowest precipitation of 335 mm occurred in 2003). In the case of surface water, the minimum discharges of the majority of observed rivers decreased more than in 2003, therefore, the low-flow situation is more comparable to 1947 or 1904 (CHMI, 2015). Moreover, the drought of 2015 in the CR was part of a continental European phenomenon, which affected large area of Central Europe, Black Sea region, the Balkans and Iberian Peninsula. Pressure lows absence due to the occurrence of a stable high-pressure field over Eurasia lead to decrease the transfer of moist air from the Atlantic Ocean and the Mediterranean Sea over the territory of the CR. While low relative humidity, limited cloud cover and heat waves caused increased evaporation (CHMI, 2015). This analysis is also confirmed by drought monitoring based on the global 0.5° gridded Standardized Precipitation Evapotranspiration Index (SPEI) at time scales between 1 and 48 months over European domain (Begueria *et al*., 2014; http://sac.csic.es/spei), which SPEI provides a measure of the balance between the water availability and the atmospheric water demand (Vicente-Serrano *et al*., 2015).

In the CR, field vegetables are predominantly grown in areas around the lowland basins of such rivers as the Elbe, Vltava, Ohře, Morava, Dyje and Svratka which are agriculturally the most productive, but have a lowland climatic characteristics “low rainfall and higher potential evapotranspiration” and often affected by drought (Potop *et al*., 2014a, 2014b). Vegetable production (depending of the grown-vegetable region) is being affected by high temperatures (South Moravia), occurrences of drought (Elbe lowland and South Moravia), late and early frosts (in all regions), waterlogging (in the wetness growing seasons e.g. 2010 and 2013 in Central Bohemian region) and field accessibility during key field operation. Droughts and extreme high temperatures, cannot be seen as independent phenomena as in many regions droughts additionally are connected with high temperature extremes (e.g. 2003, 2015). Thereby, in this study we applied the SPEI’s main advantage to identify the role of evapotranspiration and temperature variability with regard to drought assessments in the context of global warming (Vicente-Serrano *et al*., 2011, 2012). The combination of high temperatures and droughts initiate a positive regional feedback mechanism: the precipitation deficits and enhanced evaporative demand generally associated with warm spells (e.g. atmospheric blockings) triggers soil moisture deficit, thus suppressing evaporative cooling (Teuling *et al*., 2013) and leading to hotter and drier conditions if soil moisture becomes limiting for evapotranspiration (Whan *et al*., 2015). Trnka *et al*. (2015b) concluded that increased global radiation and air temperature together with decreased relative humidity led to increase of reference evapotranspiration in all month of the growing season (particularly in April, May and August) over the CR. Longer intervals between rainfall events may increase the duration and severity of soil drought stress. In contrast, longer intervals between heavy rainfall events may reduce periods of anoxia and be favourable to plant growth in more hydric ecosystems (Frank *et al*., 2015). Plant responses to water stress differ significantly depending on (i) the intensity and duration of stress, (ii) the vegetable types, and (iii) its stage of development.

The objective of this research was to investigate, under field conditions, the effect of drought stress quantified by the SPEI on yield variability of key vegetable crops growing in the Elbe River lowland (ERL). Additionally, we also tried to determine the period of crop with the highest sensitivity to drought of vegetables.

2. Data and methods

2.1. Study area and yield datasets

The Elbe River lowland (Polabská nížina, Czech name) has traditionally been a region (Fig. 1) of cultivation of large assortment of *brassica vegetables* (kohlrabi, Savoy cabbage, white-headed cabbage and cauliflower), *root vegetables* (celeriac, carrot and root parsley), *bulb vegetables* (onion and garlic) and *legumes* (green pea), while in the warmest parts of the Elbe lowland, growing *thermophilic (fruiting) vegetables* such as tomatoes and cucumbers. The potential impacts of climate change on the types of vegetables grown in the ERL (observed and projected of the frequency of frost occurrences, and changes in the timing of the growing season) has been described by Potop *et al*. (2014a, 2014b) and Potopová *et al*. (2015c). The ERL was chosen as study area because of particularly affect by a strong inter-annual variation in rainfall patterns and increases of temperature trends, and it also becoming a major producer of a large assortment of thermophilic vegetables. This region is more sensitive to anomalies in water balance although it is located on the Atlantic Ocean-Black See continental divide, but supplemental surface water reserves are absent. However, ERL has a more productive soil conditions, particularly in the valley around the middle course of the Elbe River. The Chernozems, fluvisols and Haplic Luvisol are the prevailing soil groups with a high and medium-high soil water-holding capacity (Tomašek, 2000). The study applied the newly acquired and homogenized database of the annual yields of thirteen vegetable crops as reported by the Czech Statistical Office. This study employs the same methodology for the de-trending crop yields over time, as was described by Potopová *et al*. (2015a, 2015d). The statistical analysis of crop production was conducted using the average yields derived from all traditionally growing districts in the Elbe lowland (Liberec Region: Litoměřice, Roudnice, Lovosice, Chomutov and Ústí nad Labem;

