Nat Hazards
DOI 10.1007/s11069-014-1215-3

ORIGINAL PAPER

Vulnerability of Bulgarian agriculture to drought and climate variability with focus on rainfed maize systems

Z. Popova · M. Ivanova · D. Martins · L. S. Pereira · K. Doneva · V. Alexandrov · M. Kercheva

Received: 12 November 2013 / Accepted: 29 April 2014

Abstract Bulgarian agriculture is affected by droughts and, likely, by climate change. Thus, aiming at assessing its vulnerability, this study includes a general characterization of climate variability in eight selected locations, both in northern and southern Bulgaria. Trend tests were applied to monthly precipitation, maximum and minimum temperature and to the Standardized Precipitation Index with two-month time step (SPI-2) relative to the period of 1951–2004. Negative trends were identified for precipitation and SPI-2 at various locations, mainly in the Thrace Plain, indicating that dryness is likely to be increasing in Bulgaria. The vulnerability of rainfed maize systems to drought was studied using the previously calibrated WinISAREG model and the Stewart's yield model to compute both the relative yield decrease (RYD) due to water stress and the corresponding net irrigation required to overcome those losses. Results identified a strong relation between SPI-2 for July–August (SPI-$2_{\text{July–Aug}}$) and RYD. Results also show that yield losses are higher when the soils have a smaller soil water holding capacity. For the various regions under study, thresholds for RYD were defined considering the related economic impacts and the influence of soil characteristics on the vulnerability of the rainfed maize systems. Finally, to support drought risk management, SPI-$2_{\text{July–Aug}}$ thresholds were developed to be used as indicators of the economic risk of rainfed maize for various climate regions and soil groups in Bulgaria.

Z. Popova · M. Ivanova · K. Doneva · M. Kercheva
N. Poushkarov Institute of Soil Science, Agrotechnology and Plant Protection - Academy of Agriculture, 7 Shosse Bankya Str., 1080 Sofia, Bulgaria

D. Martins · L. S. Pereira (✉)
CEER-Biosystems Engineering, Institute of Agronomy, University of Lisbon, Tapada da Ajuda, 1349-017 Lisbon, Portugal
e-mail: lspereira@isa.utl.pt; lspereira@isa.ulisboa.pt

V. Alexandrov
National Institute of Meteorology and Hydrology, Bulgarian Academy of Sciences, 66 Tsarigradsko Chaussee Blvd., 1784 Sofia, Bulgaria

Published online: 09 May 2014

Keywords Relative yield decrease · SPI drought index · WinISAREG model · Stewart's water-yield model · Climate uncertainties · Total available soil water

1 Introduction

Drought is a long-lasting period of precipitation deficit that results in impacts on agricultural and natural ecosystems and water supply systems, thus causing economic impacts in various sectors (Pereira et al. 2009; Dow 2010; Mishra and Singh 2010). Droughts may occur in all climates, but their characteristics and impacts vary significantly from region to region. In the lowlands of South East Europe (SEE), including Bulgaria, drought is a recurrent phenomenon (Slavov et al. 2004; Koleva and Alexandrov 2008; Hlavinka et al. 2009). The need to develop methodologies and simulation tools that support drought risk management in agriculture became evident after the droughts of 2000, 2007 and 2012 when the average maize grain yield in Bulgaria dropped to less than 1.8 t ha^{-1}. The recent study by Olesen et al. (2011) on the impacts of climate change in European agriculture supports the hypothesis that Bulgarian agriculture is becoming more vulnerable to droughts and climate variability. This study shows that most negative effects are expected for the Pannonian zone—that includes Bulgaria, Hungary, Serbia, and Romania—where increased heat waves and drought events are expected.

A variety of indices exist to support operational drought management (Keyantash and Dracup 2002; Pereira et al. 2009; Mishra and Singh 2010; NDMC 2014). The Standard Precipitation Index, SPI (McKee et al. 1993, 1995), is probably the mostly used, namely in South East Europe (Gregoric 2012). It is a standardized index on which computation is based on the long-term precipitation record cumulated over a selected timescale, shorter when meteorological or agricultural droughts are considered, longer when the analysis aims at water supply management. That long-term precipitation record is fitted to a selected probability distribution, often the gamma distribution, that is transformed through an equal-probability transformation into a normal distribution. Positive SPI values indicate greater-than-median precipitation and negative values indicate less-than-median precipitation. Guttman (1998) recommended the SPI because it is standardized and contains a probabilistic interpretation, hence can be used in risk assessment and decision-making. Although analysing precipitation characteristics is fundamental when studying drought risk, if there is the need to perform comparisons among areas having different precipitation regimes or climate characteristics, adopting a standardized variable like the SPI is preferred to capture dryness and wetness conditions (Bordi et al. 2009). As referred by Lana et al. (2001), the SPI offers an appropriate picture of rainfall-deficit and excess patterns because a unique pluviometric scale is used instead of different range amounts for months and weather stations. Moreover, SPI gives the departure from the mean precipitation on a variety of timescales depending on the objectives of the analysis.

The SPI, more often with the twelve-month timescale, is commonly used to monitor and characterize droughts (e.g. Vicente-Serrano 2006; Raziei et al. 2009; Santos et al. 2010; Martins et al. 2012), to predict drought class transitions and support implementation of mitigation measures (Mishra and Desai 2005; Paulo and Pereira 2008; Moreira et al. 2008) or to assess possible relationships between drought aggravation and climate change (Lloyd-Hughes and Saunders 2002; Bordi and Sutera 2004; Bordi et al. 2009; Moreira et al. 2012).

Differently, when adopting a two-month timescale (SPI-2), the SPI indicates short-term precipitation anomalies that affect crop water use; therefore, the SPI-2 may be adopted to assess effects of dryness conditions on crops production.

Despite drought indices do not evaluate drought impacts on various sectors affected and are mainly used to support drought monitoring and management, indices such as SPI can be related with observed impacts and used to assess the vulnerability of ecosystems and agricultural systems to drought and dryness conditions (e.g. Conde et al. 1997; Wilhelmi and Wilhite 2002; Sönmez et al. 2005; Simelton et al. 2009; Fraser et al. 2013). Vulnerability can be approached in various ways, mainly indicating the degree to which a system is susceptible to or unable to cope with adverse effects of climate extremes. In agriculture, vulnerability to droughts and climate variability can be considered like a risk, which combines the climate hazard with yield and economic consequences. Thus, agriculture vulnerability to droughts varies with the local climate, the severity of the stress and its time of occurrence, the type of crop, soil characteristics, land use and access to irrigation water (Wilhelmi and Wilhite 2002). In addition, vulnerability relates to the capacity of adaptation of the society to overcome potential damages and therefore socio-economic indicators may be used (Simelton et al. 2009). Drought and wetness anomaly indicators, namely the SPI (Sönmez et al. 2005; Xu et al. 2012; Liu et al. 2013) and the Palmer Z anomaly index (Hlavinka et al. 2009), were therefore used to assess the agricultural vulnerability to drought and climate uncertainty.

The identification of the agricultural vulnerability to drought and climate uncertainty requires the use of long-term weather data sets and prediction models (Alexandrov 2011). In Bulgaria, Alexandrov (1999) and Alexandrov and Hoogenboom (2000) adopted statistical techniques to relate precipitation and temperature scenarios with crop yield. Those authors used general circulation models (GCM) to create the climate scenarios and further assess impacts on maize and wheat yields. Conde et al. (1997) also used GCMs to create climate change scenarios that were used with the CERES-Maize model to assess maize yields. Zhang (2004) also assessed the agricultural risk to dry events through relating crop yields and crop-sown areas with climatic and weather indicators.

Crop models are often used for assessing water stress impacts on crop yields. Hence, they are highly useful in vulnerability and crop risk assessment studies as recently reviewed by Kang et al. (2009). Wu and Wilhite (2004) purposefully developed a model to assess drought risk using weather predictions for the various crop stages. Wang et al. (2013) applied the model EPIC to wheat. Differently, Popova and Kercheva (2005) used the CERES models to assess impacts of drought on maize and wheat and identified the role of soil characteristics on those impacts. Popova and Pereira (2008) combined the use of the soil water balance model ISAREG with the Stewart's yield model to assess impacts of climate variability in the Thrace Plain of Bulgaria.

In addition to those modelling studies, there is the need to detect possible trends in precipitation and temperature, which may relate with the referred vulnerability of the rainfed maize crop to the variability and possible change of climate. In this perspective, it is appropriate to also assess trends of SPI in addition to precipitation amounts because, as referred above, it is a standardized variable denoting positive or negative anomalies of precipitation independently of the precipitation amount. Trend analysis with SPI is now common in climate variability studies, either using SPI time-series relative to the weather stations under analysis or applied to the principal components that resulted from a principal component analysis (PCA) application. Studies by Vicente Serrano et al. (2004), Li et al. (2008), Hoffman et al. (2009), Zhang et al. (2009), Krysanova et al. (2008) and Paulo et al. (2012) are among those that analysed local trends of SPI using nonparametric tests to search for changes in the frequency and severity of droughts. Capturing trends by applying PCA to SPI has been accomplished by others, e.g. Lloyd-Hughes and Saunders (2002), Bordi et al. (2009) and Martins et al. (2012). However, applications with SPI-2 aimed at detecting variability or changes related to agricultural droughts have not been reported.

Considering previous studies detecting a great vulnerability to droughts of agricultural systems based on rainfed maize, the objective of this study is to assess the vulnerability of these Bulgarian agricultural systems to drought and climate variability and further support drought risk management. Therefore, the study aims at (a) better detecting whether climate is changing towards higher dryness and increased crops water demand; (b) defining drought-related economic thresholds due to yield decreases; (c) assessing irrigation requirements assumed as an adaptation measure to overcome consequences of water stress; (d) defining thresholds on yield losses taking into consideration the SPI values and the soil water holding capacity; and (e) defining SPI thresholds to be used for water stress risk management.

