ORIGINAL PAPER

Comparison of SPI and SPEI applicability for drought impact assessment on crop production in the Danubian Lowland and the East Slovakian Lowland

L. Labudová[1,2] · M. Labuda[1] · J. Takáč[3]

Abstract Drought belongs among the main impact factors considering crop yields. Therefore, this paper is focused on the assessment of drought occurrence and intensity as well as on its impact on crop yields on the Danubian and the East Slovakian lowlands with the spatial resolution at district level. Yield data were the main limitation of the study, which resulted in the limited length of the assessed period (1996–2013). The standardized yields of ten crops (winter wheat, spring wheat, winter barley, spring barley, rye, maize, potatoes, oil-seed rape, sunflower, and sugar beet) were correlated with monthly, 2-, and 3-monthly standardized precipitation index (SPI) and standardized precipitation and evapotranspiration index (SPEI). For this purpose, the common significance level of alpha = 0.05 was used. The temporal evolution of both indices and drought occurrence during the period 1961–2013 were assessed for each district. Most crops show a higher correlation with the SPEI than with the SPI in contrast to potatoes, which reached a higher significant correlation using the SPI. The correlation also increases with increasing number of months within a time step. The highest correlation can be seen between maize and the 3-monthly SPEI in August representing summer precipitation and potential evapotranspiration conditions. Furthermore, a very high correlation was recorded considering sugar beet, which is influenced mainly by summer precipitation, because the correlation coefficient between the sugar beet and the 3-monthly SPI is as high as using the 3-monthly SPEI. Crop yields in the East Slovakian Lowland do not seem to be influenced by wet/dry periods identified using the SPI and the SPEI as their correlation with both indices is quite low and insignificant.

1 Introduction

Drought is a slowly developing extreme climatological event, which often has the longest duration, but the lowest possibility to be predicted at the moment (Mishra and Singh 2010). In a changing climate, drought has become a global problem as the need to provide enough quality and healthy food for an increasing human population is very high. In the last decades, it was spent much effort to find methods, which would be the most suitable for drought monitoring and its practical usage (Svoboda et al. 2015). One of the most affected human activities is agriculture. Therefore, it pays still more attention to the assessment of drought impacts on agricultural yields.

The most frequently used indices for the meteorological drought assessment are the standardized precipitation index (SPI), the standardized precipitation evapotranspiration index (SPEI), and the Palmer drought severity index (PDSI). Several studies compare the SPI or the SPEI and the PDSI (Hayes et al. 1999; Szalai et al. 2000; Brázdil et al. 2008; Paulo et al. 2012; Lloyd-Hughes and Saunders 2002). The analysis by Hayes et al. (1999) shows that the SPI identifies the drought at least about 1 month earlier than the PDSI. A similar

✉ L. Labudová
livia.leskova@uniba.sk; livia.labudova@shmu.sk

M. Labuda
mlabuda@fns.uniba.sk

J. Takáč
j.takac@vupop.sk

1 Faculty of Natural Sciences, Comenius University in Bratislava, Mlynská Dolina, Ilkovičova 6, 842 15 Bratislava, Slovakia

2 Slovak Hydrometeorological Institute, Jeséniova 17, 833 15 Bratislava, Slovakia

3 National Agricultural and Food Centre-Soil Science and Conservation Research Institute, Gagarinova 10, 827 13 Bratislava, Slovakia

study was published by Paulo et al. (2012) for Portugal. The correlation between the PDSI and the SPI or the SPEI is in a semiarid zone higher than in a humid zone, especially when using longer time scales (9- and 12-monthly scales). In contrast, the correlation coefficients between the SPI and the SPEI decrease from high values in the humid zone to lower values in the semiarid zone.

The SPI is a worldwide used index, which is based only on monthly precipitation sums. The simplicity of its calculation enables its usage in different disciplines such as agriculture and water management. Therefore, many studies, which were focused on drought assessment, used this index (Capra and Scicolone 2012; Agnew 2000; Lloyd-Hughes and Saunders 2002; Brázdil et al. 2008, Vicente-Serrano and Lopéz-Moreno 2005).

Eitzinger et al. (2009) concluded that agriculture not only in the Mediterranean region but also in central Europe is at risk by drought in combination with heat waves. It resulted in higher attention to this phenomenon in the last named region. Büntgen et al. (2010) used historic tree rings and meteorological data from Brno from 1803 to analyze drought occurrence using the PDSI in the south of Moravia. They identified several historical dry periods and proved a drying tendency since 1981. Similar results were presented by Potop et al. (2012a and 2013) for the Czech Republic, where especially lowlands showed the increasing frequency of drought occurrence using the SPEI at the end of the twentieth and the beginning of the twenty-first century. Short- and midterm droughts occur in the whole territory every 3 and 5 years, respectively. The tendency to more intensive drought periods was verified for the southeastern part of the Czech Republic (Trnka et al. 2009; Trnka et al. 2013; Dubrovsky et al. 2008). Szalai et al. (2000) proved drying tendencies in the late spring and early summer as well as during the late autumn in Hungary. Their correlation analysis between soil moisture and the SPI with various time steps showed the closest relationship with the 2-monthly SPI.

Considering agriculturally oriented studies, Potop (2011) assessed drought severity and its impact on maize in Moldova. The analysis showed that the SPEI reaches higher correlation with corn yields than the SPI. Droughts in May, July, and August contribute the most to yield losses in that region. In the next years, several similar studies have been made for Czech Republic (Potop et al. 2012b; Kolář et al. 2013; Potopová et al. 2015). Potop et al. (2012b) noted that dry/wet periods are the most important for vegetable during sowing and 3 weeks prior harvest. Considering drought occurrence during the whole twentieth century and the beginning of the twenty-first century, winter droughts prevailed approximately till 1960s, while spring and summer droughts prevailed in the rest of the study period. Kolář et al. (2013) focused on the two most important cereals in the Czech Republic, spring barley and winter wheat. Extremely

or very high losses for both cereals, but especially for spring barley, were recorded in 2000. In that year, high temperatures, low precipitation, and the negative PDSI during all months were typical. Similar patterns occurred also in 1993 and 2007. The latest study by Potopová et al. (2015) assessed drought impact on 11 crops in 1961–2012 in the Czech Republic on a national level. The highest yield-drought correlation was found for cereals considering the crop type and in the months April to June considering the temporal occurrence. Among them, the most vulnerable are spring cereals as overwintering cereals are better to cope with drought. The highest yield losses were noted in years 2000, 2003, and 2007 as well as in 2012 due to very dry spring months.

The assessment of meteorological drought occurrence (Šiška and Takáč 2009) in Slovakia using climatic and agroclimatic indices such as the climatic water balance (PET–R, where PET is a potential evapotranspiration and R is a precipitation) and evapotranspiration deficit (PET–ET, where ET is an actual evapotranspiration) identified two very dry regions, where water deficit exceeds 250 mm. They are the Danubian Lowland and the East Slovakian Lowland, the two most agriculturally productive regions in Slovakia. Eitzinger et al. (2013) concluded that the productive potential of the Danubian Lowland will be limited by decreasing water availability for plants and by heat waves. Therefore, the assessment of drought impact on crop yields is of very high importance in this region. A similar study has not been done yet in the territory of Slovakia.

In this paper, drought occurrence was assessed using the SPI and the SPEI. The SPI has been used often in hydrological studies in Slovakia, but never in climatological or agricultural studies. In such studies, the PDSI was more frequently used. The SPEI has never been used in Slovakia as only the absolute values of the climatic water balance (PET–R) were used in the past. Therefore, the first aim of the study is to assess the drought occurrence in the selected territories using the indices, which are worldwide used. The second step was to find out if both indices are suitable for the drought impact assessment on crop yields in the two selected lowlands. Only the percentage of precipitation normal has been used in agriculturally oriented studies in Slovakia. Therefore, our task was to discover if the SPI and the SPEI can be used in such focused studies. The standardized yield data were correlated with these indices to find relationship between drought and crop yields in the two agriculturally most important lowlands in Slovakia. It stands to reason that this correlation is quite high according to the results found in neighboring countries, which were described in the earlier paragraph. Even though the SPI is the worldwide used index, it deals only with the precipitation totals. According to the climate change, connected with an increasing air temperature, it has been discussed recently that it is not enough to monitor only precipitation, but the variables reflecting the change in evapotranspiration should be involved

in the drought assessment. Therefore, the SPEI was developed by Vicente-Serrano et al. (2010). Labudová et al. (2015) showed changes in air temperature and precipitation in Slovakia in the period 1931–2014. The significant increase of mean air temperature means also higher importance of evapotranspiration for drought occurrence in the conditions without significant precipitation increase. This led us to the question, which of these two indices is more suitable for the drought impact assessment on crop yields in Slovakia? We assumed that the role of evapotranspiration is very important in the selected territory and cannot be omitted. In principal, the SPI and the SPEI differ only in the involving of the PET, which means that the difference in their results lies in it. If we would assess the correlation between the crop yields and the PET as a single variable, it would not prove its importance as it is necessary to consider it in the context of water balance (considering not only water demand—PET, but also water surplus—precipitation). Therefore, we compared the correlation coefficients between the SPI and the crop yields on one side and the correlation coefficients between the SPEI and the crop yields on another.

2 Data and methods

2.1 Data

For drought indix estimation, monthly precipitation totals from 13 meteorological stations were used in the period 1961–2013. The data were provided by the Slovak Hydrometeorological Institute (SHMI). The SHMI checked their homogeneity using the MASHv3.03 software (Szentimrey 2003).

The eight selected stations are located in the Danubian Lowland (DL) and the others in the East Slovakian Lowland (ESL) (Fig. 1). The stations are equally distributed in the lowlands to catch all regional differences. Their density was satisfactory for the purposes of our study and offered a view on precipitation distribution without large deviations from their "real" proposition as the differences within the regions are quite low. Both regions are the most important regions for agriculture in Slovakia.

The raw yield data were provided by the Statistical Office of the Slovak Republic (2015) and they were tested for the normality of distribution. The assessed period was 1996–2013 due to several reasons. The main of them is the fact that the administrative division before the year 1996 was totally different. Some districts did not exist and were only parts of other districts. It was not possible to get data for districts, which are known at the present. Another problem was to access data, which are kept as confidential or are simply missing. Therefore, rye yields were not considered for the Dunajská Streda, Galanta, Hlohovec, Šaľa, and Topoľčany districts.