Central Bohemian Region: Brandýs nad Labem, Mělník, Kralupy nad Vltavou, Kolín, Český Brod, Nymburk, Mladá Boleslav and Praha and Hradec Králové Region: Nový Bydžov, Hradec Králové, Dobruška and Jaroměř). The annual series of the vegetable yields of celeriac, carrot, root parsley, kohlrabi, savoy cabbage, cauliflower late, tomato, cucumber, cabbage late, peas, onion and garlic at the regional level for the period 1989-2014 were used to assess the crop sensitivity to drought as quantified by the SPEI for each month of the growing season. The selected production period correspond to socioeconomic transformation of the farming industry in the CR after 1989 (Hlavinka *et al*., 2009), and possible also due to recent temperature increases as suggested by Brázdil *et al*. (2012).

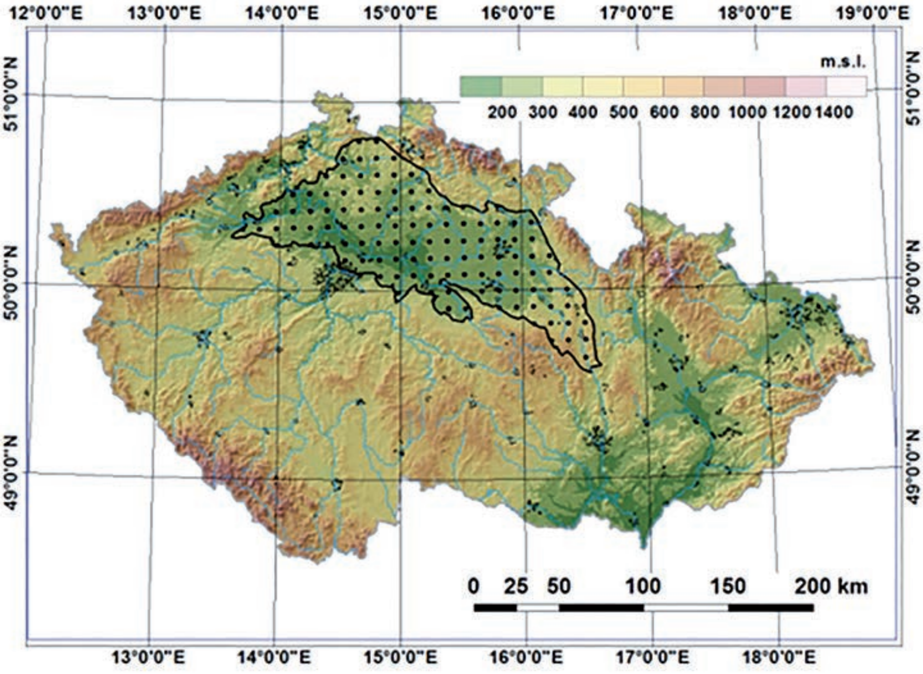

Figure 1. Distribution of the grid-points in the vegetable producing areas in the Elbe River Lowland, and their boundaries within the Czech Republic.

2.2. *Climate datasets*

This study combines a dense station and gridded networks, which makes to evaluate drought stress impact on vegetable yields at the high temporal and spatial resolution. Historical climate data for a regular gridded network with a high horizontal resolution of 10 km (CZGRIDS) and 305 climatological stations for the period 1961-2014 from the Czech Hydrometeorological Institute (CHMI) were applied. High-density gridded datasets allow very precise and detailed delimitation of areas with growing vegetables compared with station network datasets in the ERL. The station network with altitude less than 300 m a.s.l. has significantly fewer units located primarily in non-vegetable growing regions. Whereas to illustrate the drought risk shifts during the crop cycle at the national level, the tendency of the drought months for the multi-temporal scales, we used 305 climatological stations. The climatological stations and gridded network across the country, and the quality control of the datasets were previously described by Štěpánek *et al*. (2011). Monthly means of daily values of maximum and minimum temperature, mean temperature, wind speed, sunshine duration, relative humidity, and rainfall have been used to calculate reference evapotranspiration (ET_r), crop evapotranspiration, (ET_c), water balance for each crop (*D*) and the SPEI. The procedures mentioned here were conducted using the software packages ProClimDB and AnClim (Štěpánek, 2010).