2 Materials and methods

2.1 Climate data, SPI and trend analysis

The study was performed for various locations in Bulgaria: Lom, Pleven, Silistra and Varna as to represent the northern regions, and Sofia, Plovdiv, Stara Zagora and Sandanski in the southern regions (Fig. 1). Different climates are therefore considered: a moderate continental climate in Sofia, Pleven, Lom and Silistra; a transitional continental climate at Stara Zagora and Plovdiv; a northern Black Sea climate in Varna; and a transitional Mediterranean climate in Sandanski.

Monthly precipitation and reference evapotranspiration (ETo) relative to the period 1951 to 2004 at selected locations of northern and southern Bulgaria are presented in

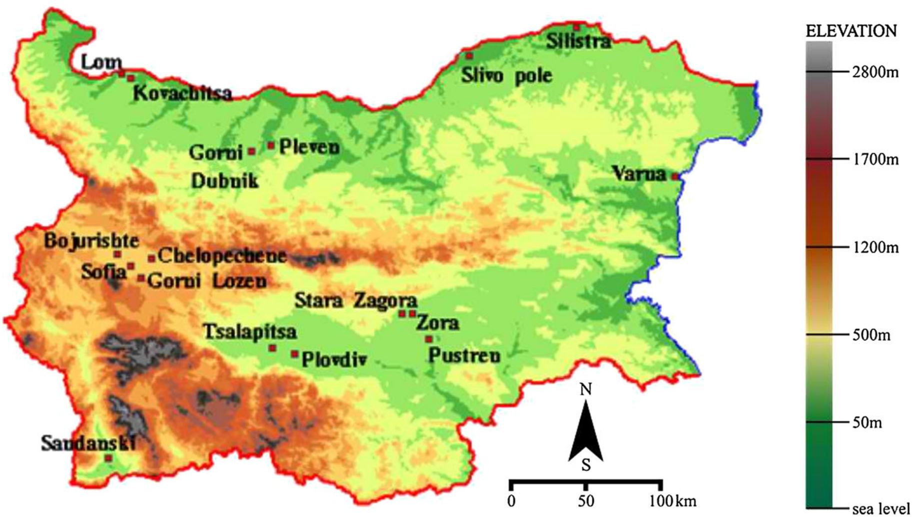

Fig. 1 Experimental fields of ISSNP and meteorological stations of NIMH in Bulgaria

Fig. 2. Data refer to the maize crop season. Precipitation represents wet, average and dry years, i.e. when the probability for being exceeded is, respectively, 10, 50 and 90 %. ETo was computed with the PM-ETo equation (Allen et al. 1998) using only temperature data as described by Popova et al. (2006a). ETo refers to low, average and high climatic demand conditions, when ETo values are exceeded with a probability of 90, 50 and 10 %, respectively. The precipitation during the maize cropping season shows a great inter-annual variability and a nonnegligible seasonality, with less precipitation during the months of July, August and September, when maize flowering and yield formation occur. There is also an evident spatial variability, with larger precipitation in Sofia and the northern locations. ETo shows much less inter-annual variability than precipitation and is higher in southern regions. ETo follows a regular seasonal distribution, with maxima in July and August when precipitation is smaller (Fig. 2).

The procedures used to compute the SPI with 2-month timescale followed those described by Lloyd-Hughes and Saunders (2002) and Paulo et al. (2003), including the SPI classes. The entire period of precipitation records was used to estimate the parameters of the gamma probability distribution function for each referred location.

A trend analysis was applied to precipitation and maximum and minimum temperature, and to the SPI-2 using the Mann–Kendall original and modified trend test (Hamed and Rao 1998), which accounts for temporal autocorrelation and has been applied for trend detection of drought indices, mainly the SPI, as referred before, and the PDSI (Sousa et al. 2011). A significance level of 0.05 was adopted. The magnitude of the existing trend, when significant, was estimated with the Sen's slope estimator (Sen 1968; Helsel and Hirsch 1992; Huth and Pokorná 2004).

2.2 Soil water balance and water-yields modelling

Maize is a main summer crop in Bulgaria. During the period 1960–1990, irrigated maize attained more than 100,000 ha. However, in the last 25 years, due to abandonment of irrigation systems, maize is predominantly grown under rainfed conditions. Maize crop parameters required for modelling consist of crop coefficients (Kc), water depletion fractions for no stress (p) and the water-yield response factor (Ky), as defined by Allen et al. (1998). Crop parameters were obtained when calibrating the WinISAREG and Stewart's models using field data. The calibration and validation of the WinISAREG and the Stewart's models for Pustren and Zora (Stara Zagora), Tsalapitsa (Plovdiv) and Bojurishte (Sofia) were described, respectively, by Popova et al. (2006b), Popova and Pereira (2011) and Ivanova and Popova (2011). Calibration and validation of both models were performed using data relative to different irrigation management conditions and for rainfed maize.

The WinISAREG model, described by Liu et al. (1998) and Pereira et al. (2003), uses the soil water balance approach proposed by Doorenbos and Pruitt (1977) and the updated methodology proposed by Allen et al. (1998) to compute crop ET and irrigation requirements. Data required to perform the soil water balance with ISAREG consist of (1) weather data on precipitation and ETo; (2) soil water data, the total available soil water (TAW, mm m^{-1}), i.e., the difference between soil water storage at field capacity and wilting point for a soil depth of 1.0 m (Allen et al. 1998) and (3) crop data relative to the crop development stages and corresponding dates, crop coefficients, root depths and the soil water depletion fractions for no stress. The model allows various simulation options including to simulate an irrigation schedule using selected irrigation thresholds, executing the water balance without irrigation and computing the net irrigation requirements. Yield impacts of water stress are assessed with the Stewart's one-phase model (Stewart et al. 1977;

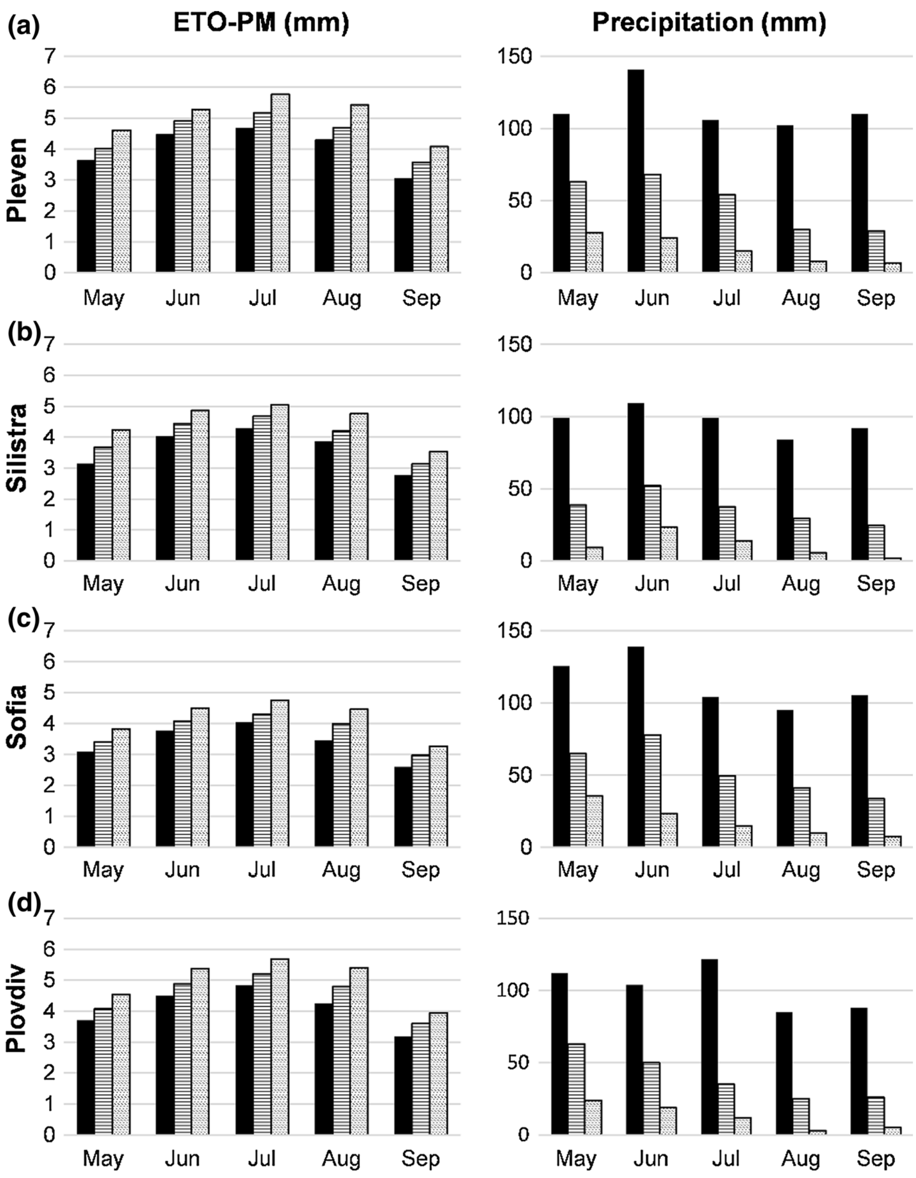

Fig. 2 On right, monthly precipitation for the wet (■), average (▤) and dry (▒) years and, on left, reference evapotranspiration for the low (■), average (▤) and high (▒) climatic demand conditions at **a** Pleven, **b** Silistra, **c** Sofia and **d** Plovdiv, May–September of 1951–2004

Doorenbos and Kassam 1979), whose Ky value of 1.6 was calibrated as referred in the above-mentioned studies.

Data used with WinISAREG model consisted of:

1. Daily (and monthly) precipitation and ETo data series (1951–2004) relative to the eight locations referred above, with ETo computed as described by Popova et al. (2006a).