None of the districts had rye yield data for the year 2013 due to the same problems that excluded the Bratislava, Komárno, Pezinok, Michalovce, Sobrance, and Trebišov districts from the sugar beet yield assessment and the Bratislava, Hlohovec, Nitra, Pezinok, Piešťany, Šaľa, Topoľčany, Zlaté Moravce, Sobrance, and Trebišov districts from the spring wheat yield assessment.

According to Hydromeliorácie š.p., which is the only provider of irrigation systems in Slovakia, the irrigated area covered 316,000 ha of the whole country in 1990 and 297 mil m^3 of water was spent by irrigation. Most of this area was located in the DL and the ESL. In the 1990s, the irrigation in Slovakia was inhibited and the irrigated area covered only 8000 ha with water requirements 6 mil m^3 in 2010. In the last 5 years, the acreage varies from 14,000 ha to 25,000 ha and the water requirements vary from 6 to 21 mil m^3. It is a very low number to consider an irrigation impact on the crop yields due to the fact that only a part of it lies in the analyzed lowlands. The irrigation is used mainly for vegetable production and also for sugar beet and maize production.

2.2 Study area

Although they are located in the south of Slovakia and the distance between them is only about 300 km, specific site conditions cause climatic differences between them. Both lowlands are located in the precipitation shadow of the Carpathians for westerly, northwesterly, and northerly air masses. The ESL is located in the precipitation shadow of the mountains in the middle of Slovakia, which results in drier conditions during the westerly extratropical cyclonic situations. But another particularity of the ESL is that one of the lowest parts of Carpathians is located northward from it and the air masses can easier cross the barrier of the mountains. After then, the air masses flow along the river basins, which are oriented in north to south direction. Therefore, the ESL is wetter during the northwesterly and the northerly extratropical cyclonic situations than the DL. For the same reasons, cold air accumulated on the Polish side of the mountains can cross the Carpathians more easily in winter than in the western part of the country. It happens mostly in winter during both cyclonic and anti-cyclonic situations, when colder air mass is on the northern side of the mountains. The speed of air flow depends on the pressure gradient. On the other hand, only the Little Carpathians, a low mountain range, represent a barrier for the westerly cyclonic air masses considering precipitation in the DL. Both lowlands are on the windward side for southwesterly, southerly, and southeasterly cyclonic situations, but the ESL is wetter during the last named situations than the DL. On the both lowlands, most of the precipitation falls during May, June, and July, which are usually the months, which are rich in precipitation in comparison to the winter months.
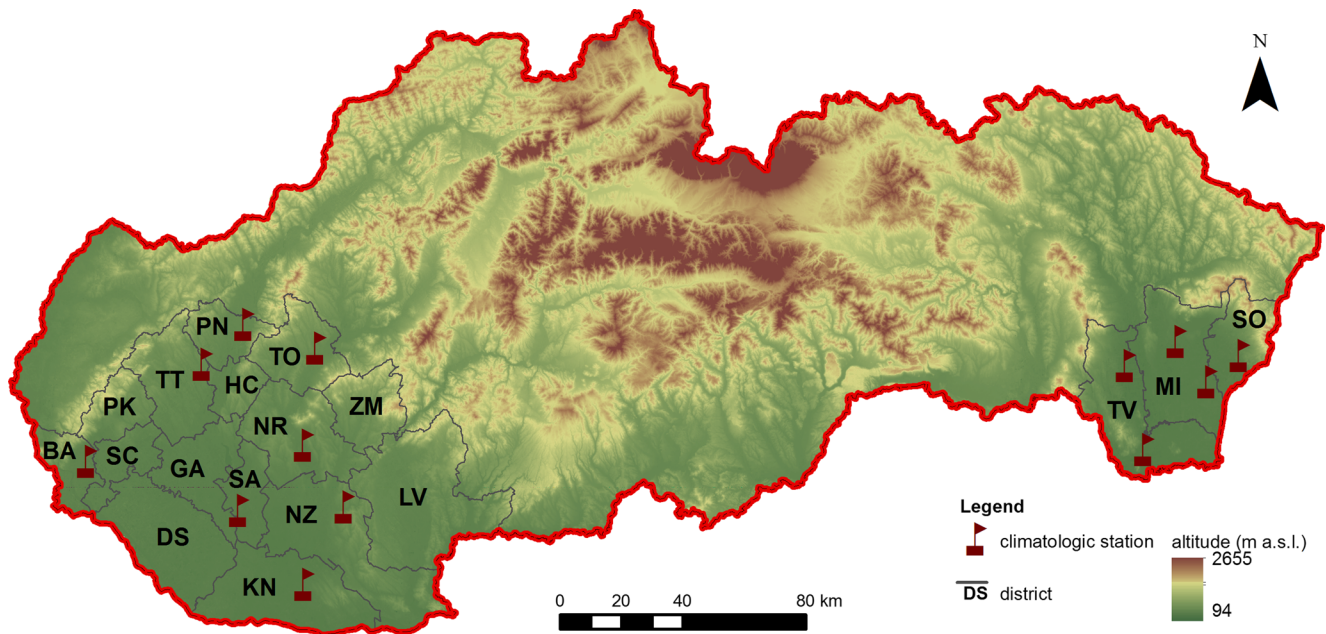
Fig. 1 Location of selected lowlands and meteorological stations

The Danubian Lowland is situated to the north of the Danube river in the SW part of Slovakia (Fig. 1). Its climate is warm (average annual air temperature between 9 and 10.5 °C) and dry (mean annual precipitation of 500 to 550 mm). Winter is mild (with an average air temperature in January from −1 to −2 °C) and the average air temperature in July varies from 19 to 21 °C (Šťastný et al. 2015). Major soil types occurring in the DL are Chernozems (47 %), Luvisols (22 %), Fluvisols (15 %), and Phaeozems (14 %). A dominant soil texture is silt loam, covering 72 %. The total cropland area covers 672,000 ha (Takáč et al. 2015). According to groundwater monitoring proceeded by SHMI, a groundwater table is in the depths of <1.5 m on the floodplains of the DL and on the Žitný ostrov (Rye Island—a river island between the Danube and the Little Danube, which is an important fresh water reservoir).

The East Slovakian Lowland is located in the SE part of Slovakia. Its climate is warm (average annual air temperature from 8 to 9 °C) and dry to moderately humid with mean annual precipitation of 550 to 750 mm. Winter is mild due to climate change in the last decades (Labudová et al. 2015). The average air temperature in January varies from −2 to −3 °C and the average air temperature in July reaches from 19 to 20 °C (Šťastný et al. 2015). Dominant soil types in the ESL are Fluvisols (39 %), Stagnosols (19 %), Gleysols (16 %), and Cambisols (9 %). Considering a soil texture, silt loam covers 52 %, clay loam 20 %, and clay 21 % of the total area (Vilček et al. 2007). The total cropped area is 52,000 ha. According to groundwater monitoring, a groundwater under pressure prevails in the ESL and almost all samples show groundwater tables in the depths of >2.5 m.

2.3 Methods

The standardized precipitation index (SPI) has been widely used in studies focused on drought assessment since mid-1993, when it was defined by McKee et al. (1993). The index is based on the probability distribution of precipitation using the gamma distribution. The parameter fitting method was based on unbiased probability weighted moments. For all calculations, the R-package "SPEI" was used, which enables different options for the SPI and the SPEI estimation.

The SPI has some advantages. It is based only on the monthly precipitation and the estimation of only two parameters is necessary in comparison with 68 parameters, which are necessary for PDSI calculation (Hayes et al. 1999). The soil moisture is not involved, which allows its usage for summer as well as for winter. Its application is possible on different time scales, which enables its usage for different hydrological and agricultural issues. The calculation of the PDSI demands the data, which are not available in many regions. Therefore, we chose the SPI and the SPEI in our study.

The standardized precipitation evapotranspiration index (SPEI) was established as the improvement of the SPI by Vicente-Serrano et al. (2010). It is based on a simple water balance. Therefore, the first step of the SPEI estimation was the calculation of the simple water balance, which is defined as a difference between the precipitation (P) and the potential evapotranspiration (PET). The SPEI was originally calculated using the Thornthwait's PET estimation method (Thornthwaite 1948). In this paper, the potential evapotranspiration was estimated according to Penman-Monteith method (Allen et al. 1998). This method is generally recommended by

the Food and Agriculture Organization (FAO) and World Meteorological Organization (WMO). The estimation was based on minimum and maximum air temperature, wind speed, and sunshine duration (Begueria and Vicente-Serrano 2013). Next, the water balance data were fitted by the Log-logistic distribution with the use of unbiased probability weighted moments as a parameter fitting method. It is a normalized index like the SPI; therefore, the results can be compared worldwide.

In the context of climate change, the SPI does not reflect the influence of an air temperature increase, as only the monthly precipitation data are considered. But the impact of the air temperature is considered by the use of the potential evapotranspiration as an additional variable in the calculation of the SPEI. The results of the SPEI highly correlate also with the results of self-calibrated Palmers drought severity index (sc-PDSI) (Vicente-Serrano et al. 2010).

Both indices, the SPI and the SPEI, were calculated using three-time steps: 1-, 2-, and 3-monthly scales. The longer the time scale, the smaller the weight of the monthly value. As a result, the values of the short time scales change frequently from positive to negative values. The long time scale values respond slower. Therefore, they express longer drought periods (McKee et al. 1993). The assessment focuses on drought occurrence, mainly on a monthly base, which is the most important for crop cultivation. Months were categorized according to the SPEI, the SPI respectively, into four categories (Table 1).

Drought data were compared with standardized yield residual series (SYRS) of ten crops at district level (Table 1): spring barley, winter barley, maize, potatoes, rapeseed, rye, sugar beet, sunflower, spring wheat, and winter wheat. The methodology of calculating SYRS from the raw yield data was described by Potopová et al. (2015). The residuals of detrended yield are known as an indicator in agricultural drought risk assessment (Wu et al. 2004; Potopová et al. 2015). In this study, we use only the residuals of not detrended yield. We assumed that our study period is too short to expect a significant trend in yields as the agricultural techniques have not been changed fundamentally during this period. The residuals were standardized using the Gaussian normal distribution. The SYRS values were divided into five categories to express better the height of losses (Table 2).