2.3. Estimation of evaporative demand

The evapotranspiration was calculated for each month of the year for several methods: Thornthwaite (1948), Hargreaves (1985, 2003) and Penman-Montheith (PM, Alen *et al*., 1998), but for this study, only PM equation and the months of the growing season of each crop were selected for analysis. Recent drought studies (e.g. Dai, 2011; Vicente-Serrano *et al*., 2011; Begueria *et al*., 2014; Trnka *et al*., 2015a, 2015b) have enhanced the debate on the effect of ET_r, actual evapotranspiration (ETa), and/or potential evapotranspiration (PET) on drought quantification. The ET_r expresses the evaporating power of the atmosphere at a specific location and time and does not consider the crop characteristics and soil factors (Allen *et al*. 1994). But, ET_r calculated at different locations or in different seasons are totally comparable. ET_a is the evapotranspiration of particular crop at particular place and time (Allen *et al*., 1998) which takes into account also the plant characteristics and stress caused by non-standard conditions (i.e. pests and diseases, soil fertility, water shortage or water logging). The methods described above enables us to predict the effects of climate on the evapotranspiration of the reference crop. However, to relate ET_r with crop evapotranspiration (ET_c), it is possible to use crop coefficient (Kc), which represent differences in the soil evaporation and crop transpiration rate between the crop and the grass reference surface. The usefulness of the $ET_r \cdot$ Kc method (ET_c) has already been demonstrated at a national scale (Hlavinka *et al*., 2011). As soil evaporation may fluctuate daily as a result of rainfall or irrigation, the Kc expresses only the time-averaged (multi-day) effects of crop evapotranspiration.

In order to evaluate differences between the crop water availability and the atmospheric water demand of the majority vegetables, we applied the following approaches: (i) ET_r by the PM equation has been calculated; (ii) daily ET_c for each crop has been calculated by multiplying K_c and $ET_{r.}$; and (iii) differences between daily precipitation and ET_c has been used to calculate mean crop water balance (*D*) per main growth stages, as an indicator of plant stress. The Kc depends on the kind of vegetable and its phenological stage (i.e., crop height and the leaf area index) (Table 1). Consideration of Kc in crop growth during the life cycle of vegetables obtained from bibliography referring to area similar to those of the central European agriculture conditions (Geisenheim Irrigation Scheduling, 2014) and indirectly in field experiments at farm level from ERL (e.g. Potop and Turkott, 2014), together with evaporative demand values (ET_r), allowed us to determine the period of the highest crop sensitivity to drought stress (PCSD).

Table 1. Overview on the crop coefficients (Kc) for selected vegetables during stages of development.

Type of vegetables		**1st Stage**	**2nd Stage**	**3rd Stage**	**4th Stage**
Apium graveolens L. var. rapaceum	Celeriac	*after transplanting*	*≥7 leaves*	*bulb starts to develop*	*100% ground cover*
		$K_c = 0.5$	$K_c = 0.8$	$K_c = 1.1$	$K_c = 1.4$
		$K_c = 0.3$	$K_c = 0.6$	$K_c = 0.8$	
Brassica oleracea L. convar. *capitata* var. *capitata*	Cabbage	*after transplanting* $K_c = 0.5$	*≥8 leaves* $K_c = 0.8$	*≥11 leaves* $K_c = 1.2$	*developing heads* $K_c = 1.3$
Allium cepa L.	Onion	*after emergence* $K_c = 0.5$	*≥5 leaves* $K_c = 1$	*≥8 leaves* $K_c = 1.2$	*bending leaves* $K_c = 0$
Solanum lycopersicum L.	Tomato	*after transplanting* $K_c = 0.5$	*height≥0.75m* $K_c = 0.8$	*height≥1m* $K_c = 1.2$	-