2. Soil water holding capacity values, herein the TAW values, relative to the three main soil types occurring in the regions represented by each of the eight locations. TAW values were determined in former studies (Koinov et al. 1998; Stoyanov 2008; Boneva 2012). In southern Bulgaria, the most common soils are the chromic luvisols and cambisols that have predominantly medium TAW (136 mm m^{-1}) and vertisols of large TAW ($170 \leq TAW \leq 180$ mm m^{-1}). In the plains of northern Bulgaria, TAW ranges from 157 to 180 mm m^{-1} in chernozems soils or $TAW > 170$ mm m^{-1} in vertisols. In the terraces along the rivers, small TAW ($\leq$116 mm m^{-1}) are found, which correspond to light-textured luvisols and alluvial soils (Boneva 2012).
3. Crop data originated from long-term field experiments, mainly reported by Varlev et al. (1994), Eneva (1997) and Varlev and Popova (1999). The parameters Kc, p and Ky were those obtained from the above-referred model calibration. The related parameterization and data on crop growth stages and root depths were extended to other locations using data obtained by Rafailov (1995, 1998), Varlev (2008) and Stoyanov (2008), which referred to various maize hybrids (Popova 2012; Popova et al. 2012).

Combining both the ISAREG and the Stewart's models, it was possible to estimate crop water and irrigation requirements and the yield impacts of water stress for each year of the series 1951–2004, i.e. the relative yield decrease (RYD) due to water stress. A test of the combined use of those models aimed at assessing alternative irrigation management issues in response to detected climate change was previously performed (Popova and Pereira 2008). Computations were performed for all eight locations and using the available TAW data and for all years of the weather data series. It resulted three RYD series, one for each soil type—low, medium and high TAW—for each location. Empirical curves relating RYD with the probability of their occurrence (P_{RYD}) were therefore built. The corresponding net irrigation requirements (NIR) were also estimated for all of years of the series and related empirical probabilities curves (P_{NIR}) were also built.

Since RYD could be related with economic losses, the RYD thresholds representing the values when yields become insufficient to achieve a positive farm return were identified for all locations. Thresholds used in the present study base upon the assumption that rainfed maize cultivation is profitable if the harvested yield is above 4,500 kg; however, this value changes with production costs and commodity prices and needs to be updated for practical use. These thresholds varied from one location/region to another because potential yield productivity was different among all locations. For example, the RYD thresholds indicative of economic losses correspond to 60 % at Plovdiv and to 48 % at Sofia: for Tsalapitsa, Plovdiv, the average potential yield for the period 1971–1991 using tardy maize hybrids (H708, 2L-602 and BC622) is $Y_{max} = 11{,}228$ kg ha^{-1} while for Gorni Lozen, Sofia, $Y_{max} = 8{,}460$ kg ha^{-1} was observed for the same period with semi-early maize hybrids (HD-225, SK-48A, Px-20, P37-37). Further information on yields for all locations and relative to soils with low, medium and high TAW are reported by Popova et al. (2012).

Considering the advantages of using standardized precipitation anomalies when comparing the various locations under study, the SPI-2 relative to the peak demand period of July and August (SPI-$2_{July–Aug}$) was assumed as indicator of water deficit. The RYD values were then linearly related with the SPI-$2_{July–Aug}$. Thus, since the threshold values for RYD at each location/region were known, the corresponding SPI-$2_{July–Aug}$ were computed and the SPI-$2_{July–Aug}$ thresholds indicative of conditions when dryness is likely to cause negative farm returns were identified.

3 Results

3.1 Climate variability and trends

The output of the trend analyses of precipitation (Table 1) shows no significant trends for most of the months and locations. There is a negative trend for most months in Plovdiv resulting in a significant decrease of the annual precipitation (−3.52 mm $year^{-1}$). A similar behaviour was observed for Stara Zagora, with −3.3 mm $year^{-1}$. Thus, negative trends of precipitation refer to the Thrace plain. Differently, Varna shows 6 months with a positive trend resulting in a small annual increase of 0.02 mm $year^{-1}$. A similar trend was found for Sandanski, where precipitation increases by 0.03 mm $year^{-1}$.

The trend analysis of the maximum temperature (Table 2) shows significant trends for increase, particularly in June and July, at various locations, e.g. Stara Zagora and Silistra, where a significant increase in maximum temperature is detected in 4 months. With the exception of Pleven, all stations have a positive trend for maximum temperature on a year basis, with a mean increase of 0.024 °C $year^{-1}$. Trends for increase of the minimum temperature (Table 2) are rarely significant during the cold months; differently, significant increasing trends in the summer months were found at various locations. This is the case for Sofia and Stara Zagora that show positive trends for 5 and 8 months, respectively, resulting positive annual trends for both. Differently, a negative trend was observed for Varna.

The SPI-2 relative to July–August (SPI-$2_{July–Aug}$), i.e. for the maize peak demand months, was previously identified as possibly appropriate indicator of dryness impacts on yields (Popova et al., 2012). The frequency of SPI-$2_{July–Aug}$ drought classes are shown in Fig. 3 for all locations. Frequencies computed with data relative to the first and second half of the 1951–2004 period are compared in Fig. 3 showing that the frequency of SPI-$2_{July–Aug}$ classes varies within the country and, when comparing wet and dry years, dryness is mostly increasing as indicated by the higher frequency of severe and extreme dry years

Table 1 Precipitation trend (mm $year^{-1}$; underlined when significant at 95 % probability)

	Northern locations				Southern locations			
	Lom	Pleven	Silistra	Varna	Sofia	Sandanski	Plovdiv	Stara Zagora
January	−0.17	0.25	−0.19	0.03	−0.20	0.02	−0.25	−0.39
February	$\underline{-0.56}$	0.74	−0.04	0.04	0.05	0.03	−0.09	−0.32
March	−0.23	0.39	$\underline{0.46}$	$\underline{0.06}$	0.11	0.05	−0.14	0.00
April	−0.05	0.94	0.27	0.02	0.02	0.01	−0.20	−0.39
May	−0.09	0.67	−0.21	$\underline{0.03}$	0.16	$\underline{0.04}$	−0.55	−0.58
June	−0.48	0.25	0.05	$\underline{0.02}$	−0.52	$\underline{0.06}$	$\underline{-0.92}$	−0.39
July	0.30	0.36	−0.08	0.21	−0.51	0.12	−0.31	−0.44
August	−0.05	0.15	0.18	$\underline{0.04}$	0.27	0.02	0.06	0.11
September	0.50	0.49	0.44	$\underline{0.02}$	0.17	0.01	−0.2	0.27
October	−0.11	0.71	0.14	0.03	−0.05	0.01	−0.43	$\underline{-0.29}$
November	−0.40	0.23	0.09	−0.01	−0.23	0.00	$\underline{-0.45}$	−0.43
December	−0.02	0.83	0.12	$\underline{-0.02}$	−0.01	−0.02	0.10	−0.09
Year	−1.27	0.35	1.14	$\underline{0.02}$	−0.95	$\underline{0.03}$	$\underline{-3.52}$	$\underline{-3.30}$

Table 2 Temperature trend (°C year^{-1}; underlined when significant at 95 % probability)

	Northern location				Southern location			
	Lom	Pleven	Silistra	Varna	Sofia	Sandanski	Plovdiv	Stara Zagora
Maxima								
January	0.04	−0.01	0.02	0.02	0.05	0.02	0.01	0.05
February	0.06	0.02	0.05	0.03	0.04	0.03	0.03	0.08
March	$\underline{0.07}$	0.03	$\underline{0.06}$	0.05	0.05	0.05	$\underline{0.05}$	$\underline{0.09}$
April	0.01	0.00	0.02	0.02	0.00	0.01	0.00	0.02
May	0.03	0.02	0.04	$\underline{0.04}$	0.03	$\underline{0.04}$	0.03	$\underline{0.04}$
June	0.03	$\underline{0.03}$	$\underline{0.03}$	$\underline{0.04}$	$\underline{0.05}$	$\underline{0.06}$	$\underline{0.04}$	$\underline{0.05}$
July	0.02	0.02	$\underline{0.03}$	0.03	$\underline{0.05}$	$\underline{0.04}$	0.03	$\underline{0.04}$
August	0.01	−0.01	0.02	0.03	0.04	0.02	0.01	0.05
September	−0.02	−0.02	−0.01	0.01	$\underline{0.01}$	0.01	0.00	0.00
October	0.00	−0.01	0.00	0.00	0.01	0.01	0.01	0.01
November	0.00	−0.03	−0.01	−0.01	−0.04	0.00	0.00	0.00
December	−0.01	−0.03	$\underline{0.02}$	−0.01	−0.01	−0.02	−0.01	0.00
Year	$\underline{0.02}$	0.00	$\underline{0.02}$	$\underline{0.02}$	$\underline{0.02}$	$\underline{0.03}$	$\underline{0.02}$	$\underline{0.04}$
Minima								
January	0.00	−0.01	0.02	−0.01	0.04	0.00	−0.01	0.03
February	0.02	0.01	0.03	−0.02	0.02	0.00	−0.01	0.04
March	0.04	0.04	$\underline{0.05}$	0.02	$\underline{0.05}$	0.02	0.03	$\underline{0.06}$
April	0.00	0.03	0.02	0.00	$\underline{0.03}$	0.00	0.01	0.02
May	0.01	0.01	0.00	−0.02	$\underline{0.03}$	0.02	0.01	$\underline{0.03}$
June	0.00	0.02	0.02	−0.01	$\underline{0.04}$	$\underline{0.02}$	$\underline{0.02}$	$\underline{0.02}$
July	0.02	0.02	$\underline{0.03}$	0.03	$\underline{0.05}$	$\underline{0.04}$	0.03	$\underline{0.04}$
August	0.01	0.02	0.00	−0.01	0.04	0.02	$\underline{0.02}$	$\underline{0.04}$
September	0.00	0.02	0.00	$-\underline{0.02}$	0.01	0.01	0.02	$\underline{0.02}$
October	0.00	$\underline{0.03}$	0.01	−0.02	0.02	$\underline{0.02}$	0.01	$\underline{0.03}$
November	$-\underline{0.04}$	−0.02	−0.03	−0.04	−0.01	−0.02	$-\underline{0.04}$	−0.01
December	$-\underline{0.04}$	−0.02	−0.01	$-\underline{0.04}$	0.00	−0.02	−0.02	$-\underline{0.02}$
Year	0.00	0.01	0.01	$-\underline{0.01}$	$\underline{0.03}$	0.01	0.01	$\underline{0.02}$

in the current 1978–2004 period (Fig. 3). These results indicate an aggravation of the crop water deficits and therefore a larger vulnerability of rainfed maize to drought and climate variability. However, the trend analysis for the SPI-2 (Table 3) does not show a significant trend to dryness increase during the maize crop season and the entire period of 1951–2004 except for Plovdiv. SPI results are consequent with the referred trend for rainfall decrease (Table 1).