To assess the impact of drought on crop yields, we used the Spearman correlation coefficient and the significance of correlation was checked by an F test on the level of $\alpha = 0.05$. Smaller districts, such as Bratislava, Pezinok, and Senec, had one representative meteorological station for all of them. Bigger districts, such as Nové Zámky, could be represented by two stations. In this particular case, the mean of their monthly precipitation totals and potential evapotranspiration were used for index estimation. The results of correlation analysis for winter wheat, spring barley, maize, and sugar beet

Table 1 List of districts and their abbreviations

District	Abbreviation
Bratislava	BA
Dunajská Streda	DS
Galanta	GA
Hlohovec	HC
Komárno	KN
Levice	LV
Michalovce	MI
Nitra	NR
Nové Zámky	NZ
Pezinok	PK
Piešťany	PN
Šaľa	SA
Senec	SC
Sobrance	SO
Topoľčany	TO
Trebišov	TV
Trnava	TT
Zlaté Moravce	ZM

are also presented in summary figures, where spatial pattern in both lowlands is clearly visible in all months on the 1- and 3-monthly time scales. The districts in these figures are listed according to its geographical location to group the districts with similar conditions and through that to get better spatial overview. The first three crops were selected as they are the most important crops of both lowlands and sugar beet was selected due to its high correlation with the drought indices.

3 Results

3.1 Drought occurrence

There is a difference in drought occurrences in the Danubian Lowland (DL) and the East Slovakian Lowland (ESL). Longer drought periods occurred in the early 1960s, early 1970s, and early and mid-1990s and in the years 2002–2003 and 2011–2012 in the DL (Fig. 2). Evidently, more humid periods were noted only in the mid- and late 1960s and in

Table 2 Drought categories according to the SPEI and the SPI and the categories of yield losses according to the SYRS

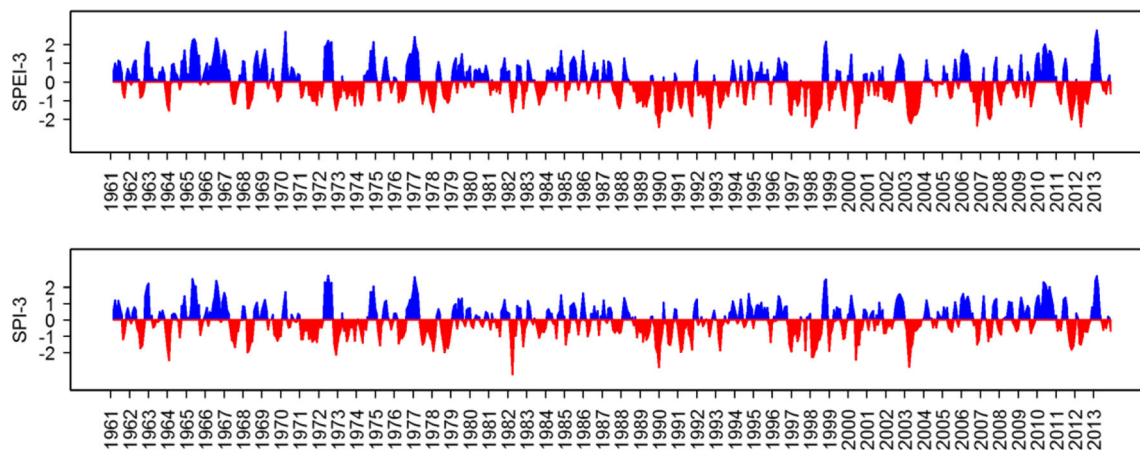| SYRS	SYRS category	SPEI/SPI	Drought category
0 to −0.49	Normal	0 to −0.99	Normal
−0.5 to −0.99	Low yield losses	−1.0 to −1.49	Moderate drought
−1.0 to −1.49	Moderate yield losses	−1.5 to −1.99	Severe drought
−1.5 to −1.99	Severe yield losses	≤−2.0	Extreme drought
≤−2.0	Extreme yield losses		

Fig. 2 Temporal evolution of the 3-monthly SPEI (*top*) and the 3-monthly SPI (*bottom*) in the Trnava district

the year 2010. All these most evident periods are also notable when using the 1-monthly SPEI (SPEI-1). The SPEI-1 is more variable in time and turns from negative to positive values more often due to the high weight of an individual month. The weight of an individual, even extreme month is lower for longer time steps. Therefore, the duration and importance of such identified periods are high. The DL experienced more precipitation during the 1960s in comparison to the ESL, but this period was also colder on the lowlands. Longer drought periods were concentrated in the second half of the investigated period, which is in very good agreement with increasing air temperature and potential evapotranspiration (Labudová et al. 2015). This phenomenon is visible considering results of all time steps of the SPEI. The importance of the PET is also notable comparing the SPEI and the SPI values over time. The 1960s were evidently colder. Here, the SPI indicated also dry months, but the SPEI reached positive values. The temporal distribution of drought periods in the DL is more proportional using the SPI, which indicates significant changes in air temperature and PET and almost no changes in precipitation totals. The longest drought period identified by the SPI occurred in late 1980s and early 1990s.

Considering the 3-monthly SPEI (SPEI-3), drought periods were recorded more proportionally during the whole period in the ESL and their intensity was comparatively within the period too. The temporal distribution of drought periods in the ESL is similar considering the SPI, but their intensity is lower without involving the potential evapotranspiration (Fig. 3). On the other hand, the SPI-1 reached more extreme values in some months during the study period.

In the East Slovakian Lowland, August is a month, which experiences severe to extreme droughts the most, often considering each of the indices on a 1-monthly time scale. Among districts, it is the most obvious in the Michalovce district, where 12 % of August faced drought with the SPEI equal to or lower than −1.5. If we consider only the most productive months (March to September), 8.6 % of them (32 months) are classified in just named drought categories, which equals to 66.6 % of all severe to extreme drought months. Considering all drought categories in the ESL, the highest rates of drought occurrences are identified again in August, but it is not rare to record drought in the winter season as well (Fig. 4).
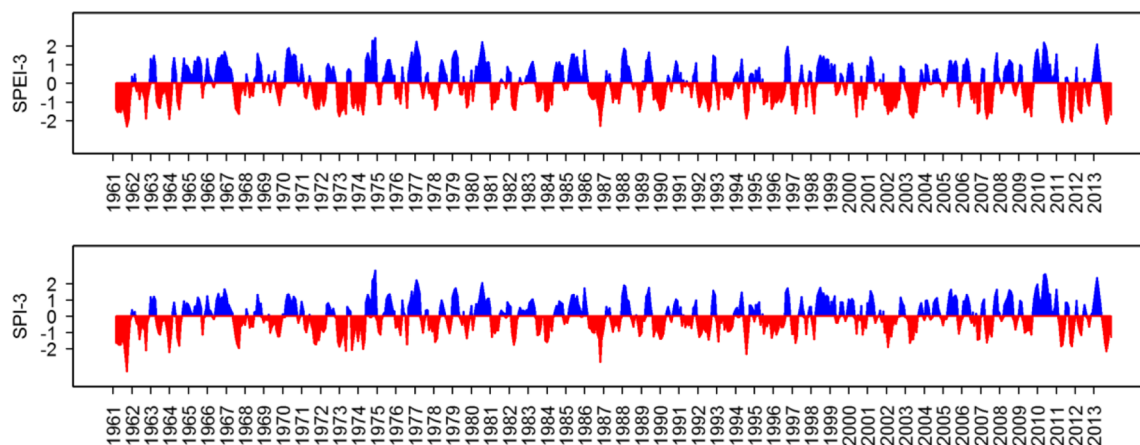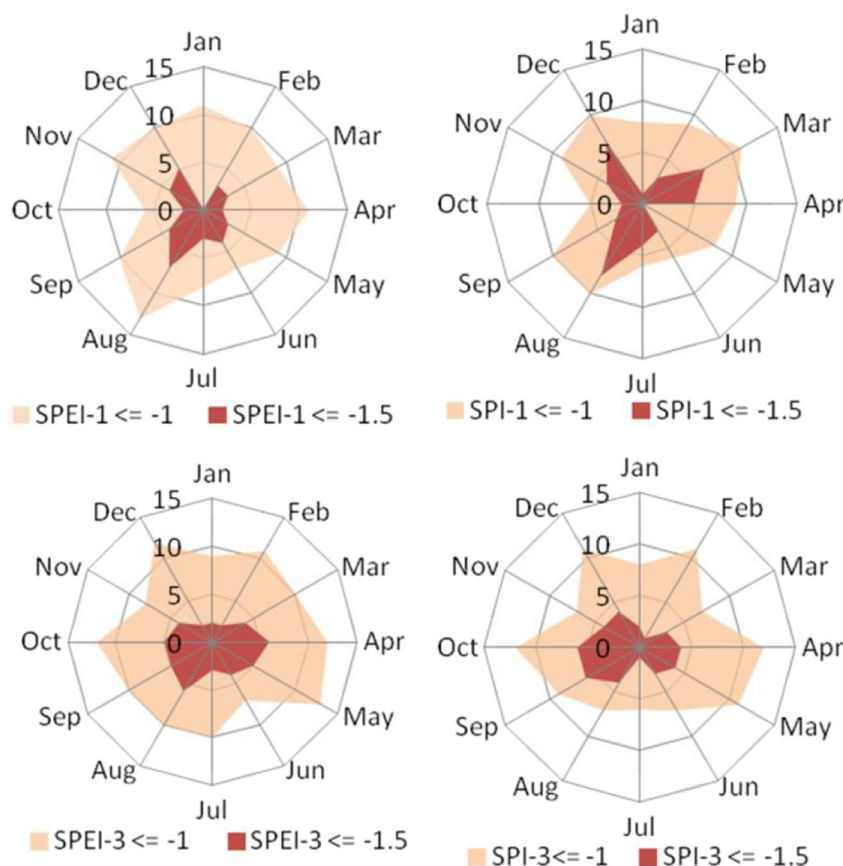

Fig. 3 Temporal evolution of the 3-monthly SPEI (*top*) and the 3-monthly SPI (*bottom*) in the Michalovce district

Fig. 4 Number of drought months during the year using the 1-monthly SPEI (*top left*) and SPI (*top right*) and the 3-monthly SPEI (*bottom left*) and SPI (*bottom right*) in the Trebišov district

With an increasing time step, the drought occurrence spreads over spring and autumn, especially in April, May, and October. The values equal to or below −1.5 occur mostly in August using SPEI due to high potential evapotranspiration and in September and October using the SPI (Fig. 4), which is connected with a singularity called "Indian summer." Severe to extreme drought occurrence is also not rare in the second half of spring.