2.4. Identification of drought stress impact on vegetable yields

In this study the R package SPEI and ProClimDB software have been run to calculate the SPEI at 1-, 3-, and 6-month lags, which uses as input variables monthly precipitation totals, station/grid latitude, and the PM algorithm to calculate ET_r, based on the method developed by Vicente-Serrano *et al*. (2010) and Begueria *et al*. (2014). Precipitation has accumulated over a period of time in the SPEI stands for the water availability, while ET_r stands for the atmospheric water demand. District and specific sowing dates are not available. For each crop-district combination a fixed sowing date is assumed during the entire period study. Thus, the gridded dataset with a spatial resolution of 10x10 km was used to calculate the monthly and/or seasonal SPEI for each crop from planting to harvest: April-October (for celeriac), April 15 to September 30 (for carrot), March to October (for root parsley), March 15 to June 30 (for kohlrabi and peas), April 15 to August 31 (for savoy cabbage), May 15 to September 30 (for cauliflower late, tomato and cucumber), May to October (for cabbage late) and March-August (for onion). Lagged impacts of drought stress of more than one vegetation season are a minor importance in field-grown vegetables compared with the other agriculture crops (e.g., winter cereals, grapevine). The relationship between drought and de-trended yields of vegetables was assessed with time series of the SPEI at 3-month lag being the independent variable and the series of yield residuals being the dependent variable. As such, this lag captures the drought conditions for the PCSD. In our analysis, the coefficient of determination (R^2) shows the percentage of variability in the yield losses explained by the effects of drought stress.

3. Results and discussions

3.1. Drought patterns and their tendency during the main crop growth cycle of vegetables

Here, to understand the evolution of significant changes in drought frequency, the linear trends and regression slopes of the number of drought months per decade for each station between 1961 and 2014 at 1-, 3-, and 6-month lags were calculated. Magnitude of the trends of the number of drought months detected by the SPEI at 3-month lag is presented as an example in Fig. 2a. The SPEI computed over several time scales indirectly considers the effect of accumulating precipitation deficit and high potential evapotranspiration, which are critical for growing field vegetables. The significance of these trends was tested using a Student's one-tailed t-test at the 95% significance level in all months of the year and during the main growing season. Overall, the spatial distribution of the magnitude of the trends varied depending on the month and accumulated period.

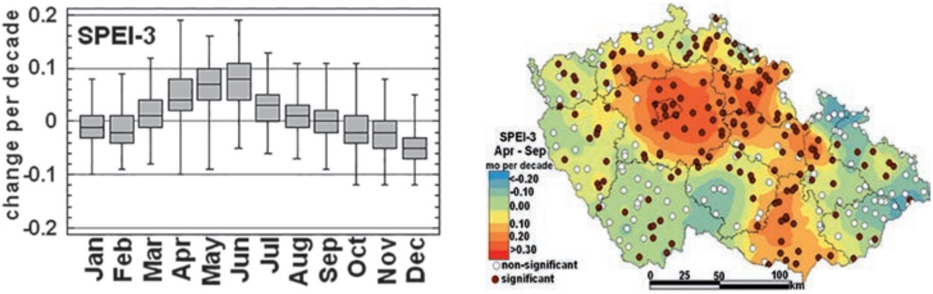

Figure 2a. Magnitude of the trends (unit month per decade) of the number of drought months in all months of the year (left panel), and during April-September (right panel) detected by the SPEI at 3-month lag from 1961 to 2014.

The Elbe River Lowland (Fig. 2b) experienced a general drying tendency in the spring months at short-term lags with a decreasing trend from the 1970s-1980s, and a sharp increasing trend after 1990s. Moreover, the majority of the stations were characterized by increasing drought risk occurrences in the April-June period. For the SPEI-1, significant positive trends predominated (i.e. increasing frequency of dryness) in April (at 286 stations), while non-significant negative trends (i.e. decreasing frequency of dryness) were observed in October (not shown). For the 3-month SPEI, significant positive trends were detected in June (at 290 stations), followed by May (at 283 stations) (Fig. 2a). For the SPEI -6, positive trends predominated in the June-September period, whereas almost all of the stations were characterised by non-significant negative trends in the winter months.

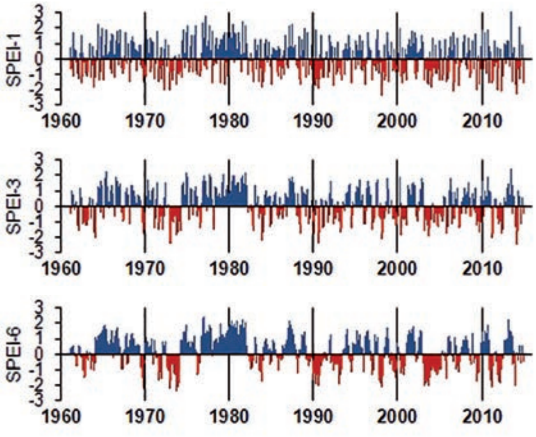

Figure 2b. Temporal evolution of the SPEI at 1-, 3- and 6-month lags from 1961 to 2014 at the Nymburk district (Elbe River lowland). 1961 to 2014.