Overall, results indicate that the Thracian Plain is likely submitted to an increased stress, with decreasing precipitation, increased maximum and minimum temperature and increased drought severity and frequency. However, the climate uncertainty is very high and results of trend analysis are yet insufficiently clear. When it would be possible to use longer data series, results could be less uncertain.

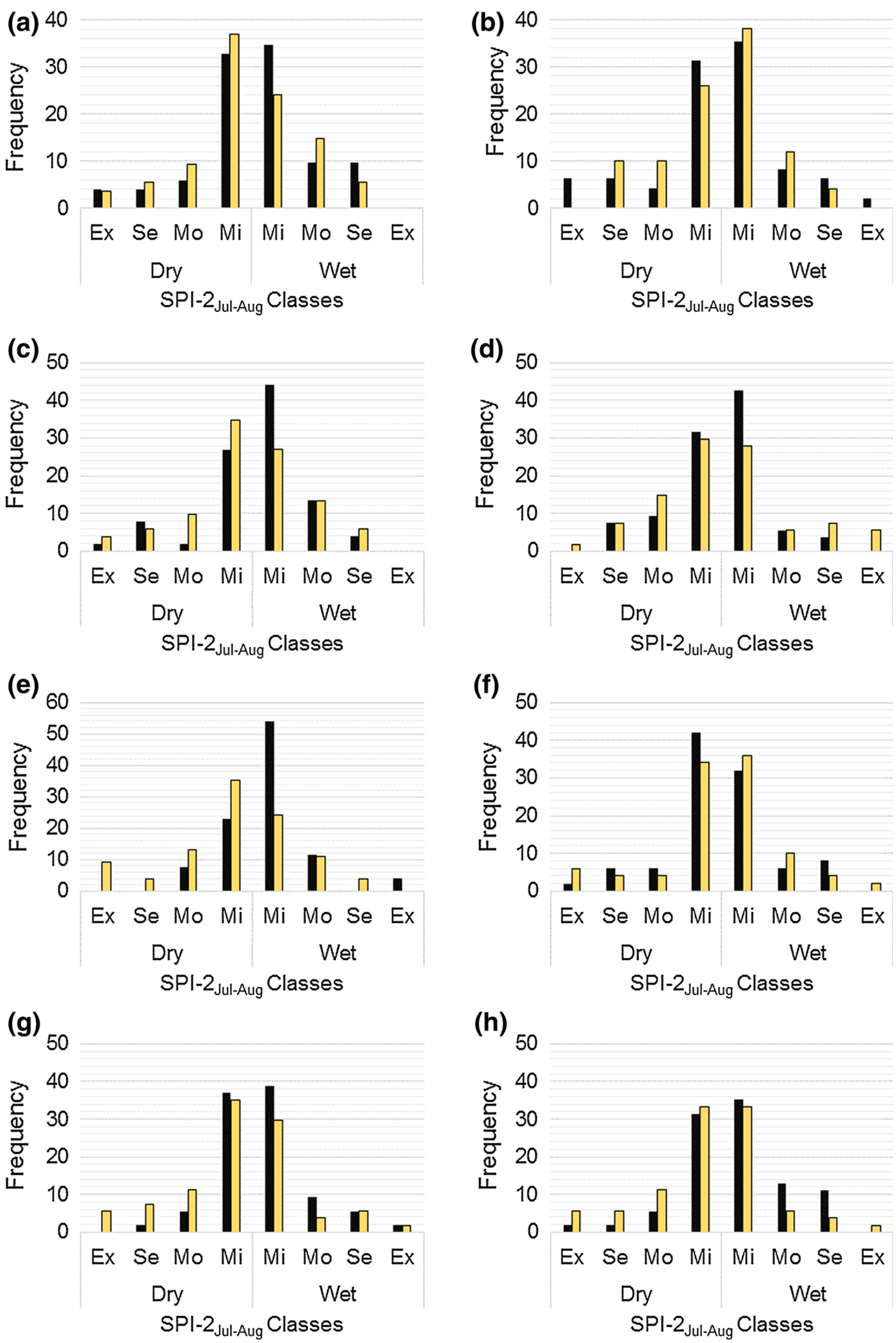

Fig. 3 Frequency (%) of SPI-2$_{July–Aug}$ drought and wet classes (Extreme-Ex; Severe-Se; Moderate-Mo and Mild-Mi) comparing the current (1979–2004;) and past (1951–1978;) observation periods at: **a** Lom, **b** Pleven, **c** Silistra, **d** Varna, **e** Sofia, **f** Stara Zagora, **g** Sandanski and **h** Plovdiv

Table 3 Trend of SPI-2 (underlined when significant at 95 % probability)

	Northern location				Southern location			
	Lom	Pleven	Silistra	Varna	Sofia	Sandanski	Plovdiv	Stara Zagora
January	−0.01	−0.01	−0.01	−0.01	$-\underline{0.02}$	−0.02	−0.01	−0.02
February	$-\underline{0.02}$	−0.01	−0.01	−0.01	−0.02	$-\underline{0.02}$	−0.01	−0.02
March	$-\underline{0.02}$	−0.01	0.01	0.01	−0.01	$-\underline{0.03}$	−0.01	0.01
April	−0.01	0.00	0.02	0.02	0.00	$-\underline{0.02}$	−0.01	0.01
May	−0.01	0.00	−0.01	−0.01	−0.01	−0.02	−0.02	−0.01
June	−0.02	−0.02	−0.01	−0.01	−0.02	$-\underline{0.02}$	$-\underline{0.03}$	−0.02
July	−0.01	−0.01	0.00	0.00	−0.02	−0.02	$-\underline{0.02}$	0.00
August	0.00	0.00	−0.01	−0.01	−0.02	0.00	$-\underline{0.01}$	0.01
September	0.01	0.00	0.01	0.01	−0.01	0.00	$-\underline{0.01}$	0.02
October	0.01	0.00	0.01	0.01	−0.01	−0.01	$-\underline{0.02}$	0.01
November	−0.02	−0.01	0.00	0.00	−0.02	$-\underline{0.02}$	$-\underline{0.03}$	0.00
December	−0.01	−0.01	0.00	0.00	−0.02	−0.01	$-\underline{0.01}$	−0.01
Year	−0.01	−0.01	0.00	0.00	−0.01	$-\underline{0.01}$	$-\underline{0.02}$	0.00

3.2 Relative yield decrease in relation to climate and soil characteristics

The empirical probability curves of occurrence of a relative yield decrease (RYD, %) for rainfed maize cropped in soils of small TAW (116 mm m^{-1}) are shown in Fig. 4 for Chelopechene, Sofia, and Tsalapitsa, Plovdiv. Similar analyses were performed for all other locations. Results show that RYD for Sofia has lower values than for Plovdiv for the same probabilities (P_{RYD}) because precipitation is more abundant at Sofia (Fig. 2), and the amount of precipitation required to satisfy maize demand is larger at Plovdiv. These results indicate that when soils have low soil water holding capacity, as for the referred cases (116 mm m^{-1}), rainfed maize yields are not only affected by droughts but also by climate variability because the RYD thresholds refer to high impacts on yields when a drought occurs or when rainfall is insufficient to cover the requirements of maize aimed at attaining a positive return. This is clear for Plovdiv when compared with Sofia (Fig. 4).

Results in Fig. 5 refer to the empirical probability curves of the relative yield decrease at Pleven and Plovdiv, respectively, in northern and southern Bulgaria, where RYD is affected by the soil water holding capacity, considering the late maize hybrids H708, 2L602 and BC622. When comparing Fig. 5a, b, it becomes evident that the vulnerability is much higher for southern (Plovdiv) than for northern locations (Pleven) despite climate favours maize yields in southern regions. Moreover, both figures show that cultivation in soils with high TAW (180 mm m^{-1}) leads to much less RYD relative to soils with low TAW. For Pleven, the RYD threshold refers to only 12 % of years if a soil with high TAW is considered, and to 30 % of the years when maize is cropped in a soil with low TAW (Fig. 5a). Differently, for Plovdiv, the same thresholds correspond to 30 and 68 % of the years, respectively (Fig. 5b). These examples clearly show the combined effects of climate and soil type.