Drought occurs more or less equally in all months in the northern part of the Danubian Lowland using the 1-monthly SPEI. In the southern half of the DL, the SPEI-1 indicates drought, mostly in March and December as well as August in the Komárno district and September in the Dunajská Streda district. Considering only severe and extreme drought, the summer months are on the top of the list, July being the most prominent. In the northeastern districts, such values are frequent also in September.

It is totally different from the occurrence assessed using the 1-monthly SPI. All drought categories occurred mostly in the months of the cold half-year (October to March), especially in the winter months. It is a sign that potential evapotranspiration plays an important role in drought occurrence in the DL. The same phenomenon was recorded using longer time steps, e.g., the 3-monthly indices. The lowest number of the severe to extreme drought months was found in the summer months,

mostly in July and August using the 3-monthly SPI (Fig. 5). It is connected with a singularity, which is frequently observed at the end of June and in the first half of July and brings much precipitation into Slovakia. But a significant increase in air temperature (Labudová et al. 2015) enhances the evapotranspiration. Moreover, there were recorded changes in the precipitation regime during the year, which influences the frequency and strength of the mentioned singularity (Faško et al. 2008). This often results in severe drought occurrence even in months, which are quite rich in precipitation considering the annual precipitation regime. This was proved by the use of the 3-monthly SPEI, which reached most of the values equal to or below −1.5 in August (Fig. 5). These drought months are caused by high evapotranspiration, and the SPI does not seem to be very suitable for drought monitoring in the summer months in the territory of the DL. The intensity of drought can be strengthened by precipitation in the form of thunderstorms with high intensity. Such intense precipitation is not effective for soil water storage, especially after a longer lasting drought. After a long drought, the topsoil layer is too solid and the infiltration into the soil is low. Hence, most of the received precipitation forms a runoff and plants are not able to profit from it.

The total number of drought months when using the SPEI increases in the north-south direction on the 1-

Fig. 5 Number of drought months during the year using the 3-monthly SPEI (*left*) and SPI (*right*) in the Nitra district
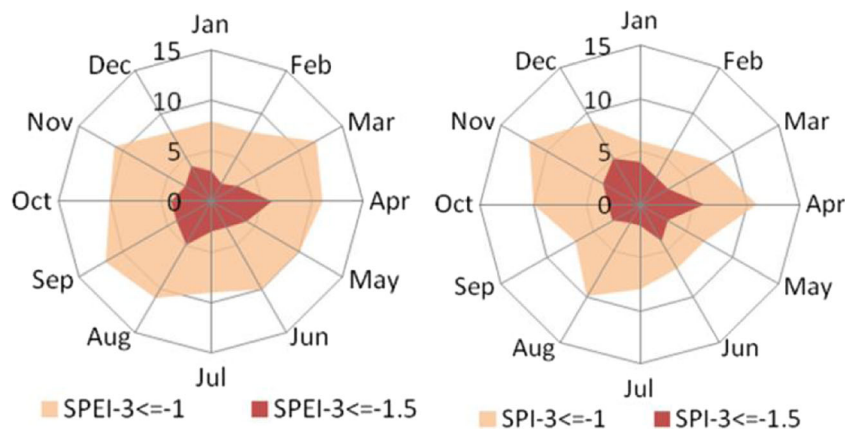
monthly time scale and in the west-east direction on the 3-monthly time scale. For example, the eastern districts experience drought in 19.5 % of all months using the SPEI-3 and the southern districts reach the same number using the SPEI-1. The same spatial pattern is observed considering only drought periods in the most productive months, but more drought episodes in those months (20 % of months March–September) occur on the 3-monthly time scale. There are only small spatial differences considering the severe to extreme drought months on all time steps. On average, 6.5 % of all months and 6.7 % of the months from March to September belong to those two drought categories. Less drought months were identified by the SPI on both time steps and even less of them occurred in the months March to September. The west-east pattern is visible also using the SPI-1, but it is hard to recognize any such patterns using the SPI-3.

3.2 Impact of drought on crop yields

3.2.1 Spring barley

High significant correlation is reached correlating standardized spring barley yields with the SPEI-1 in June, but mostly in the western part of the Danubian Lowland (Fig. 6). Correlation in spring is not significant, except April in the Dunajská Streda and the Senec districts. The same results are recorded using the SPI-1. The number of months and number of districts, in which the correlations are significant and high, increases with the time scales of the used indices. Spring and early summer values of the SPEI-2 show most often significant values in the western part of the DL again, but the importance of the SPEI-2 in July increases also in other districts (Fig. 7). The difference between the SPEI-2 and the SPI-2 is remarkable. Correlation coefficients are lower and
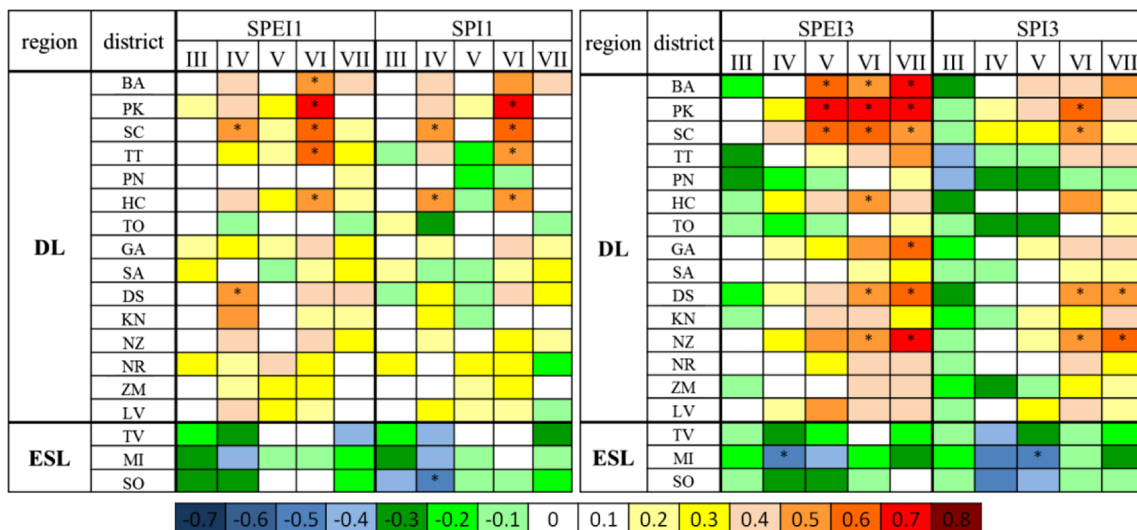

Fig. 6 Correlation coefficients between spring barley yields and 1- and 3-monthly SPI or SPEI, respectively, in months, which are relevant for the crop according to its phenology. Statistically significant correlations are marked with *asterisk*
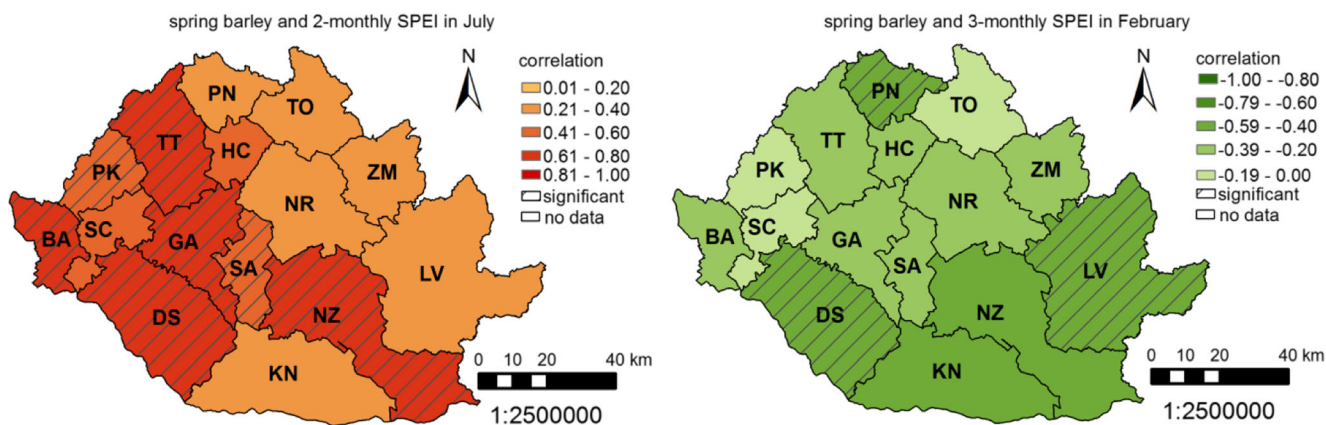
Fig. 7 Correlation between the 2-monthly SPEI and standardized spring barley yields in July (*left*) and between the 3-monthly SPEI in February and standardized spring barley yields (*right*) in the Danubian Lowland

mostly insignificant when using the SPI-2. The spatial and seasonal importance of the SPEI-2 is higher and reaches significant correlation coefficients between 0.5 and 0.67 in July in almost half of districts located in the DL. This means that the evapotranspiration plays an important role during the grain filling of spring barley and it is not enough to consider only precipitation deficit/surplus. Even more significant correlations are recorded using the SPEI-3 in the months May to July (Fig. 6). On this time scale, the importance of winter precipitation during sowing and at the beginning of the spring barley vegetation period is clearly visible (Fig. 7). The most extreme year was the year 2000, when almost all districts of the DL recorded extreme or very high losses.

The ESL shows almost no significant correlation between spring barley yields and the SPI or the SPEI, respectively. Moreover, the correlation coefficients are negative reaching values up to −0.5 in April and May using the SPI-3.

3.2.2 Winter barley

In the case of winter barley, precipitation in winter seems to be the most important factor, especially in December. It is interesting that the correlation coefficient is negative in all districts of the DL considering both indices. Spatially, the highest extension of significant correlations is recorded using the SPI-1 as evapotranspiration is only very low in the winter months.