During the main growing season at 1-, 3-, and 6-mo lags, there were many more positive trends than negative trends, with positive trends also tending to be larger than negative trends. Moreover, for the spatial distribution of stations with significant positive trends, it is worth noting that these stations are predominantly located in the main grown-vegetable regions (right panel of Fig. 2a). Interestingly, the SPEI also detected the fact that the significant drying trends seem to be more frequent at stations in the northeast and north-central parts of the country. The results fit the general picture described by Trnka *et al*. (2015a, 2015b) which used other drought indices. Analysis of the magnitude of the trends per decade at 3-month lag, with ranges from 0.20 to 0.35 months per decade, showed that more than half of the stations (174) inclined toward a higher drought frequency during April-September. The changes are most pronounced in the *Fruiting*, *Root* and *Brassicas* regions (mainly in the South Moravian Region, Central Bohemian Region, Ústí nad Labem Region, Hradec Králové Region, and South Bohemian Region). A pronounced trend towards higher drought frequency can be observed in the Prague plateau in conjunction with the Elbe river valley. Increasing drought severity should be evident in increasing impacts on systems sensitive to drought, including vegetable field production.

3.2. Regional cropping patterns and yield losses

The temporal evolution of crop yields from 1989 to 2014 presents increased trends for all field-grown vegetables, besides of garlic and cauliflower in Elbe lowland (Fig. 3a). Because of plant breeding and improved horticultural practices, the vegetable production of carrots, celeriac, cabbage, picking and salad cucumber have significantly increased with trends of 7.2, 5.3, 5.2, 4.5 and 9.1 tha^{-1} decade^{-1}, respectively. Field-grown vegetable production in this region, in the observed period, was yearly organized on 4353 hectares on average, with decreasing tendency. Focusing on sowing structure, the largest areas were under onion production, which occupied 34% on average of total used areas in farm grown-vegetable. After that, a significant contribution came from: root parsley (15%

of total planting vegetable areas), cabbage (10%), cauliflowers (8%), green peas (7%), celeriac (5%) and carrots (5%) (Fig. 3b).

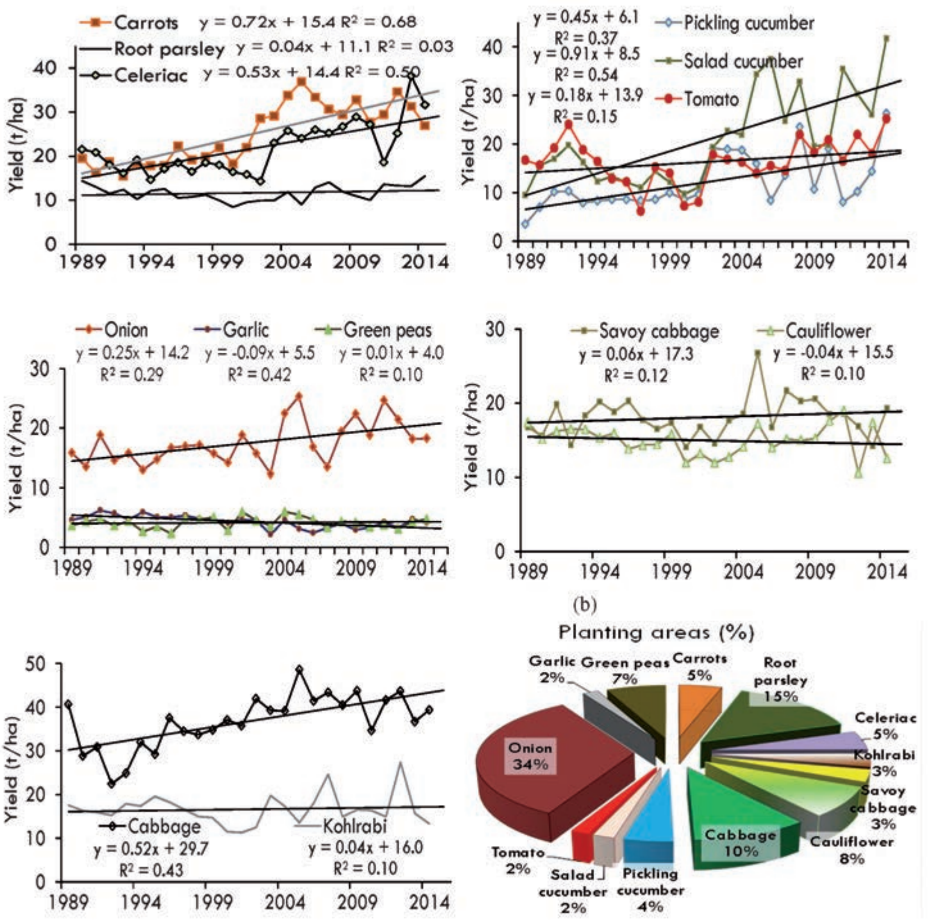

Figure 3. Temporal trends of vegetable yields (a) and total sowing/planting area (b) in Elbe lowland region during the 1989-2014 farming years.