The empirical probability curves of RYD relative to six climate regions—Silistra, Pleven and Varna in northern Bulgaria, and Sofia, Plovdiv and Sandanski in south—are compared in Fig. 6a for rainfed maize cultivated in soils of medium TAW

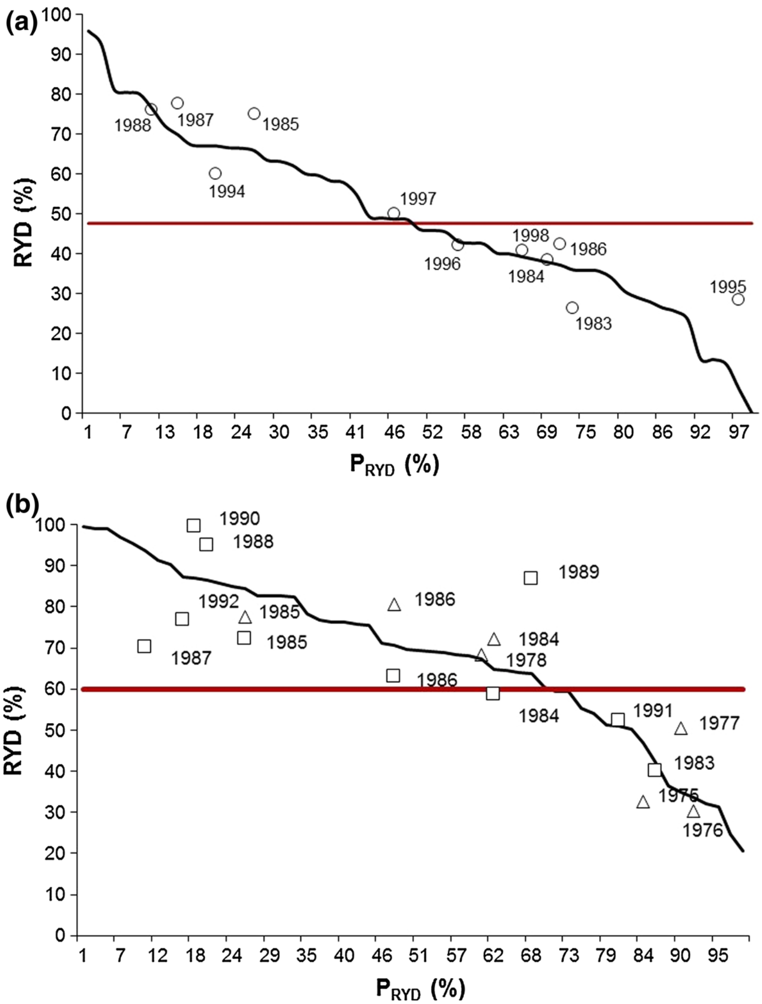

Fig. 4 Probability curves of occurrence of a relative yield decrease RYD (—) for rainfed maize, Ky = 1.6, cropped in a soil of small TAW (116 mm m^{-1}) and observed data for **a** Chelopechene (○), in Sofia, and **b** Tsalapitsa, Plovdiv (□, △), with identification of the RYD thresholds (—) for both cases

(136–157 mm m^{-1}). In Fig. 6b, the probability curves for the same locations are compared when the soil has a large TAW. It can be noticed that the northern locations have the respective probability curves grouped below the Plovdiv and Sandanski curves, while Sofia behaves differently of other southern locations, and the respective curve is the lowest because precipitation is higher there. Consequently, the RYD threshold is the lowest (48 %) at Sofia, i.e. the vulnerability to droughts and climate variability is smaller for the region of Sofia. The RYD curve for Sandanski is above all others, which means that vulnerability is highest in this southern region where climate approaches the Mediterranean climate. In fact, rainfed maize is generally not feasible in regions with Mediterranean climate (Rodrigues et al. 2013) because yields heavily decrease when water is lacking during the sensitive tasselling and cob formation stages (Çakir 2004).

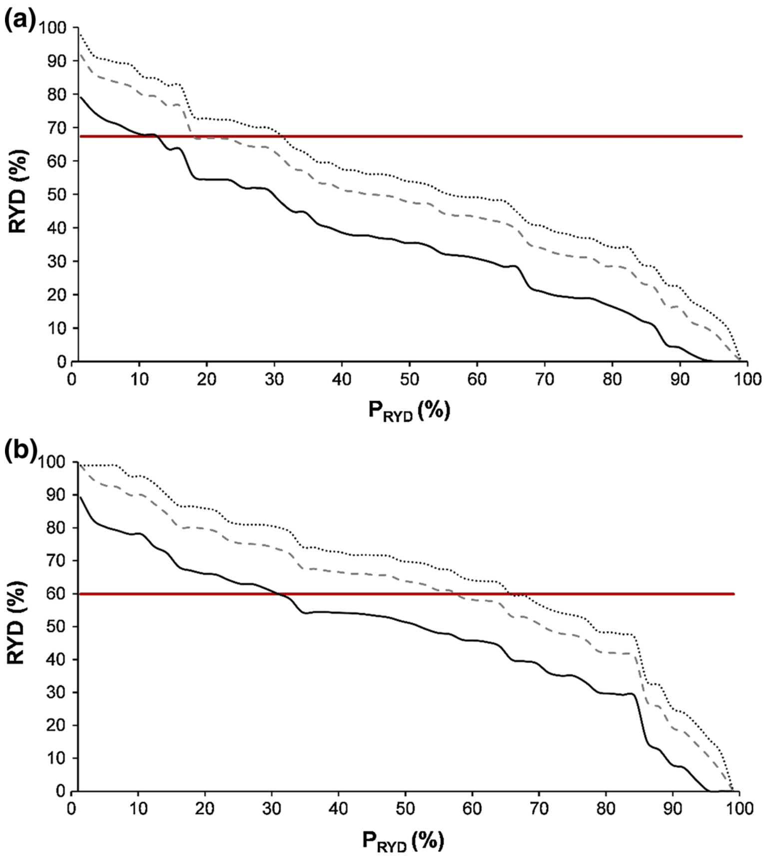

Fig. 5 Probability curves of relative yield decrease RYD for rainfed maize comparing soil groups of small (·····), medium (---) and large (—) TAW at: **a** Pleven and **b** Plovdiv, (late maize hybrids H708, 2L602 and BC622 having Ky = 1.6, 1951–2004) with identification of the RYD thresholds (—) for both locations

The RYD curve of Pleven is the lowest but above that of Sofia. As it may be observed comparing Fig. 6a, b, the relative position of the empirical probability curves is the same for soils with medium and high TAW. The difference is that RYD increase when soil TAW decreases. Comparing all six RYD curves, it may be concluded that the vulnerability decreases in the following order: Sofia, Pleven, Silistra, Varna, Plovdiv and Sandanski. These results indicate a decrease of vulnerability mainly depending upon the amount of precipitation during the maize crop season.

In northern Bulgaria, the economical RYD threshold are 67, 55 and 60 %, respectively, for Pleven, Lom and Silistra. They correspond to the average yield potential for the period 1971–1991 of $Y_{max} = 13{,}790$ kg ha^{-1} at Gorni Dubnik, Pleven, $Y_{max} = 9{,}910$ kg ha^{-1} at Kovachitsa, Lom, and $Y_{max} = 11{,}130$ kg ha^{-1} at Slivo, Silistra. When TAW = 180 mm m^{-1}, only 10 % of the years are at risk of economic losses at Pleven and Silistra and near 20 % in Lom region. When TAW is medium (157 mm m^{-1}), the risky years are 18, 35 and 45 % in those three sites and reach 50 % in Varna (Fig. 6a).

Rainfed maize is associated with great yield variability (results not shown), with the coefficient of variation relative to 1951–2004 in the range $29 < Cv < 72$ %. The

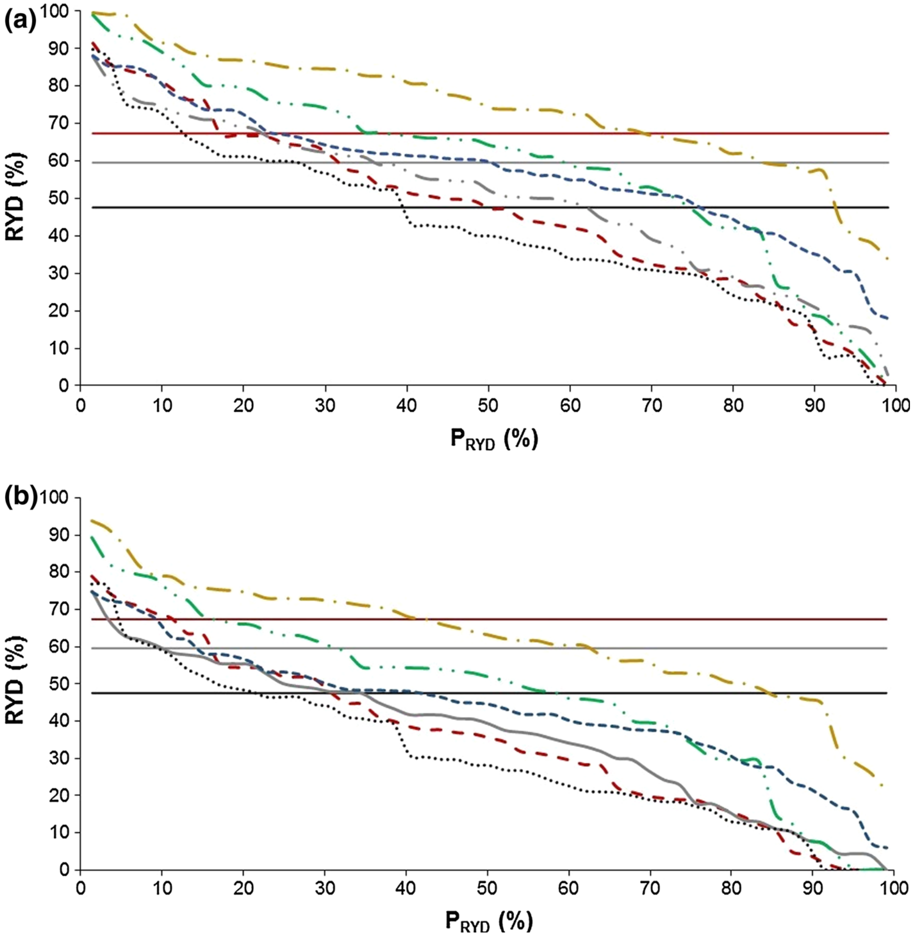

Fig. 6 Comparison of empirical probability curves of the relative yield decrease (RYD, %) relative to six regions: Silistra (—), Pleven (----), and Varna (---) in northern Bulgaria, and Sofia (····), Plovdiv (–··), and Sandanski (-·) in south—for two soil groups: **a** medium TAW (136–157 mm m^{-1}) and **b** large TAW (180 mm m^{-1}). Also represented the RYD thresholds for Pleven (—), Plovdiv (—) and Sofia (—)

coefficient of variability ranges 29–42 % in Sofia, with Cv = 29 % for soils with larger TAW. Higher Cv are for the other southern regions, namely in Sandanski (Cv = 72 %), Plovdiv (Cv = 69 %) and Stara Zagora (Cv = 59 %). The variability of rainfed maize in the Danube Plain (Pleven, Varna and Silistra) is much lower than in the Thracian Lowland. However, in the region of Lom, the yield variability is also high (35 < Cv < 55 %).