3.2.3 Spring wheat

Most of the districts do not have complete data about spring wheat yields. Therefore, only eight districts were considered. Among them, the highest significant correlation was recorded in the Trnava district (from 0.57 in May using the SPEI-1 up to 0.8 in June using the SPEI-3), where the correlation coefficient increases with increasing time step of the SPEI. High losses (−1.89) occurred in this region in 2000 due to extremely

dry months May to June (SPEI-3 in June = −2.47), which continued with the severe dry months July and August.

3.2.4 Winter wheat

Winter wheat is another example of crop, which is highly influenced not only by precipitation but also by potential evapotranspiration. The correlation is noticeably higher and spatially more extended using the SPEI than the SPI. Again, yields are mostly impacted by drought indicated through the 3-monthly SPEI. We can observe three vulnerable winter wheat growing phases. The first one is sowing, when highly positive significant correlations (coefficients in the range from 0.51 up to 0.68) were identified in six districts of the DL (Fig. 8) and in the Trebišov district (ESL) in October using the SPEI-2. The second one is an overwintering. In this phase, precipitation, especially very wet conditions, seems to be crucial as a quite high negative significant correlation was observed in five districts of the DL in January using the SPI-1 (coefficient in the range −0.53 up to −0.64; Fig. 9). Very high positive significant correlation (coefficient in the range from 0.49 up to 0.73) was recorded in July using the SPEI-3 (Figs. 8 and 9) and in June using SPEI-1. In the case of densely seeded crops, the most vulnerable phenophases are generally anthesis and grain filling period, which are normally observed in June in this region. The high correlation coefficients show that the occurrence of drought in these phases has a big impact on winter wheat yields. Extremely high losses in the Trebišov and the Michalovce districts were recorded in 2000 due to a moderately dry autumn in combination with severe drought in spring and summer (SPEI-3 in May = −1.2 and in June = −1.76). High losses in the DL and the ESL were recorded also in 2003. They were caused by severe to extreme drought from March to October 2003 (SPEI-3 in the range from −1.34 up to −2.23).
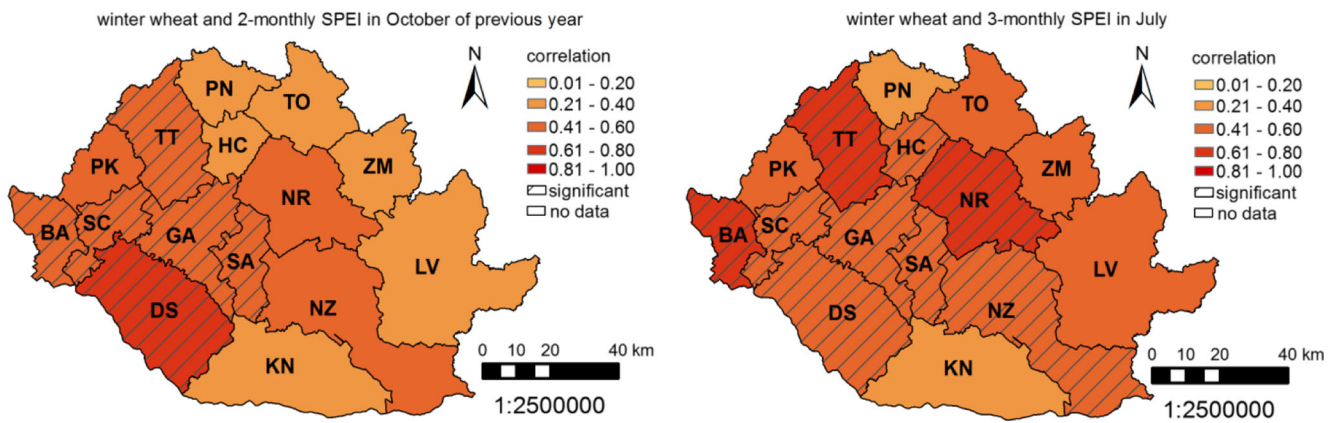
Fig. 8 Correlation between the 2-monthly SPEI in October of the previous year and standardized winter wheat yields in the Danubian Lowland (*left*) and correlation between the 3-monthly SPEI in July and standardized winter wheat yields in the Danubian Lowland (*right*)

3.2.5 Maize

Maize shows very high and significant sensibility to late spring and summer precipitation (Figs. 10 and 11). The lowest coefficients were noted using 1-monthly time scale for both indices. The correlation between the SPEI-2 and maize yields is slightly higher than that with the SPEI-3 (Fig. 10), but the

SPEI-3 correlates very good and significantly with maize yields as well. Only five districts in the DL did not show significant relationship between the yields and the index in July and August. Again, the importance of PET for final drought impact analysis is clearly visible. All correlations with the SPI are lower than those with the SPEI. Only very low and insignificant correlations were noted in the ESL, where a bit
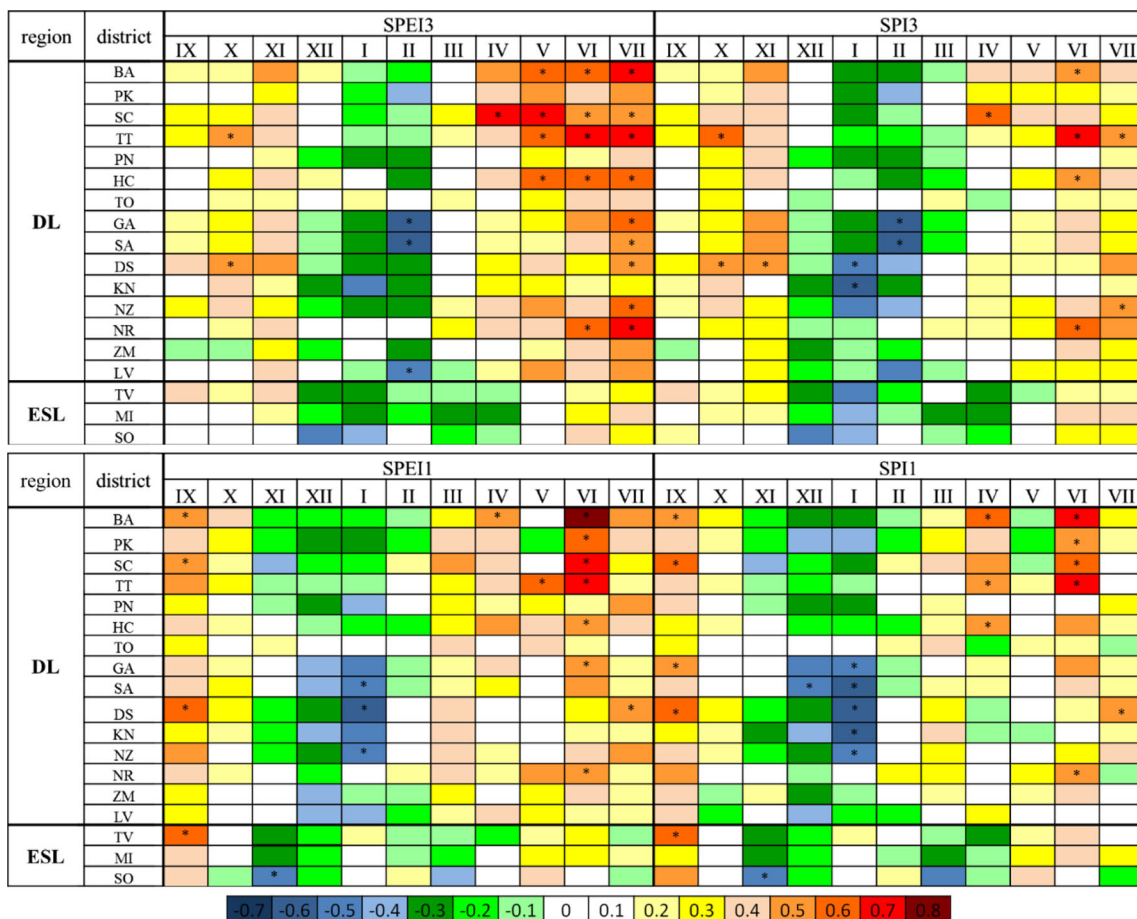

Fig. 9 Correlation coefficients between winter wheat yields and 1- and 3-monthly SPI or SPEI, respectively, in months, which are relevant for the crop according to its phenology. Statistically significant correlations are marked with *asterisk*
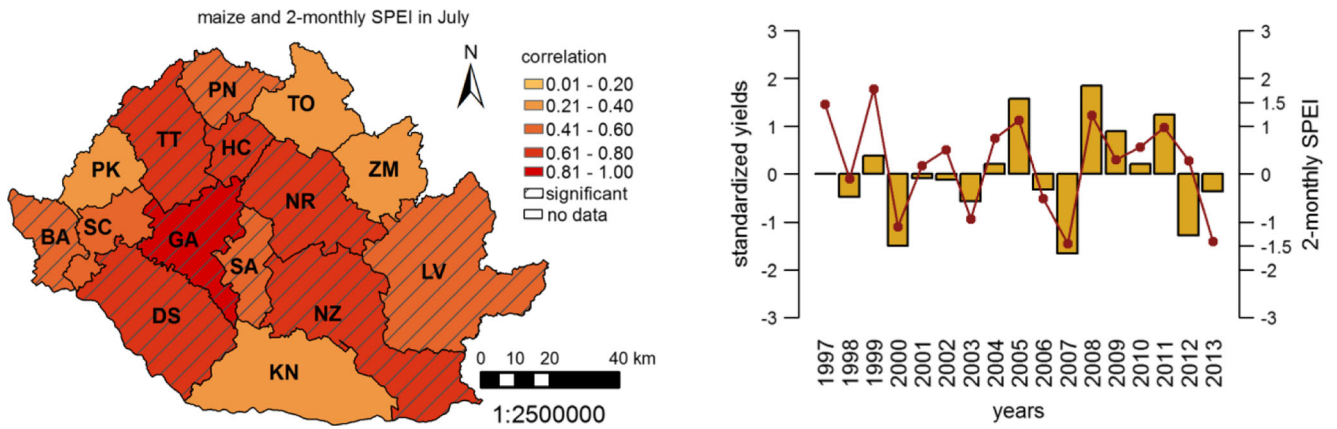
Fig. 10 Correlation between the 2-monthly SPEI in July and standardized maize yields in the Danubian Lowland (*left*) and standardized maize yields (*right*, *bars*) and the 2-monthly SPEI in July (*right*, *line*) in the Galanta district

higher coefficients were reached only in June on the 1-monthly time scale (Fig. 11).