To understand how the SPEI within the growing season, over the period 1989-2014, controlled the yield variation, we calculated the percentage of yield losses and gains for each crop in the ERL (Fig. 4). Estimation of yield responses to tendency of the SPEI is illustrated in Fig. 4. The average yield of *Root vegetables* from 1989 to 2014 was 25.1 tha^{-1} for carrots, 11.6 tha^{-1} for root parsley, and 21.8 tha^{-1} for celeriac. The yield gaps and gains of *Root vegetables* ranged from -35% to 37%, respectively. The highest losses for celeriac were by -35% (2011), -27% (2002) and -18% (1994); for carrots were by -27% (2000) and -16% (2014); for root parsley were by 19% (2010) (Fig. 4). The long-term average *Brassicas* yields were 16.6 tha^{-1} for kohlrabi, 18.1 tha^{-1} for savoy cabbage, 14.9 tha^{-1} for cauliflower and 36.8 tha^{-1} for cabbage. The estimated yield gaps and gains ranged from -31% and 55%, respectively. While the highest losses for kohlrabi were by -30% (2001), -28% (2000) and -27% (2014); for savoy cabbage were by -24% (2000) and -22% (2013); for cauliflower were by -31% (2012) and -21% (2014) and cabbage were by -28% (1992), -22% (1993) and -15% (2010).

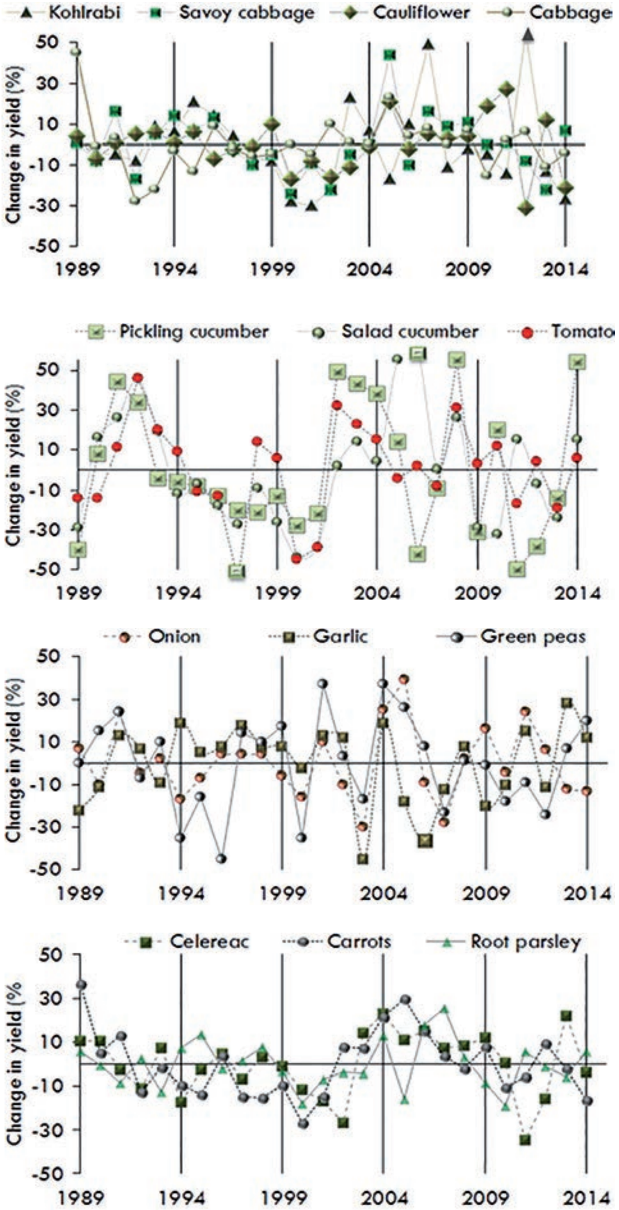

Figure 4. The temporal evolution of relative changes in yield (%) of vegetables as result of impacts of drought (wet) stress represented by the SPEI during the growing season of each crop.