3.3 Irrigation requirements in relation to climate and soil characteristics

Probability curves of net irrigation requirement (NIR, mm) for maize were built using WinISAREG over the period 1951–2004 (Popova 2012). Results relative to Plovdiv (Fig. 7a) show that for soils of large TAW (180 mm), NIR vary 0–40 mm in wet years, i.e. when the probability of exceedence is $P_{NIR} > 95$ %, 140–220 mm in average demand

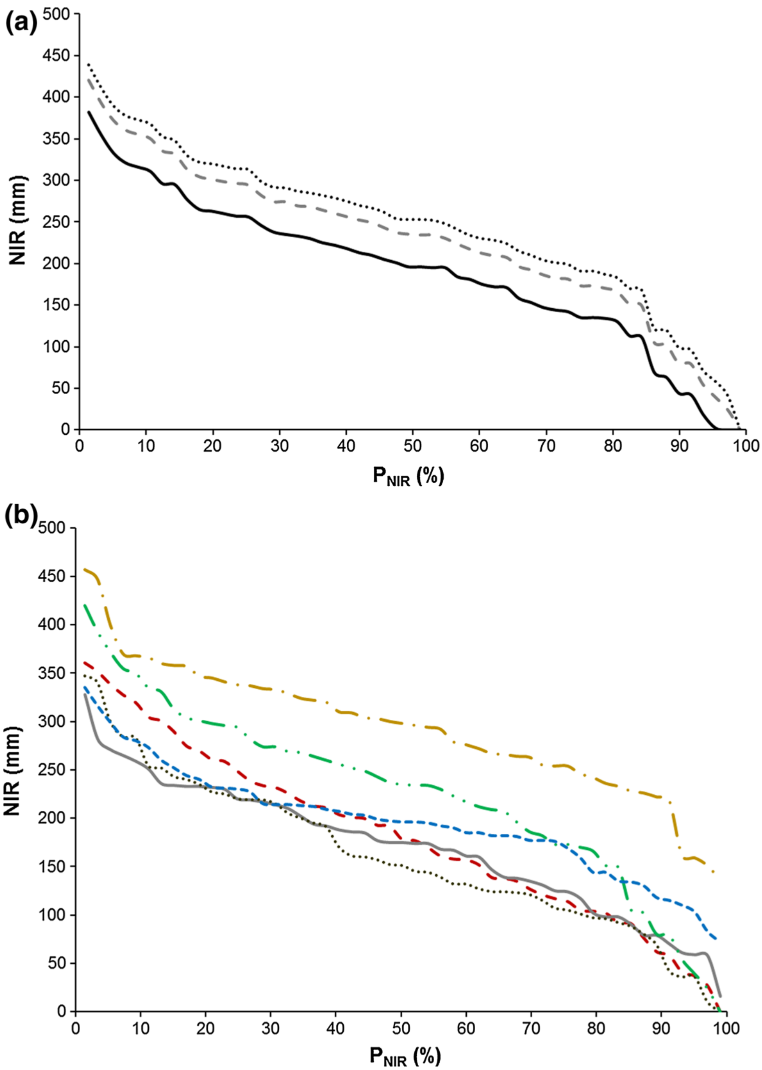

Fig. 7 Probability curves for net irrigation requirements (NIR): **a** at Plovdiv as influenced by small (·····), medium (---) and large (—) TAW; **b** NIR for 6 regions: Silistra (—), Pleven (----), Sofia (····), Plovdiv (–··), Sandanski (-·) and Varna (---); considering soils of medium water holding capacity (TAW = 136–157 mm m^{-1})

years (40 % < P_{NIR} < 75 %), and 350–380 mm in very dry years (P_{NIR} < 5 %). In soils with small TAW (116 mm), NIR increase and reach 440 mm in the very dry year. Differently, NIR in Sofia and Silistra (Fig. 7b) are about 100 mm smaller than in Plovdiv, while in Sandanski they are about 110 mm larger.

An empirical trend analysis was performed for both NIR and RYD (results not shown), which shows that both NIR and RYD may increase for the last years of the period (1951–2004). Then, NIR for Plovdiv region may increase by 80 mm, and RYD may increase by 0.35 % $year^{-1}$, i.e. a decrease of about 40 kg ha^{-1} $year^{-1}$ may be expected if

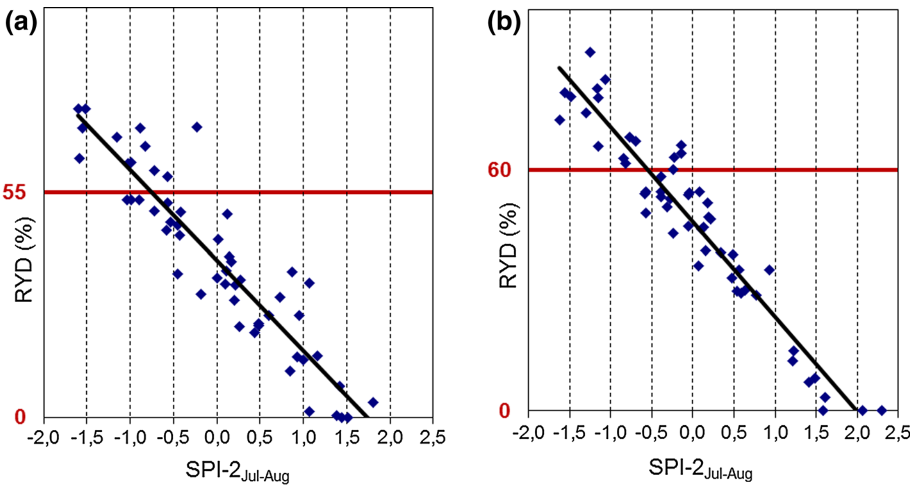

Fig. 8 Linear regressions between Relative yield decrease and SPI-$2_{\text{July–Aug}}$ for: **a** Lom and **b** Plovdiv considering soils of large TAW (180 mm m^{-1}), with respective threshold (—)

irrigation is not applied. Similarly, NIR for the region of Stara Zagora may increase by 27 mm while grain production may decrease by 0.14 % $year^{-1}$. However, significant trends were not found and further analysis is required, namely for other regions.

3.4 Using the SPI-2 as water stress indicator for rainfed maize

It is important to relate RYD with the SPI-$2_{\text{July–Aug}}$ because the SPI is standardized and therefore is well comparable among locations and from a year to another (Guttman 1998; Lana et al. 2001; Bordi et al. 2009). In addition, it contains a probabilistic interpretation (Fig. 3). Thus, when using SPI values, one knows when precipitation at a given location is near normal, or is anomaly in excess or deficit, and may easily compare among locations with different climatic characteristics. SPI-$2_{\text{July–Aug}}$ provides therefore a quick information for management, namely when mapped at country level.

SPI-$2_{\text{July–Aug}}$ were related to RYD for all eight climate regions under study. Examples of the linear relationships obtained are shown in Fig. 8. Statistical results are given in Table 4, and they include the determination coefficient (R^2), the regression coefficient (b) and the intercept when relationships are computed for low, medium and high TAW soils.

The determination coefficients are generally high, which means that a large fraction of the RYD variation is explained by the SPI-$2_{\text{July–Aug}}$, i.e. by the dryness conditions during the maize peak demand period. Changes of R^2 for different soils are negligible. These results confirm the preceding analysis and the possibility of using SPI-$2_{\text{July–Aug}}$ as an indicator of water deficit not depending upon the soil type. The regression coefficients may be assumed as indicators of the linear yield decrease of RYD when SPI-$2_{\text{July–Aug}}$ decreases from its maximum (wet conditions) to low (and negative) values referring to dryness (see Fig. 8). Results show that their values change little among the regions and, for each location, among soil groups. Differently, the intercept (value of RYD when SPI-$2_{\text{July–Aug}} = 0$) depends upon the soil group: the intercept decreases from low to high TAW

Table 4 Parameters of the linear regression between RYD (%) and SPI-$2_{\mathrm{July-Aug}}$ for all climate regions and considering three soil water holding capacities (TAW) for the period 1951–2004

Region	Soil groups according to TAW		
	Small TAW ($116\ \mathrm{mm\ m^{-1}}$)	Medium TAW ($136–157\ \mathrm{mm\ m^{-1}}$)	Large TAW ($180\ \mathrm{mm\ m^{-1}}$)
Northern locations			
Lom			
Determination coefficient	0.86	0.86	0.86
Regression coefficient	−0.24	−0.24	−0.22
Intercept	54	48	36
Pleven			
Determination coefficient	0.82	0.81	0.79
Regression coefficient	−0.23	−0.23	−0.22
Intercept	56	49	36
Silistra			
Determination coefficient	0.86	0.86	0.86
Regression coefficient	−0.21	−0.20	−0.19
Intercept	64	57	43
Varna			
Determination coefficient	0.82	0.81	0.80
Regression coefficient	−0.18	−0.18	−0.17
Intercept	48	43	31
Southern locations			
Sofia			
Determination coefficient	0.76	0.75	0.73
Regression coefficient	−0.18	−0.18	−0.19
Intercept	31	31	31
Sandanski			
Determination coefficient	0.75	0.77	0.78
Regression coefficient	−0.15	−0.16	−0.16
Intercept	65	59	45
Plovdiv			
Determination coefficient	0.92	0.92	0.91
Regression coefficient	−0.25	−0.25	−0.24
Intercept	67	62	51
Stara Zagora			
Determination coefficient	0.80	0.82	0.83
Regression coefficient	−0.20	−0.21	−0.21
Intercept	67	62	51

since dryness has larger influence on RYD when TAW is small as already discussed before.