The year 2012 was a bit specific. Even though the SPEI-2 was near the value of 0 (e.g., +0.27 in the Galanta district; Fig. 11), moderate to high losses in maize yields were

recorded and even extremely high losses in some districts in the DL. These losses were caused by a severe drought lasting from autumn 2011 till May 2012. A different situation occurred in the East Slovakian Lowland, where the same drought period was also severe, but it was interrupted two to

Fig. 11 Correlation coefficients between maize yields and 1- and 3-monthly SPI or SPEI, respectively, in months, which are relevant for the crop according to its phenology. Statistically significant correlations are marked with *asterisk*
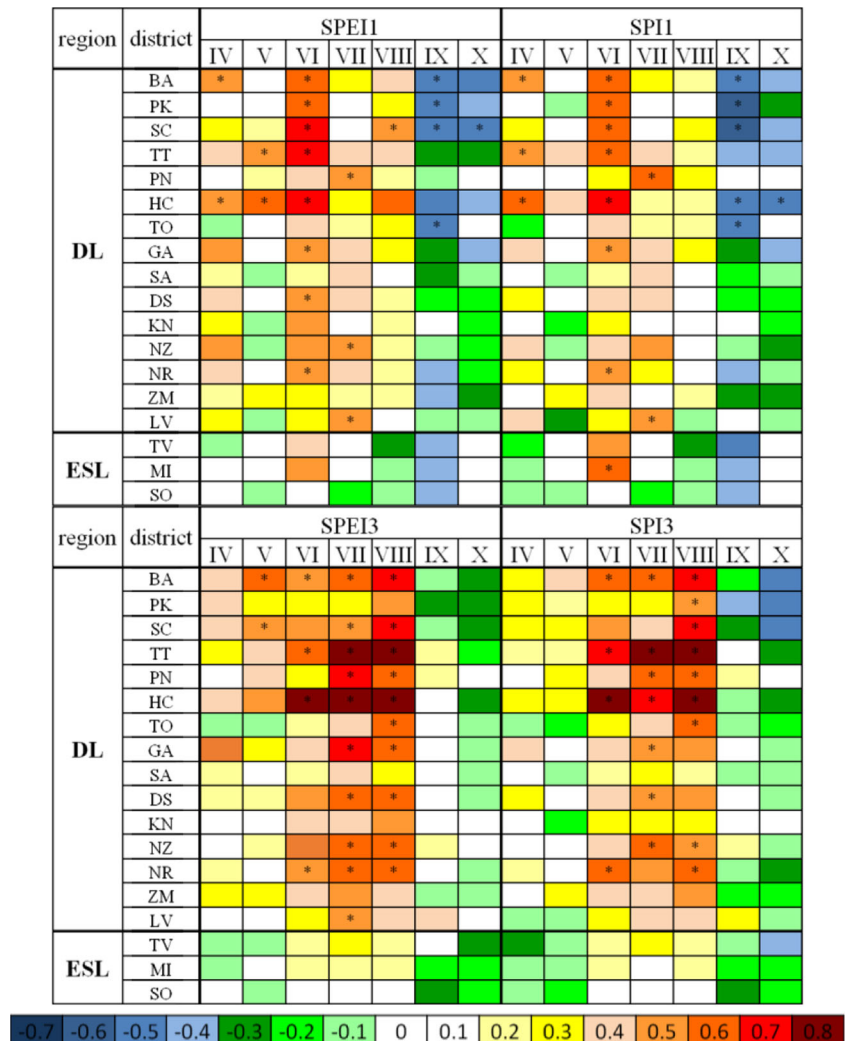
three times. It caused better water reserves for corn during sowing and its early stages. The highest losses were recorded in the years 2000 and 2007, when the SPEI-2 indicated moderate to severe drought not only in July, but also in May and June.

3.2.6 Potatoes

Considering potatoes, the 1-monthly scale seems to be more suitable, as it reaches higher spatial extension of positive significant values in the DL. Significant negative correlations were found in April (the SPI- and the SPEI-1, 2, and 3) and May (the SPI-3 and the SPEI-3) in the Michalovce district (ESL). Correlation coefficients vary from −0.52 up to −0.66. In this case, the SPI records higher correlation coefficients than the SPEI. It indicates that very wet conditions in spring can cause high losses in yields. It must be noted that the highest yield loss in the period in the Michalovce district occurred in 2010. This year was extremely wet in Slovakia, especially in late spring, early summer, and autumn, which caused a number of floods over many parts of the country. One of the most affected regions covers a big part of the Michalovce district, which resulted in higher yield losses of all crops. On the other hand, the high precipitation totals occurred in July after a dry winter and spring in 2011. Water surplus from June and July precipitation ensured high potatoes yields. Dry autumn did not affect the potato yield (Fig. 12) in the contrast to the yield of maize. In addition, it preserved it against rotting. In the DL, the 1-monthly SPEI gives higher correlation coefficients than the SPI, and they are statistically significant in six districts.

3.2.7 Rapeseed

The highest possible impact of drought on rapeseed is observed in June using the SPEI-1 and in May to July using the SPEI-3 (Fig. 13). The correlation coefficient is very high
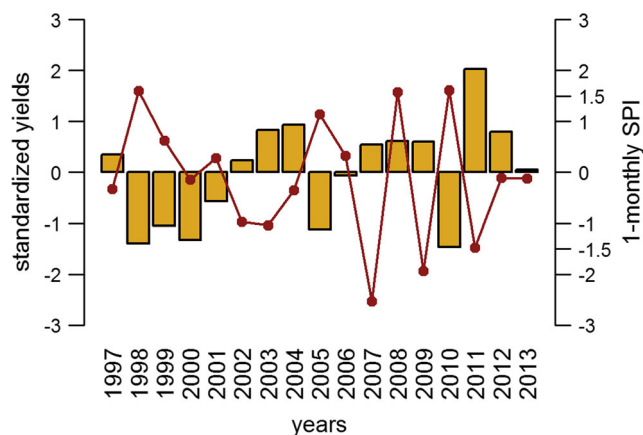

Fig. 12 Correlation between the 1-monthly SPI in April (*line*) and standardized potato yields (*bars*) in the Michalovce district

and significant in most of the districts in the DL. On the contrary, the same districts exhibit significant correlations only in June using the SPI-3. This observation indicates that precipitation is crucial for rapeseed in June and March (in some districts), but potential evapotranspiration totals in May to July significantly influence its yields too. In 2003, high precipitation in spring was followed by a lack of precipitation, but also high air temperatures in summer. All districts in the DL and the ESL recorded high or extremely high losses that year. Similar conditions and subsequent high losses were also recorded in the years 2000 and 2012. In 2012, the main cause was the very dry period during autumn 2011–spring 2012, which has already been mentioned earlier. In 2000, extremely low values of the SPI and the SPEI occurred in June 2000.

3.2.8 Rye

The assessment of drought impacts on rye yields is limited due to incomplete data for five districts in the DL. Yields in other districts show only very low, insignificant correlations with the SPI or the SPEI. The only exceptions are the Pezinok and the Senec districts located in the southwestern part of the DL, which reached the coefficient values of almost 0.6 in June using the SPEI-1 and in the case of the first mentioned also using the SPEI-3 in July.

3.2.9 Sugar beet

Sugar beet was cultivated earlier in almost all districts of the DL and the ESL, which have very good climatic conditions for high yields, and a prospering sugar industry had a long tradition there. At the end of 1990s, the sugar factory in Trebišov (ESL) was closed and it has not been profitable to cultivate sugar beet in the east of Slovakia anymore as the closest sugar factory is located about 170 km far from that region. Therefore, the data from the ESL have been missing for 10 years. The Pezinok, Bratislava, and Komárno districts have also a lack of yield data and were not used in the analysis.

Sugar beet seems to be the most vulnerable plant to drought in summer as the highest significant correlations (from 0.54 in Nitra up to 0.83 in Hlohovec) were reached in August using the SPEI-3 (Figs. 14 and 15). Despite that, the summer precipitation is more important than the potential evapotranspiration as the correlation coefficients are very high also using the SPI-3 and they have the highest spatial extension in the DL. While the 3-monthly time step is more suitable for summer months, the 1-monthly time step gives more sufficient results in the second half of spring (Fig. 14).