The average yield of *Fruit vegetables* was 12.1 tha^{-1} for pickling cucumber, 20.8 tha^{-1} for salad cucumber and 13.3 tha^{-1} for tomato. Their yield gaps yield gains ranged from -55% to 60%, respectively. The highest losses for pickling cucumber were by -45% (2011), -42% (2006) -40% (1989) and -38% (2012); for salad cucumber were by -44% (2000), -39% (2001), -32% (2010), and for tomato were by -45% (1997), -44% (2000), -39% (2001) (Fig. 4). The long-term average *Bulb* yields were 17.5 tha^{-1} for onion and 4.3 tha^{-1} for garlic. Their yield gaps and gains ranged from -30% to 39%, respectively. The highest losses for onion were by -30% (2003) and -28% (2007), for garlic: -45% (2003) and -36% (2006). The long-term average *Legume* yields was 4.2 tha^{-1} for green peas and it yield gaps and yield gains ranged from -45% to 37%, respectively (Fig. 4). The highest losses for green peas were by -45% (1996), -35% (1994, 2000) and -24% (2012). For *Fruit* vegetables, the years with yield losers prevailed upon years with yield winners.

3.3. Period of the highest crop sensitivity to drought

Vegetable crops do not tolerate well large soil moisture anomalies; they are susceptible to even short-term droughts. In addition to intensity and duration, the timing of droughts is a crucial factor due to the pronounced seasonal cycle of many vegetable crops (Potopová *et al*., 2015c). In order to detect period of the highest crop sensitivity to drought stress, we used *D* impact indicator ($P-ET_r\ Kc$) for individual growth stages (Table 1) over the period 1989-2014, with the aim of finding the best period during the growing season when extensive yield losses are attributed to strong moisture deficit. As shown in Table 1, values of Kc for the majority vegetables increase from a minimum value at planting until maximum Kc is reached at about full canopy cover. Conversely, late in the season, the ET_c of Bulb vegetables (onion) declines relative to ET_r because of aging, so the K_c and ET_c (water requirements) decreases. Results showing the strength of relationship between the monthly *D* and yield departures are summarized in Table 2.

Table 2. Correlation coefficients (r) between the mean crop water balance (D) with yield departures over the period 1989-2014.

	March	April	May	June	July	August	September	October
Fruiting	0.01	0.01	0.39	0.30	0.28	0.18	0.13	0.11
Root (celeriac)	0.01	0.09	0.10	0.11	0.14	0.41	0.28	0.24
Brassicas	0.10	0.11	0.26	0.37	0.51	0.12	0.16	0.10
Bulb	0.30	0.35	0.12	0.14	0.20	0.18	0.10	0.02
Legumes	0.19	0.23	0.16	0.48	0.06	0.01	0.01	0.01

Periods of crop sensitivity to drought (PCSD) within the growing season were marked as shaded.

Fruiting vegetables were susceptible to drought within the mid-May-June-July ($0.28 < r < 0.39$), when could explain most of the variability in yields reduction. The *D* (in mm/period) indicator demonstrates that the prevalence of moisture deficit (≤-80 mm) during PCSD of *Fruiting* tends to increase (not shown). The *Fruiting* vegetables are most sensitive to water deficit during and immediately after transplanting and during flowering and yield formation. Water deficit during the flowering period causes flower drop (Petříková *et al.,* 2006, 2012).

While for tomatoes moderate water deficit (D≤-50 mm) during the vegetative period enhances root growth. Among vegetables, tomato is an efficient user of water in terms of total dry matter production.

The PCSD for *Bulb* vegetable occurs in March-April period ($0.30 < r < 0.35$), when plants are a small and relatively inefficient rooting system. The PCSD for Legumes vegetable occurs in June ($r = 0.48$), when drought and high temperatures could cause substantial yield losses. In relation to the *D* for *Brassicas* and *Root*, the moisture deficit increases during the growing period with a peak toward the end of the season (from -45 to -155 mm). Whereas the PCSD occurs from heads begin to form up to 80% expected head size reached (May-June-July; $0.26 < r < 0.51$). For *Root,* the PCSD occurs when the beginning of the storage root up to 80% (in particularly for celeriac, August-September-November) of the expected root diameter ($0.28 < r < 0.41$).

3.3. Relationship between the SPEI and yield losses

The SPEI was averaged during PCSD for each type of vegetables, which includes the months that are important for yield formation. Further, regression analysis was made to study the relationships between the yield losses and SPEI at 3-month lag for PCSD (Table 3). The 3-month lag incorporates moisture conditions from the current month and the preceding two months. The values of the SPEI are thresholds when yield departures (%) dropped under regional average. The regression model based on the SPEI series explained only 19% (R^2=0.19) of the variability of the annual yield losses in onion (*Bulb* vegetables). The *Bulb* yield losses controlled by water deficit during PCSD were not as substantial, for example, when the SPEI was below -1.9, yield gaps was slightly more than -12% (with exception of 2003 and 2006). Overall, the onion is most sensitive to water deficit during the first part of the growing season. However, according to the SPEI-3, onion is less affected by even the longest dryness episodes in this period.