The SPI-$2_{\mathrm{July-Aug}}$ threshold, when computed for the values of RYD that, for each soil group, do not produce negative economic results, may be used as indicators of dryness that

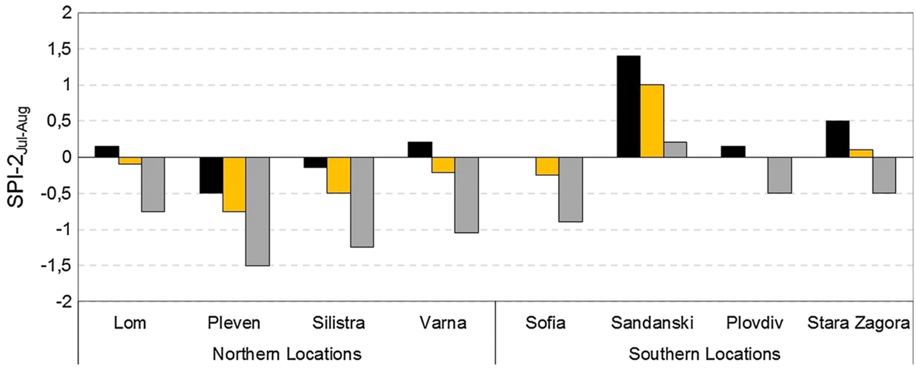

Fig. 9 Threshold values of SPI-$2_{\text{July–Aug}}$ indicative of economic risk for rainfed maize in various regions and soil types having small (■), medium (■) and large (■) TAW

affects yields. These values are represented in Fig. 9 for all locations and soil groups. It can be observed that for Pleven and soils with high TAW, negative economic impacts occur only in severely/extremely dry peak demand periods when SPI-$2_{\text{July–Aug}} < -1.5$ while for Sandanski such impacts occur for SPI-$2_{\text{July–Aug}} < +0.20$ in Sandanski. This also indicate that the region of Sandanski is extremely vulnerable to water deficits in rainfed maize systems or, in other words, that rainfed maize is not viable there. This is due to the predominant climate, of Mediterranean type, where rainfall in summer is low, much less than in all other regions of Bulgaria.

Results in Fig. 9 show that in the Thrace Plain (Plovdiv and Stara Zagora), for soils with low or medium TAW, rainfed maize is vulnerable to dryness even when SPI-$2_{\text{July–Aug}}$ are not negative, which indicates a high vulnerability to water stress in that area. However, that vulnerability is lower for soils with high TAW when SPI-$2_{\text{July–Aug}}$ thresholds are not lower than -0.50 (Fig. 9). In north Bulgaria, conditions are more favourable but the risk of economic losses is high for soils with low TAW (Fig. 9) mainly along the Black Sea coast (Varna) and in the region of Lom.

When monitoring precipitation, the adoption of SPI-$2_{\text{July–Aug}}$ may be useful to manage the risk of economic losses with rainfed maize by advising farmers to adopt supplemental irrigation if water is available at farm. The related farm advising may be regionally oriented and take into consideration peculiar aspects of farming, mainly the dominant soil type. However, the SPI-$2_{\text{July–Aug}}$ threshold values need to be updated every year to reflect the actual economic farming conditions.

4 Conclusions

This study, applied to eight Bulgarian locations representing main agricultural regions and three soil groups relative to different TAW, allowed an analysis of climate variability during 1951–2004 and of related impacts on rainfed maize systems. Significant negative trends were identified for precipitation, maximum and minimum temperature and the SPI-2 in a few months, mainly during the maize season, and for the southern locations. Overall, trends allow to perceive a slight increase of dryness in the Thrace region and Sandanski.

Analysing the empirical probability curves of occurrence of RYD, it could be concluded that RYD varies with climate, mainly with precipitation during the maize season, and with the soil type relative to soil water holding capacity. It was observed that vulnerability of rainfed maize systems is larger in southern regions and for soils with low TAW. In addition, economic impacts on yields were observed not only for drought years but also for other years when precipitation was insufficient to satisfy the minimum water requirements of the maize crop.

Linear relationships were found relating RYD with the SPI-$2_{\text{July–Aug}}$. The determination coefficients were generally high, thus indicating that a large fraction of the RYD variation is explained by the SPI-$2_{\text{July–Aug}}$, i.e. by the dryness conditions during the maize peak demand period. These results allow considering the SPI-$2_{\text{July–Aug}}$ as an indicator of water deficit for rainfed maize, which is not depending of the soil type. The regression coefficients may be assumed as indicators of the linear yield decrease of RYD when SPI-$2_{\text{July–Aug}}$ also decreases from maximum values (wet conditions) to low negative ones, again not depending upon the soil type. Differently, the intercept (value of RYD when SPI-$2_{\text{July–Aug}} = 0$) reflects the soil group and decreases from low to high soil TAW.

The above-referred analysis suggested the use of threshold values of SPI-$2_{\text{July–Aug}}$ resulting from the inverse computation of the RYD values that, for each soil group and location, do not produce negative economic results. These SPI-$2_{\text{July–Aug}}$ values may then be used as threshold indicators of dryness that affects yields. These values change among locations, with higher thresholds for southern regions and lower ones for northern and less vulnerable regions. SPI-$2_{\text{July–Aug}}$ threshold values also change with soil types, being higher when TAW is low. SPI-$2_{\text{July–Aug}}$ values also change with the economic balance of maize production and may be used for water management purposes. SPI-$2_{\text{July–Aug}}$ values may therefore support advising farmers about the risk for economic losses and to adopt the supplemental irrigation if water may be available. Results show that vulnerability to water stress may be well identified with the approach described above and mitigated if that methodology is purposefully explored in the water management practice. Further studies are desirable in terms of analysing the constraints of irrigation as an adaptation measure to cope with droughts and climate change.

Acknowledgments Authors gratefully acknowledge the financial support of Drought Management Centre for South East Europe Project, South East Europe Transnational Cooperation Programme co-funded by the European Union and FCT-Portugal funded project PTDC/GEO-MET/3476/2012.

References

Alexandrov V (1999) Vulnerability and adaptation of agronomic systems in Bulgaria. Clim Res 12:161–173

Alexandrov V (ed) (2011) Methods for monitoring and estimation of drought vulnerability in Bulgaria. National Institute of Meteorology and Hydrology and Bulgarian Academy of Sciences, Sofia, 216 (in Bulgarian)

Alexandrov VA, Hoogenboom G (2000) The impact of climate variability and change on crop yield in Bulgaria. Agric For Meteorol 104:315–327

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration—guidelines for computing crop water requirements. Irrigation and drainage paper 56, FAO, Rome

Boneva K (2012) Study on soil characteristics related to calibration and use of "crop-water-yield" simulation models. In: Z Popova (ed) Risk assessment of drought in agriculture and irrigation management through simulation models. "N. Poushkarov" Institute of Soil Science, Sofia, pp 141–165 (in Bulgarian)

Bordi I, Sutera A (2004) Drought variability and its climatic implications. Glob Plan Chang 40:115–127

Bordi I, Fraedrich K, Sutera A (2009) Observed drought and wetness trends in Europe: an update. Hydrol Earth Syst Sci 13:1519–1530

Çakir R (2004) Effect of water stress at different development stages on vegetative and reproductive growth of corn. Field Crops Res 89:1–16
Conde C, Liverman D, Flores M, Ferrer R, Araújo R, Betancourt E, Villarreall G, Gay C (1997) Vulnerability of rainfed maize crops in Mexico to climate change. Clim Res 9:17–23
Doorenbos J, Kassam AH (1979) Yield response to water. Irrigation and drainage paper 33, FAO, Rome
Doorenbos J, Pruitt WO (1977) Crop water requirements. Irrigation and drainage paper 24. FAO, Rome
Dow K (2010) News coverage of drought impacts and vulnerability in the US Carolinas, 1998–2007. Nat Hazards 54:497–518
Eneva S (1997) Irrigation and irrigation effect on field crops. Problems of crop production science and practice in Bulgaria. Agricultural University of Plovdiv (in Bulgarian)
Fraser ED, Simelton E, Termansen M, Gosling SN, South A (2013) "Vulnerability hotspots": integrating socio-economic and hydrological models to identify where cereal production may decline in the future due to climate change induced drought. Agric For Meteorol 170:195–205
Gregoric G (ed) (2012) Drought management centre for South-East Europe—DMCSEE. Summary of project results, Slovenian Environmental Agency, Ljubljana. http://www.met.hu/doc/DMCSEE/DMCSEE_final_publication.pdf
Guttman NB (1998) Comparing the Palmer drought index and the standardised precipitation index. J Am Water Res As 34:113–121
Hamed KH, Rao RA (1998) A modified Mann Kendall test for autocorrelated data. J Hydrol 204:182–196
Helsel DR, Hirsch RM (1992) Statistical methods in water resources. Elsevier, Amsterdam
Hlavinka P, Trnka M, Semeradova D, Dubrovsky M, Zalud Z, Mozny M (2009) Effect of drought on yield variability of key crops in Czech Republic. Agric For Meteorol 149:431–442
Hoffman MT, Carrick PJ, Gillson L, West AG (2009) Drought, climate change and vegetation response in the succulent karoo, South Africa. S Afr J Sci 105:54–60
Huth R, Pokorná L (2004) Parametric versus non-parametric estimates of climatic trends. Theor Appl Climatol 77:107–112
Ivanova M, Popova Z (2011) Model validation and crop coefficients for maize irrigation scheduling based on field experiments in Sofia. In: "100 years soil science in Bulgaria", Trans Nat Conf, Sofia, pp 542–548 (in Bulgarian)
Kang Y, Khan S, Ma X (2009) Climate change impacts on crop yield, crop water productivity and food security—a review. Prog Nat Sci 19:1665–1674
Keyantash J, Dracup JA (2002) The quantification of drought: an evaluation of drought indices. Bull Am Meteorol Soc 83:1167–1180
Koinov V, Kabakchiev I, Boneva K (1998) Atlas of the soils in Bulgaria. Zemizdat, Sofia
Koleva E, Alexandrov V (2008) Drought in Bulgarian low regions during the 20th century. Theor Appl Climatol 92:113–120
Krysanova V, Vetter T, Hattermann F (2008) Detection of change in drought frequency in the Elbe basin: comparison of three methods. Hydrol Sci J 53:519–537
Lana X, Serra C, Burgueño A (2001) Patterns of monthly rainfall shortage and excess in terms of the standardized precipitation index for Catalonia (NE Spain). Int J Climatol 21:1669–1691
Li W, Fu R, Juarez RIN, Fernandes K (2008) Observed change of the standardized precipitation index, its potential cause and implications to future climate change in the Amazon region. Phil Trans R Soc B 363:1767–1772
Liu Y, Teixeira JL, Zhang HJ, Pereira LS (1998) Model validation and crop coefficients for irrigation scheduling in the North China Plain. Agric Water Manag 36:233–246
Liu X, Wang Y, Peng J, Braimoh AK, Yin H (2013) Assessing vulnerability to drought based on exposure, sensitivity and adaptive capacity: a case study in middle Inner Mongolia of China. Chin Geogr Sci 23:13–25
Lloyd-Hughes B, Saunders MA (2002) A drought climatology for Europe. Int J Climatol 22:1571–1592
Martins DS, Raziei T, Paulo AA, Pereira LS (2012) Spatial and temporal variability of precipitation and drought in Portugal. Nat Hazards Earth Syst Sci 12:1493–1500
McKee TB, Doesken NJ, Kleist J (1993) The relationship of drought frequency and duration to time scales. In: Proceedings of 8th conference on applied climatology, American Meteorological Society, Boston, pp 179–184
McKee TB, Doesken NJ, Kleist J (1995) Drought monitoring with multiple time scales. In: Proceedings of 9th conference on applied climatology, American Meteorological Society, Boston, pp 233–236
Mishra AK, Desai VR (2005) Drought forecasting using stochastic models. Stoch Environ Res Risk Assess 19:326–339
Mishra AK, Singh VP (2010) A review of drought concepts. J Hydrol 391:202–216