Similar to maize, the highest losses were recorded in 2000 due to moderate to severe drought in late spring and summer. Both sugar beet and maize are highly vulnerable to drought in summer. Especially, prolonged drought periods starting in
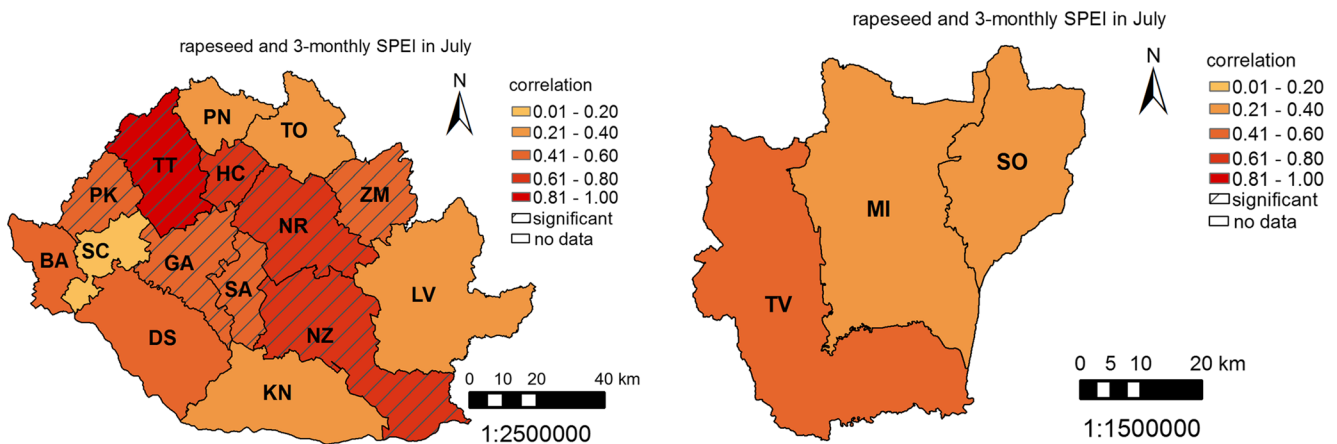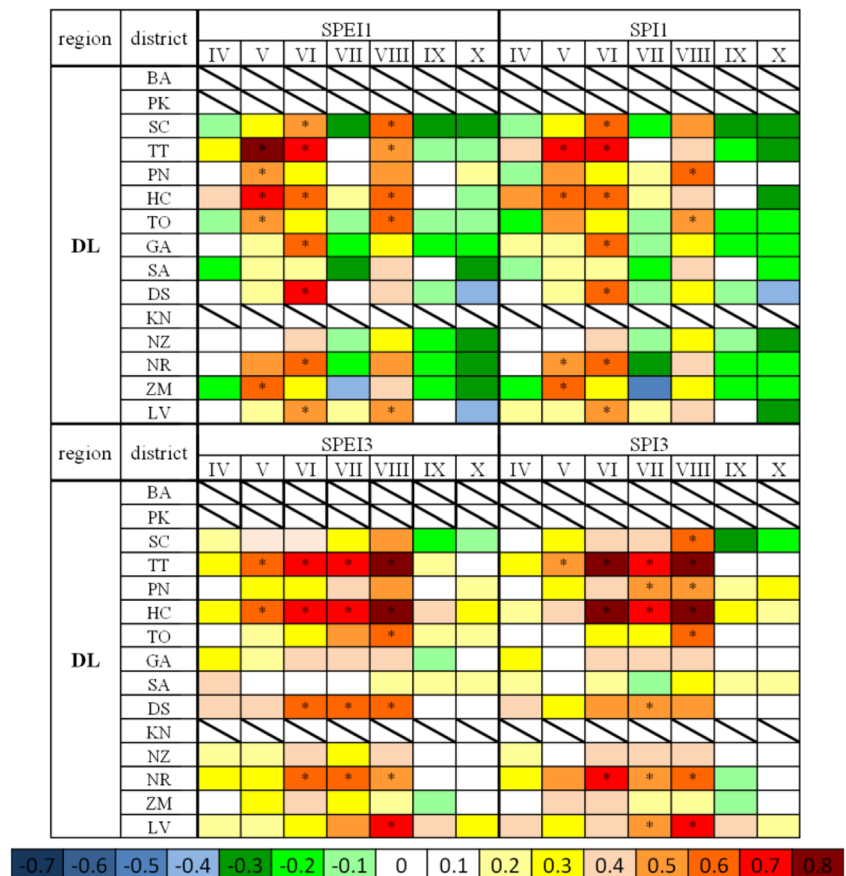
Fig. 13 Correlation between the 3-monthly SPEI in July and standardized rapeseed yields in the Danubian Lowland (*left*) and in the East Slovakian Lowland (*right*)

spring cause high losses. But there is a difference in drought parameters, which should be considered assessing drought impacts. It is sufficient to monitor only precipitation regarding sugar beet as the values of correlation coefficient with the SPI and the SPEI are similar. Lower yields occurred only in years, when the low SPEI was caused by precipitation deficit, not by high PET amounts. On the other side, even smaller precipitation deficits accompanied with high PET have high impact on

maize. This is shown in the higher correlations between the yields and the SPEI than with the SPI. Another aspect is that as it is mentioned in the methodology, the irrigation is mainly used for vegetable, sugar beet, and maize production. Sugar beet covers only a very small part of the cropped area. Therefore, it is very probable that irrigated area is bigger in comparison to the irrigated area, where the maize is cultivated due to economic reasons.

Fig. 14 Correlation coefficients between sugar beet yields and 1- and 3-monthly SPI or SPEI, respectively, in months, which are relevant for the crop according to its phenology. Statistically significant correlations are marked with *asterisk*
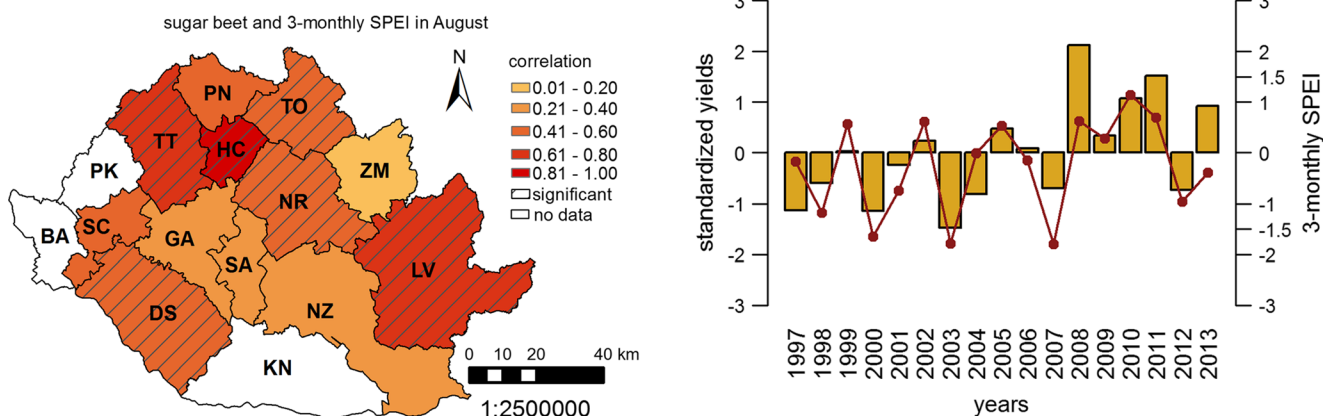
Fig. 15 Correlation between the 3-monthly SPEI in August and standardized sugar beet yields in the Danubian Lowland (*left*) and the 3-monthly SPEI in August (*right*, *bars*) and standardized sugar beet yields (*right*, *line*) in the Hlohovec district

3.2.10 Sunflower

Sunflower shows only a low correlation with each of the indices. Statistically significant coefficient occurs only rarely and only in a single district at once. A negative significant correlation was identified using the SPI or the SPEI in the late spring and in the summer in the Piešťany district. Sunflower in this district seems to be vulnerable to wet conditions due to high precipitation during flowering and shortly before it as a significant correlation coefficient is higher correlating the yields with the SPI than with the SPEI. Similar tendency was recorded in the ESL in the Michalovce district. For instance, high losses (SYRS = −1.55) were noted in the Michalovce district in 1998, when moderate to severe wet prevailed from May to August.

4 Discussion and conclusions

The results of drought occurrence using the SPEI are in agreement with the studies published in the recent years for the central Europe. Potop et al. (2013) identified the driest periods in 1972–1974, 1985–1986, and 1989–1994, and the wettest seasons were during 1965–1968, 1978–1982, and 1995–1999. The driest year in the selected lowlands in Slovakia was 2003 and 2011/2012. The first mentioned year was also detailed and analyzed in several studies over the Europe (e.g., Trigo et al. 2006; Lloyd-Hughes 2012). Longer drought periods occurred in the early 1960s, early 1970s, and early and mid-1990s and in the years 2002–2003 and 2011–2012 in the DL. Evidently, more humid periods were noted only in the mid- and late 1960s and in the year 2010.

Quite big differences in drought occurrence were found between two selected lowlands. The East Slovakian Lowland seems to be less affected by the increasing PET than the Danubian Lowland. It appears from the fact that drought periods noted by the SPEI occurred more frequently and have a longer duration in the second half of the period in the Danubian Lowland, while the periods derived from the SPI were temporally distributed quite proportionally. But considering the 3-monthly SPEI (SPEI-3), drought periods were recorded more proportionally during the whole period in the ESL and their intensity was comparatively within the period too. The temporal distribution of drought periods in the ESL is similar considering the SPI, but their intensity is lower without involving the potential evapotranspiration.

The highest losses caused mainly by severe drought were recorded in the years 2000, 2003, 2007, and 2012. In the first three listed years, severe to extreme drought occurred from late spring months till the end of summer, especially in the year 2003. A drought in the year 2012 began in the autumn 2011, when the most extreme dry month (November 2011) was recorded. Therefore, high losses were noted not only for spring crops but also for overwintering ones. It is in agreement with the results by Potopová et al. (2015). Analogically, the results for spring barley and winter wheat are similar to those of Kolář et al. (2013). Most of the crops in the DL show significant correlation with the SPI and even higher with the SPEI. It means that our hypothesis about high relation between the used indices and crop yields was right and they are suitable for drought impact assessment in the DL. Only some crops show significant correlation in the ESL. Therefore, other topographic or climatic factors should be considered in future studies.

The intensity of drought can be strengthened by precipitation in the form of rainstorms with high intensity. Such intense precipitation is not effective for a soil water storage, especially after long-lasting drought, because the topsoil layer is too solid and the infiltration into the soil is low. Most of the precipitation forms a runoff and plants are not able to profit from it. In such cases, maize is the most vulnerable to droughts according to very high significant correlations with the 3-monthly SPEI in the summer months.

Crop yields in the East Slovakian Lowland do not seem to be significantly influenced by wet or dry periods identified using the SPI and the SPEI as their correlations with both indices were mostly quite low and insignificant. Therefore, other climatic or topographic conditions influenced them more crucial. A potential reason might be that soils in this region are very loamy. Therefore, soil is often very wet in spring after snow melt. But on the other hand, it dries up very fast during a lack of precipitation (Fulajtár 1986). It was the reason why drainage channels were built at the same time as the irrigation system. Due to the drainage channels, we did not find any negative correlation between winter crops and the used indices in the winter months. Even though the soils are very loamy and retained meltwater could cause damage, the drainage possibly mitigates its impact. On the contrary, a significant negative correlation was observed in the DL. But, melting snow does not present a problem in the spring, but in the winter. The snow cover is on average thinner on the lowland than in the mountainous parts of Slovakia, and it disappears not later than in February. Due to mild winters, a long-lasting snow cover is rare in the DL and snow melts through the whole winter. Therefore, high precipitation totals in liquid, or solid form can cause too wet conditions for winter crops. Also, the soil type does not seem to be crucially important in this case as the negative significant correlation was also noted in the districts with prevailing Chernozems.