Table 3. The table summarizes the coefficient of determination (R^2) of the second-order polynomial regression between the SPEI at 3-month lag (mean per PCSD) and yield losses of various vegetables for the period 1989-2014 at regional level.

	R^2	p-level	Thresholds of the SPEI	Averaged yield losses, %
Fruiting	0.28	0.05	dropped below -3.0	-30.0
Root	0.60	0.05	dropped below -1.5	-15.0
Brassicas	0.62	0.05	dropped below -1.5	-30.0
Bulb	0.19	0.05	dropped below -1.9	-12.0
Legumes	0.34	0.05	dropped below -1.0	-19.0

When the value of SPEI-3 for PCSD was between -1.49 and 0.99, the yield moderate increased for *Fruiting* vegetables. Conversely, when the SPEI-3 dropped below -3.0, the yield losses were about -30% and a negative influence is apparent from threshold of the SPEI≤-1.5. The SPEI can potentially influence the *Fruiting* yield reduction during PCSD up to 28 % (R^2=0.28). The decrease in yield of *Legumes* grown under moderate drought conditions (the mean SPEI≤-1.0 for PCSD) is largely due to the reduction in the number of pods per plant (R^2=0.34). As shown in Fig. 2, June is attributed the first most important month at the SPEI at 3-mo lag in extensive yield gaps. The consequence of dry PCSD on yield losses of *Root* vegetables was about -15% for the SPEI lower than -1.5 (R^2 =0.60). The link between the SPEI (mean per PCSD) and yield of *Brassicas* is strong, and explains 62 % of the variability of yield losses (R^2 =0.62). The negative influence of moisture anomalies was still observed when the SPEI dropped only below -1.5.

Conclusions

The advantages of this study is that it is based on calculation of drought stress within the growing season of the majority of vegetables grown under field conditions, based on the SPEI multi-scalar drought index in combination with crop specific factors, crop water balance and series of crop yields, which reflected technological progress and socio-economic conditions. The SPEI at various time scales was calculated during the main crop growth cycle of vegetables for the period 1961-2014, based on precipitation and input dataset for ETr by the PM method in the Elbe River lowland, representing central European agriculture conditions. Whereas, in order to evaluate differences between the crop water availability and the atmospheric water demand of the majority vegetables, the PM approach for grass ET_r estimation was also used in connection with K_c that are linked to phenological development, and finally ET_c was obtained. Further, mean crop water balance per main growth stages, as an indicator of plant stress, was calculated. Moreover, in order to remove the effect of new management practices and technologies, and thus to isolate the variation resulting from climate conditions, the de-trended yield was used. The correlation between the time series of averaged values of the SPEI for the period of the highest crop sensitivity to drought and yield losses of 13 vegetable crops has been done. This improvement increased the applicability of the SPEI in agriculture drought impact on rainfed and/or irrigated field crops grown under various agronomic management systems. We detected the thresholds for detrimental impact of drought defined by the SPEI during PCSD for each type of vegetables in the ERL. The SPEI at 3-month was highly correlated with yield losses in this region, which can effectively evaluate the effect of drought on vegetable production. For vegetable crops, a weak correlation between the SPEI for PCSD and yield losses of Bulbs was found; whilst the strongest correlation was found during PCSD for Root and Brassicas. The effect of the SPEI on yield formation of vegetable cultivars grown under field conditions was achieved up to 62% in the study region. The remaining variability of yield losses that was still unexpected by the SPEI was likely caused by a combination of factors that are beyond the scope of the SPEI. In a previous study (Potopová *et al.*, 2015d) was found that, for arable lands (53% in the CR), the strength of correlation between the SPEI and soil moisture is strong, and explains more than 56 % of the variability of soil water content. Thus, a strong relationship between the SPEI and yield gaps of vegetables could explain how drought in conjunction with higher temperature and higher evapotranspiration during PCSD could substantially contribute to reducing regional yield.

We can conclude that vegetable crops are one of the highest water consuming plants (especially Brassicas), and the highest negative drought impact on crops partially was compensated by high-quality soils and irrigation. Increasing drought frequency will reduced the irrigation water availability, decrease soil fertility, increase soil erosion and salinity incursion, which are major restrictive factors in sustainable vegetable production. This information can be used in developing strategies to improve the quality of crops grown in stress environments by limiting the adverse effects of drought stress.

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