Moreira EE, Coelho CA, Paulo AA, Pereira LS, Mexia JT (2008) SPI-based drought category prediction using loglinear models. J Hydrol 354:116–130

Moreira EE, Mexia JT, Pereira LS (2012) Are drought occurrence and severity aggravating? A study on SPI drought class transitions using log-linear models and ANOVA-like inference. Hydrol Earth Syst Sci 16:3011–3028

National Drought Mitigation Center (NDMC) (2014) Drought basics. National Drought Mitigation Center. http://drought.unl.edu/DroughtBasics/WhatisDrought.aspx. Accessed 10 Feb 2014

Olesen JE, Trnka M, Kersebaum KC, Skjelvåg AO, Seguin B, Peltonen-Sainio P, Rossi F, Kozyra J, Micale F (2011) Impacts and adaptation of European crop production systems to climate change. Eur J Agron 34:96–112

Paulo AA, Pereira LS (2008) Stochastic prediction of drought class transitions. Water Resour Manag 22:1277–1296

Paulo AA, Pereira LS, Matias PG (2003) Analysis of local and regional droughts in southern Portugal using the theory of runs and the Standardized Precipitation Index. In: Rossi G, Cancelliere A, Pereira LS, Oweis T, Shatanawi M, Zairi A (eds) Tools for drought mitigation in Mediterranean Regions. Kluwer, Dordrecht, pp 55–78

Paulo AA, Rosa R, Pereira LS (2012) Climate trends and drought indices based on precipitation and evapotranspiration in Portugal. Nat Hazards Earth Syst Sci 12:1481–1491

Pereira LS, Teodoro PR, Rodrigues PN, Teixeira JL (2003) Irrigation scheduling simulation: the model ISAREG. In: Rossi G, Cancelliere A, Pereira LS, Oweis T, Shatanawi M, Zairi A (eds) Tools for drought mitigation in Mediterranean Regions. Kluwer, Dordrecht, pp 161–180

Pereira LS, Cordery I, Iacovides I (2009) Coping with water scarcity. Addressing the challenges. Springer, Dordrech

Popova Z (ed) (2012) Risk assessment of drought in agriculture and irrigation management through simulation models. "N. Poushkarov" Institute of Soil Science, Sofia, 242 p (in Bulgarian)

Popova Z, Kercheva M (2005) Ceres model application for increasing preparedness to climate variability in agricultural planning—risk analyses. Phys Chem Earth, Parts A/B/C 30:117–124

Popova Z, Pereira LS (2008) Irrigation scheduling for furrow irrigated maize under climate uncertainties in the Thrace plain, Bulgaria. Biosyst Eng 99:587–597

Popova Z, Pereira LS (2011) Modelling for maize irrigation scheduling using long term experimental data from Plovdiv region, Bulgaria. Agric Water Manag 98:675–683

Popova Z, Kercheva M, Pereira LS (2006a) Validation of the FAO methodology for computing ETo with limited data. Application to South Bulgaria. Irrig Drain 55:201–215

Popova Z, Eneva S, Pereira LS (2006b) Model validation, crop coefficients and yield response factors for irrigation scheduling based on long-term experiments. Biosyst Eng 95:139–149

Popova Z, Ivanova M, Pereira LS, Alexandrov V, Doneva K, Alexandrova P, Kercheva M (2012) Assessing drought vulnerability of Bulgarian agriculture through model simulations. J Environ Sci Eng B 1:1017–1036

Rafailov R (1995) Annual reports of ISS N. Poushkarov, Sofia (in Bulgarian)

Rafailov R (1998) Annual reports of ISS N. Poushkarov, Sofia (in Bulgarian)

Raziei T, Saghafian B, Paulo AA, Pereira LS, Bordi I (2009) Spatial patterns and temporal variability of drought in Western Iran. Water Res Manag 29:439–455

Rodrigues GC, Paredes P, Gonçalves JM, Alves I, Pereira LS (2013) Comparing sprinkler and drip irrigation systems for full and deficit irrigated maize using multicriteria analysis and simulation modeling: ranking for water saving *vs.* farm economic returns. Agric Water Manag 126:85–96

Santos JF, Pulido-Calvo I, Portela MM (2010) Spatial and temporal variability of droughts in Portugal. Water Resour Res. doi:10.1029/2009WR008071

Sen PK (1968) Estimates of the regression coefficient based on Kendall's tau. J Am Stat As 63:1379–1389

Simelton E, Fraser ED, Termansen M, Forster PM, Dougill AJ (2009) Typologies of crop-drought vulnerability: an empirical analysis of the socio-economic factors that influence the sensitivity and resilience to drought of three major food crops in China (1961–2001). Environ Sci Policy 12:438–452

Slavov N, Koleva E, Alexandrov V (2004) The climate of drought in Bulgaria. In: Knight GG, Raev I, Staneva M (eds) Drougth in Bulgaria: a contemporary analog for climate change. Ashgate Publishing Limited, Aldershot, pp 39–52

Sönmez FK, Koemuescue AU, Erkan A, Turgu E (2005) An analysis of spatial and temporal dimension of drought vulnerability in Turkey using the standardized precipitation index. Nat Hazards 35:243–264

Sousa PM, Trigo MR, Aizpura P, Nieto R, Gimeno L, Garcia-Herrera R (2011) Trends and extremes of droughts indices throughout the 20th century in the Mediterranean. Nat Hazards Earth Syst Sci 11:33–51

Stewart JL, Hanks RJ, Danielson RE, Jackson EB, Pruitt WO, Franklin WT, Riley JP, Hagan RM (1977) Optimizing crop production through control of water and salinity levels in the soil. Utah water research laboratory report PRWG151-1. Utah State University, Logan

Stoyanov P (2008) Agroecological potential of maize cultivated on typical soils in the conditions of Bulgaria. Habilitation thesis, "N. Poushkarov" Institute of Soil Science, Sofia, (in Bulgarian)

Varlev I (2008) Potential, efficiency and risk under maize cultivation in Bulgaria. Academy of Agriculture, Sofia, 128 p (in Bulgarian)

Varlev I, Popova Z (1999) Water-evapotranspiration-yield. Irrig and Drain Inst, Sofia, 144 p (in Bulgarian)

Varlev I, Kolev N, Kirkova I (1994) Yield-water relationships and their changes during individual climatic years. In: Proceedings of 17th European Regional Conference of ICID, Varna, pp 351–360

Vicente Serrano SM, González-Hidalgo JC, Luis MD, Raventós J (2004) Drought patterns in the Mediterranean area: the Valencia region (eastern Spain). Clim Res 26:5–12

Vicente-Serrano SM (2006) Differences in spatial patterns of drought on different time scales: an analysis of the Iberian Peninsula. Water Resour Manag 20:37–60

Wang Z, He F, Fang W, Liao Y (2013) Assessment of physical vulnerability to agricultural drought in China. Nat Hazards 67:645–657

Wilhelmi OV, Wilhite DA (2002) Assessing vulnerability to agricultural drought: a Nebraska case study. Nat Hazards 25:37–58

Wu H, Wilhite DA (2004) An operational agricultural drought risk assessment model for Nebraska, USA. Nat Hazards 33:1–21

Xu W, Ren X, Johnston T, Yin Y, Klein K, Smith A (2012) Spatial and temporal variation in vulnerability of crop production to drought in southern Alberta. Can Geogr 56:474–491

Zhang J (2004) Risk assessment of drought disaster in the maize-growing region of Songliao Plain. China Agric Ecosyst Environ 102:133–153

Zhang Q, Xu CY, Zhang Z (2009) Observed changes of drought/wetness episodes in the Pearl River basin, China, using the standardized precipitation index and aridity index. Theor Appl Climatol 98:89–99