Climate change scenario for Slovakia shows the increase in the annual sum of evapotranspiration deficit. The temporal development of soil water storage and evapotranspiration deficit indicates that crop production and soil water regime needs to be restructured and optimized in order to enhance agricultural production of the area (Mati et al. 2011). But also the occurrence of intense storms, late spring frost, and thin snow cover in winter influencing winter crops should be considered in further study of this region. For the crop yields in the central Europe, the drought can have greater impact if it is accompanied by heat stress. The future studies should be focused on the factors such as heat waves, precipitation, and high potential evapotranspiration, e.g., using the multivariable regression analysis. It would be interesting to find out if the involving of heat impact can lead to better results in the drought monitoring than only considering the PET, which is based on a daily maximum temperature, and its values increase with the increasing daily maximum temperature.

The irrigated area covers only the very low percentage of the total cropped area to consider an irrigation impact on the crop yields on the both lowlands. The irrigation is used mainly for vegetable production and less for sugar beet and maize production. It means that the other studied crops can be considered as non-irrigated.

The potential evapotranspiration plays a great role in drought occurrence, especially in the DL. The SPI identifies severe to extreme drought, mostly in October to March. On the other hand, the SPEI recorded the most severe droughts in the summer months. The only difference between the indices is the involving of PET in the drought assessment. Therefore, we refer the improvement of the correlation coefficients between crop yields and the SPEI to the importance of the PET. Most of the assessed crops in the DL show high and statistically significant correlations with the SPEI. It is in the agreement with the results presented by Paulo et al. (2012). They found out that the correlation coefficient between the SPI and the SPEI decreases from high values in humid zone to the low values in semiarid zone. It supports the importance of the PET in the drought monitoring, especially in the regions, where the PET has an important impact on its occurrence. The investigated lowlands can be classified as the just described areas. Therefore, the SPEI is better suited for the drought monitoring for agricultural purposes than the SPI in both lowlands.

According to the result, we can conclude that there is a significant relationship between the drought occurrence identified by the SPI or the SPEI on the one side and crop yields in the Danubian Lowland on another side. This relationship was also partly indicated in the East Slovakian Lowland, but mostly without significance. As the potential evapotranspiration seems to be very important in drought occurrence in the studied areas, the SPEI is the recommended index for the drought monitoring. The index can be calculated for different time steps. According to our results, the 1-monthly SPEI suits better for the drought impact assessment on the yields of spring barley and potatoes, the 1-monthly SPI in the winter months, but the 2-monthly SPEI in the summer months suits better for winter barley, the 3-monthly SPEI correlates better with maize, rapeseed, sugar beet, spring, and winter wheat, and at the end, the 3-monthly SPI for sugar beet and sunflower. In the recommendation, there occurred also the SPI, which correlates better with the yields in some cases. But it has to be noted that these differences in the correlations are quite small and the SPEI can be properly used for the monitoring as well.

References

Agnew C (2000) Using the SPI to identify drought. Drought Netw News 12:5–12

Allen, R.G., Pereira, L.S., Raes, D., Smith, M. (1998) Crop evapotranspiration: guidelines for computing crop requirements. FAO irrigation and drainage paper 56. FAO, Rome

Begueria, S., Vicente-Serrano, S.M. (2013) Calculation of the standardised precipitation-evapotranspiration index R-package

Brázdil R, Trnka M, Dobrovolný P, Chromá K, Hlavinka P, Žalud Z (2008) Variability of droughts in the Czech Republic, 1881–2006. Theor Appl Climatol 97:297–315

Büntgen U, Brázdil R, Dobrovolný P, Trnka M, Kynsl T (2010) Five centuries of Southern Moravian drought variations revealed from living and historic tree rings. Theor Appl Climatol 105:167–180

Capra A, Scicolone B (2012) Spatiotemporal variability of drought on a short–medium time scale in the Calabria Region (Southern Italy). Theor Appl Climatol 110:471–488

Dubrovsky M, Svoboda MD, Trnka M, Hayes MJ, Wilhite DA, Zalud Z, Hlavinka P (2008) Application of relative drought indices in assessing climate-change impacts on drought conditions in Czechia. Theor Appl Climatol 96:155–171

Eitzinger J, Kubu G, Alexandrov V, Utset A, Mihalovic DT, Lalic B, Trnka M, Žalud Z, Semeradová D, Ventrella D, Anastasiou DP, Medany M, Altaher S, Olejnik J, Lesny J, Nemeshko N, Nikolaev M, Simota C, Cojocaru G (2009) Adaptation of vulnerable regional agricultural systems in Europe to climate change—results from the ADAGIO project. Adv Sci Res 3:133–135

Eitzinger J, Trnka M, Semerádová D, Thaler S, Svobodová E, Hlavínka P, Šiška B, Takáč J, Malatinská L, Nováková M, Dubrovský M, Žalud Z (2013) Regional climate change impacts on agricultural crop production in central and eastern Europe—hotspots, regional differences and common trends. J Agric Sci 151:782–812

Faško P, Lapin M, Pecho J (2008) 20-year extraordinary climatic period in Slovakia. Meteorologický časopis 11:99–105

Fulajtár E (1986) Fyzikálne vlastnosti pôd Slovenska, ich úprava a využitie. Veda, Bratislava

Hayes MJ, Svoboda MD, Wilhite DA, Vanyarkho OV (1999) Monitoring the 1996 drought using the standardized precipitation index. Bull Am Meteorol Soc 80:429–438

Kolář P, Trnka M, Brázdil R, Hlavínka P (2013) Influence of climatic factors on the low yields of spring barley and winter wheat in Southern Moravia (Czech Republic) during the 1961–2007 period. Theor Appl Climatol 117:707–721

Labudová L, Faško P, Ivaňáková G (2015) Changes in climate and changing climate regions in Slovakia. Morav Geogr Rep 23:71–82

Lloyd-Hughes B, Saunders MA (2002) A drought climatology for Europe. Int J Climatol 22:1571–1592

Lloyd-Hughes B (2012) A spatio-temporal structure-based approach to drought characterization. Int J Climatol 32:406–418

Mati R, Kotorová D, Gomboš M, Kandra B (2011) Development of evapotranspiration and water supply of clay–loamy soil on the East Slovak Lowland. Agric Water Manag 98:1133–1140

McKee, T.B., Doesken, N.J., Kleist, J. (1993) The relationship of drought frequency and duration to time scales. Eighth Conference on Applied Climatology, 17–22 January 1993, Anaheim, California

Mishra A, Singh V (2010) A review of drought concepts. J Hydrol 391: 202–216

Paulo A, Rosa R, Pereira L (2012) Climate trends and behaviour of drought indices based on precipitation and evapotranspiration in Portugal. Nat Hazard Earth Syst 12:1481–1491

Potop V (2011) Evolution of drought severity and its impact on corn in the Republic of Moldova. Theor Appl Climatol 105:469–483

Potop V, Boroneant C, Možný M, Štepánek P, Skalák P (2012a) Spatial and temporal evolution of drought conditions at various time scales in the Czech Republic during growing period. Idorajas 116:281–295

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

Potop V, Boroneant C, Možný M, Štepánek P, Skalák P (2013) Observed spatiotemporal characteristics of drought on various time scales over the Czech Republic. Theor Appl Climatol 115:563–581

Potopová V, Štepánek P, Možný M, Turoktt L, Soukup J (2015) Performance of the standardised precipitation evapotranspiration index at various lags for agricultural drought risk assessment in the Czech Republic. Agric For Meteorol 202:26–38

Szalai S, Szinell C, Zoboki J (2000) Drought monitoring in Hungary. In: Wilhite DA, Sivakumar MVK, Wood DA (eds) 2000. Early warning systems for drought preparedness and drought management, Proceedings of an Expert Group Meeting held in Lisbon, Portugal, 5–7 September 2000

Svoboda M, Fuchs BA, Poulsen CC, Nothwehr JJ (2015) The drought risk atlas: enhancing decision support for drought risk management in the United States. J Hydrol 526:274–286

Szentimrey T (2003) Homogenization software MASHv3.03. Hungarian Meteorological Service. http://www.met.hu/en/omsz/palyazatok_projektek/carpatclim/. Accessed 14 Oct 2014

Statistical Office of the Slovak Republic (2015) Slovstat Database. http://www.statistics.sk/pls/elisw/vbd. Accessed 10 Feb 2015

Šiška B, Takáč J (2009) Drought analyse of agricultural regions as influenced by climatic conditions in the Slovak Republic. Idojaras 113: 135–143

Šťastný P, Bochníček O, Faško P, Nejedlík P, Snopková Z (eds) (2015) Climate atlas of Slovakia. Slovak Hydrometeorlogical Institute, Bratislava

Takáč J, Skalský R, Morávek A, Klikušovská Z, Bezák P, Bárdyová M (2015) Spatial patterns of agricultural drought events in Danube lowland in the 1961–2013 period. Proceedings from Towards Climatic Services Conference, Nitra, Slovakia, 15–18 September 2015

Thornthwaite CW (1948) An approach toward a rational classification of climate. Geogr Rev 38:55–94

Trigo RM, Pereira JMC, Pereira MG, Mota B, Calado TJ, Dacamara CC, Santo FE (2006) Atmospheric conditions associated with the exceptional fire season of 2003 in Portugal. Int J Climatol 26:1741–1757

Trnka M, Dubrovský M, Svoboda M, Semerádová D, Hayes M, Žalud Z, Wilhite D (2009) Developing a regional drought climatology for the Czech Republic. Int J Climatol 29:863–883

Trnka M, Kersebaum KC, Eitzinger J, Hayes M, Hlavinka P, Svodoba M, Dubrovský M, Semerádová D, Wardlow B, Pokorný E, Možný M, Wilhite D, Žalud Z (2013) Consequences of climate change for the soil climate in Central Europe and the Central Plains of the United States. Clim Chang 120:405–418

Vicente-Serrano SM, Lopéz-Moreno JI (2005) Hydrological response to different time scales of climatological drought: an evaluation of the standardized precipitation index in a mountainious Mediterranean basin. Hydrol Earth Syst Sci 9:523–533

Vilček, J., Halas, J., Scholtz, P., Gutteková, M. (2007) Poľnohospodárska pôda regiónov Slovenska v kocke. Soil Science and Conservation Research Institute, Bratislava

Vicente-Serrano SM, Begueria S, Lopéz-Moreno JI (2010) A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. J Clim 23:1696–1718

Wu H, Hubbard KG, Wilhite DA (2004) An agricultural drought risk-assessment model for corn and soybeans. Int J Climatol 24:723–741